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Maximum depositional age and provenance of the Uinta Mountain Group and Big Cottonwood Formation, northern Utah: Paleogeography of rifting western Laurentia

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ABSTRACT

U-Pb detrital zircon analyses provide a new maximum depositional age constraint on the Uinta Mountain Group (UMG) and correlative Big Cottonwood Formation (BCF) of Utah, and significantly enhance our insights on the mid-Neoproterozoic paleogeographic and tectonic setting of western Laurentia. A sandstone interval of the Outlaw Trail formation with a youngest population (n = 4) of detrital zircons, from a sampling of 128 detrital zircon grains, yields a concordia age of 766 ± 5 Ma. This defines a maximum age for deposition of the lower-middle Uinta Mountain Group in the eastern Uinta Mountains and indicates that the group is no older than middle Neoproterozoic in age (i.e., Cryogenian). These data support a long-proposed correlation with the Chuar Group of Grand Canyon (younger age 742 Ma ± 6 Ma), which, like the Uinta Mountain Group and Big Cottonwood Formation, records nonmagmatic intracratonic extension. This suggests a ~742 to ≤766 Ma extensional phase in Utah and Arizona that preceded the regional rift episode (~670–720 Ma), which led to development of the Cordilleran passive margin. This is likely an intracratonic response to an early rift phase of Rodinia. Further, because the Chuar Group and the Uinta Mountain Group–Big Cottonwood Formation strata record intracratonic marine deposition, this correlation suggests a regional ~740–770 Ma transgression onto western Laurentia.

The detrital grain-age distributions from 12 samples include the following grain-age populations and interpreted provenance: 2.5–2.7 Ga (late Archean southern Wyoming province); 1.6–1.8 Ga (Paleoproterozoic Yavapai province); 1.5–1.6 Ga (Early Mesoproterozoic North American magmatic gap), 1.4–1.45 Ga (Colorado province A-type granite-rhyolite belt); 0.93–1.2 Ga (eastern Grenvillian orogen); and mid-Neoproterozoic volcanic grains (766 Ma). Sediment was transported by: (1) a major longitudinal west-flowing river system tapping the Grenville orogen, (2) local south-flowing drainages off the southern Wyoming craton, and (3) northerly and westerly flowing marine currents. The Uinta Mountain Group river system was one of several major transcontinental drainages that delivered Grenvillian zircon grains to the proto-Pacific Ocean. We propose that this river system ultimately supplied sediment to peri-Gondwanan margins along the proto-Pacific to Antarctica, Australia, and South America, providing an alternative source for explaining the problematic provenance of Grenvillian grains in these areas.

INTRODUCTION

Geochronologic constraints on Neoproterozoic successions are imperative for understanding the geologic history of the western Laurentian margin in its Rodinian and wider context. The Neoproterozoic Uinta Mountain Group (UMG) and correlative Big Cottonwood Formation (BCF) of northern Utah form a significant part of this margin. These strata are included in Succession B of North America (>720 to <1000 Ma), which is hypothesized to record intracratonic basin development marking the early stages of the breakup of Rodinia (Stewart, 1972; Young et al., 1979, 1981; Rainbird et al., 1996, 1997). Until this study, these km-thick successions have lacked geochronologic control because they contain no known tuffaceous beds or microfossils with calibrated short stratigraphic ranges.

The application of detrital zircon U-Pb geochronology has significantly advanced Proterozoic sedimentologic and stratigraphic research. Maximum depositional ages obtained from the youngest zircon age populations are now known for Proterozoic basins on many continents (e.g., Ross et al., 1992; Rainbird et al., 1997; Evans et al., 2000; Southgate et al., 2000; Smithies et al., 2001; Goode et al., 2002; Ross and Villeneuve, 2003; Jackson et al., 2005; Maclean et al., 2006; Cawood et al., 2007; Cross and Crispe, 2007; Link et al., 2007; Amato et al., 2008), although they do not always yield an age that represents the timing of deposition. Detrital zircon U-Pb age populations also provide fundamental provenance information toward understanding the paleogeographic development of Laurentia’s Proterozoic rift margins, although data are limited for middle Neoproterozoic Laurentia (Rainbird et al., 1997; Stewart et al., 2001; Cawood et al., 2007).

Provenance interpretations of the Uinta Mountain Group and Big Cottonwood Formation, based on sedimentologic, petrographic, geochemical, and Nd-isotope data, support a general model of quartz sand derived from eastern Proterozoic and distal Archean sources and feldspathic sand derived from proximal Archean sources to the north (Wallace, 1972; Sanderson, 1984; Ball and Farmer, 1998; Condie et al., 2001). Preliminary detrital zircon U-Pb and Hf data (n = 4 samples) generated from the Uinta Mountain Group show a dominant Mesoproterozoic (1.1 Ga–Grenvillian) age population with Hf isotope values suggesting derivation from enriched Grenvillian basement now in the subsurface of southeastern North America (Mueller et al., 2007). Prior to this study, Paleoproterozoic and mid-Neoproterozoic detrital zircon ages had not
be reported from the Uinta Mountain Group, and no detrital zircons had been analyzed from the Big Cottonwood Formation.

In this paper, we present new SHRIMP (sensitive high-resolution microprobe) detrital zircon U-Pb data for 12 samples from the Uinta Mountain Group and the Big Cottonwood Formation, along with stratigraphic and sedimentologic data collected in the past decade (Figs. 1 and 2; Table 1) (Ehlers and Chan, 1999; De Grey and Dehler, 2005; Brehm, 2007; Brehm, 2008; Kingsbury, 2008; Rybczynski, 2009). We hypothesize that the Uinta Mountain Group and Big Cottonwood Formation intracratonic basin can be placed into a mid-Neoproterozoic context (i.e., Cryogenian [850–635 Ma], Plumb, 1991; Knoll et al., 2004; U.S. Geological Survey Geologic Names Committee, 2006). We also test correlations within Succession B strata in western North America, as well as extracontinental correlations, thus providing a refined view of the paleogeographic and tectonic setting of the Uinta Mountain Group–Big Cottonwood Formation basin and surrounding region.

REGIONAL PRECAMBRIAN GEOLOGY

Uinta Mountain Group

The Uinta Mountain Group of north-central Utah is a thick siliciclastic succession that crops out in the east-west–trending Uinta Mountains, east of Salt Lake City (Fig. 1A). There, the UMG is a 4-km-thick succession of cross-bedded orthoquartzite and sandstone, siltstone, and shale; it has no exposed base and is unconformably overlain by Paleozoic strata (Fig. 2A). It is subdivided into six formations, four of them informal, and is interpreted to record fluvial and marine deposition (Fig. 2A and Table 1) (e.g., Wallace, 1972; Sanderson, 1984). The lower Red Castle formation and much of the Hades Pass quartzite indicate transverse fluvial and deltaic systems flowing southward (Table 1; Wallace, 1972; Kingsbury, 2008). All other units in the west flank Uinta Mountain Group are largely marine siliciclastic shelf deposits that were influenced by west-flowing longshore currents, westward- and southward-prograding deltas, and northerly directed tidal currents (Fig. 2A and Table 1; Wallace, 1972; Ehlers, 1997; Dehler et al., 2007; Brehm, 2008; Kingsbury, 2008).

In the eastern Uinta Mountains, near the Colorado-Utah border, a thicker section of the Uinta Mountain Group (~7 km) is exposed and comprises cross-bedded orthoquartzite and sandstone with lesser siltstone, shale, and conglomerate; it lies unconformably on the Paleoproterozoic Red Creek Quartzite and is unconformably overlain by Paleozoic strata (Figs. 1 and 2A; Hansen, 1965). The basal Jessie Ewing Canyon Formation represents multiple south-flowing alluvial fans and associated fan deltas that interacted with regional west- and north-flowing braided fluvial, deltaic, and shallow marine environments (Table 1; e.g., Sanderson and Wiley, 1986; Brehm, 2007; Dehler et al., 2007). The overlying ~6+ km of eastern Uinta Mountain Group strata represent part of a large west- and southwest-flowing braided river system that was subjected to at least two marine transgressions represented by laterally extensive (10s–100s of km) intervals of shale and fine-grained sandstone of the Outlaw Trail formation and the Red Pine Shale (Fig. 2A, Dehler et al., 2007; Rybczynski, 2009).
The western and eastern units of the Uinta Mountain Group are correlated using lithostratigraphy and low-resolution sequence stratigraphy (Fig. 2A). The Red Pine Shale, the uppermost formation in the Uinta Mountain Group (≤1800 m thick), is the only mappable unit exposed throughout the Uinta Mountains; the base of this shale unit can be mapped along strike for 165 km on the north side of the range (Bryant, 1997; Rybczynski, 2009). Further correlation in the Uinta Mountain Group is based on three upward-fining cycles (km thick; S1–S3, Fig. 2A), which represent fluvial to marine deposition. It is possible that some of the sequence boundaries, in particular the basal one (S1), can be traced westward into the Big Cottonwood Formation (Crittenden, 1976; Christie-Blick, 1997; Fig. 2).

The Uinta Mountain Group represents deposition in an intracratonic extensional basin with a roughly east-west–trending northern basin edge and an open, low-relief southern margin (Fig. 1B, Table 1; Dehler et al., 2007), and is entirely developed on autochthonous Laurentian continental crust (Karlstrom and Houston, 1984). The previously used term “rift basin” to describe the Uinta Mountain Group basin is problematic because there are no volcanic rocks or significant rift-type facies associated with the Uinta Mountain Group (cf. Link, 1987; Prave, 1999). Compiled data from previous work shows that the Uinta Mountain Group basin was, at least in part, extensional. Relatively coarser grained deposits and a greater percentage of immature sandstones are found upsection throughout the Uinta Mountain Group strata on the northern side of the range, inferring an east-west–trending, basin-bounding fault (Hansen, 1965; Wallace, 1972; Brehm, 2008; Rybczynski, 2009). Approximately 7 km of northward-thickening Uinta Mountain Group strata are exposed in the hanging-wall of what was likely a south-dipping growth fault (now reactivated as the Uinta-Sparks Laramide reverse fault), suggesting that the basin was a north-tilted half-graben (e.g., Sears et al., 1982; Bruhn et al., 1986; Stone, 1993; Dehler et al., 2007; Kingsbury, 2008; Rybczynski, 2009). This interpreted northern basin-bounding fault is roughly parallel with the 1.7 Ga south-dipping Cheyenne belt suture zone (between the Wyoming Craton to the north and Paleoproterozoic basement to the south) and represents syn–Uinta Mountain Group reactivation on parts of that zone (Bruhn et al., 1983; Stone, 1993).

Previous age constraints on the Uinta Mountain Group are sparse, yet correlation with the Chuar Group data sets constrains it to ~740 Ma to 770 Ma (Fig. 2B). The Uinta Mountain Group has long been correlated with the Chuar Group of Grand Canyon, Arizona (e.g., Young, 1981; Vidal and Ford, 1985; Link et al., 1993), the top of which is now known to be 742 ± 6 Ma (U-Pb age on reworked tuff at the top of uppermost member; Karlstrom et al., 2000). The distinct microfossil assemblage and C-isotope variability in the Red Pine Shale of the upper Uinta Mountain Group is very similar to that of the upper part of the Chuar Group (Vidal and Ford, 1985; Porter and Knoll, 2000; Dehler et al., 2005; Nagy and Porter, 2005). The first appearance of vase-shaped microfossils and the
abundance of the colonial bacteria Bavlinella faveolata in both the Red Pine Shale and the upper Chuar Group suggest a pre-Sturtian age (>~726–660 Ma; Dehler et al., 2007; Hoffman and Li, 2009; Nagy et al., 2009) (Fig. 2B). Paleo magnetic data from the Uinta Mountain Group also suggest a mid-Neoproterozoic age (and correlation with the Chuar Group) based on comparison with the apparent polar wander path (APWP) for Laurentia (~800–740 Ma from Chuar Group data; Weil et al., 2006). The microfossil Cerebrosphaera buickii was recently found in the lower Chuar Group (Nagy et al., 2009). This acritarch is thought to be an index fossil for pre-glacial strata younger than ~777 Ma (Hill et al., 2000). Maximum depositional ages for the Uinta Mountain Group and the Chuar Group are 900 and 942 Ma, respectively, and come from U-Pb analysis of detrital zircons (Timmons et al., 2005; Mueller et al., 2007).

**Big Cottonwood Formation**

The Big Cottonwood Formation, exposed in the central Wasatch Range east of Salt Lake City and areas to the west (Slate Canyon, East Tintic Mountains, Stansbury Island, and Carrington Island), is a 5-km-thick succession of sandstone, orthoquartzite, and argillite with a basal conglomerate interval (Figs. 1 and 2A). This unit is positioned structurally below the thrust sheets of the Sevier orogenic belt and, although associated with thrust faults (several km of displacement), has not been significantly displaced with respect to its original location on the craton (Crittenden, 1976; Ehlers et al., 1997). Ehlers and Chan (1999) interpreted this formation to represent fluvial and marine deposition based on facies architecture and analysis, and the presence of tidal rhythmites in some intervals. The Big Cottonwood Formation is interpreted to have been deposited together with the Uinta Mountain Group to the east in a tide-dominated estuary whereby a west-flowing fluvial system was intermittently drowned by the open ocean (Ehlers et al., 1997). Paleocurrent data show three modes of flow directions (NW, SW, and SE), similar to paleoflow trends in the Uinta Mountain Group units (Table 1).

The Big Cottonwood Formation basin has been interpreted as an intracratonic rift basin...
that was bounded on its northern edge by a westward continuation of the basin-bounding fault of the northern Uinta Mountain Group basin. Evidence for this includes: the northern pinchout of the Big Cottonwood Formation across a Laramide-age syncline, clasts of crystalline basement in the overlying Mineral Fork Formation suggesting that there was no BCF present to the north of the modern BCF outcrop by Mineral Fork time (i.e., Sturtian), and that the basal BCF conglomerate could reflect rift onset and be correlative with the basal conglomerate of the Uinta Mountain Group (Crittenden, 1976; Christie-Blick, 1997; Ehlers et al., 1997). The Big Cottonwood Formation, much like the Uinta Mountain Group, does not contain volcanic rocks or a significant amount of immature facies that would be expected in a classic rift basin. Big Cottonwood Formation and Uinta Mountain Group sediments were likely deposited in different parts of the same intracratonic extensional basin (Link et al., 1993).

The timing of deposition of the Big Cottonwood Formation is unknown, but the unit is correlative with the Uinta Mountain Group based on lithostratigraphic and paleomagnetic data (e.g., Link et al., 1993; Ehlers and Chan, 1999;
Further evidence for a Big Cottonwood Formation–Uinta Mountain Group correlation includes similarity of paleocurrent data, depofacies, and detrital zircon age populations (Figs. 2A and 3; Table 1; Ehlers, 1997; Ehlers and Chan, 1999; this paper). The Big Cottonwood Formation is unconformably bracketed by the underlying Paleoproterozoic (?) Little Willow Complex and the overlying Neoproterozoic (Sturtian glacial) Mineral Fork Formation (Fig. 2A; Crittenden, 1976; Christie-Blick and Link, 1988).

METHODS

Stratigraphic Units Sampled for Detrital Zircons

Twelve samples were collected from the Uinta Mountain Group (n = 10) and Big Cottonwood Formation (n = 2) (De Grey, 2005; Brehm, 2007; Brehm, 2008; Kingsbury, 2008). The samples were collected to ascertain the detrital zircon provenance from a spectrum of sandstone compositions throughout the stratigraphic successions and from sandstone units representing different depositional environments and/or different parts of the basin (Figs. 1A and 2A; Table 1; GSA Data Repository Table DR1). This sampling strategy complements the detrital zircon study by Mueller et al. (2007), whose data were presented from four samples of a limited geographic, paleoenvironmental, and stratigraphic range (Figs. 1A and 2). Eight of our samples are from the western Uinta Mountain Group, and two are from the eastern UMG. Collectively they span from the base to the top of the entire group and were collected along and across strike of the east-west–trending northern margin of the Uinta Mountain Group basin (Figs. 1A and 2A). The samples from the Big Cottonwood Formation are from the basal (fluvial-tidal) interval and from the middle interval where tidal rhythmites are present (Fig. 2A and Table 1).

Geochronology

U-Pb zircon analyses were performed on the 12 samples described above (Tables 1, DR1, and DR2 [see footnote 1]). Our samples were separated from several kg of sandstone, siltstone, and/or shale. A heavy mineral concentrate was prepared from the total rock using standard crushing, washing, heavy liquid (specific gravity 2.96 and 3.3), and paramagnetic procedures (Williams, 1998). Representative fractions of the total zircon-rich heavy mineral concentrate were poured onto double-sided tape, mounted in epoxy together with chips of the reference zircons (Duluth Gabbro-FC1 and Sri Lanka- SL13, see below), sectioned approximately in half, and polished. Reflected and transmitted light photomicrographs were prepared for all zircons. Cathodoluminescence (CL) scanning electron microscope (SEM) images were prepared for all zircon grains and used to examine the internal structures of the sectioned grains. The U-Th-Pb analyses were made using a combination of SHRIMP I, SHRIMP II, and SHRIMP reverse geometry (RG) at the Research School of Earth Sciences, the Australian National University, Canberra, Australia. For the provenance studies, the zircons were analyzed sequentially and randomly with total number of grains analyzed ranging from 30 to 72 grains, except for one special case where 128 grains were analyzed (see discussion of sample SCUMG-9 below). In some cases, as determined from CL imaging and resultant U-Pb ages, the zircon populations were deemed to be remarkably homogeneous, in which case the total number of grains run was less than in other samples. The analyses consisted of four to six scans through the mass range, with a reference zircon analyzed for every five unknown zircon analyses (Williams, 1998, and references therein). The data have been reduced using the SQUID Excel Macro of Ludwig (2003).

Pb/U ratios have been normalized relative to a value of 0.01859 for the FC1 reference zircon, equivalent to an age of 1099 Ma (see Paces and Miller, 1993). Uncertainties given for individual analyses (ratios and ages) are at the one sigma level; however, the uncertainties in concordia age are reported as 95% confidence limits. Wetherill concordia plots (Fig. DR1 [see footnote 1], probability density plots with stacked histograms, and concordia age calculations were carried out using ISOPLOT/EX (Ludwig, 2003). For grains that are less than 1000 Ma, the $^{207}\text{Pb}/^{206}\text{U}$ age was used for the relative probability plots, and for those over 1000 Ma, the $^{208}\text{Pb}/^{232}\text{Th}$ age was employed. Analyses that are more than 20% discordant were not included in the relative probability plots. However, samples 76PL05 and 90PL05 are dominated by Archean age grains, many of which are metamict, have lost radiogenic Pb, and so are greater than 20% discordant. From Wetherill concordia plots, it
Figure 3 (continued). (B) Relative probability plots, with stacked histograms for the ten samples from the Uinta Mountain Group. See Figure 2A for corresponding stratigraphic data and Tables DR2 and DR3 [see footnote 1] for additional detrital zircon analytical data.
is clear that this discordance arises from radiogenic Pb loss at or near the present day, because the data define a simple lead loss discordia line. In these specific cases, the $^{206}\text{Pb}/^{207}\text{Pb}$ age is considered to reflect the crystallization age of the detrital zircons (Fig. DR1 [see footnote 1]), and thus were included in our spectra. If one were to exclude all such discordant analyses, the data set would be biased against these significantly older grains. It should be noted that the analyses for sample 36PL06 also show significant discordance. However, in this case, the Wetherill concordia plot (Fig. DR1 [footnote 1]) shows that the radiogenic Pb loss did not occur at or near the present day. In this case, the $^{206}\text{Pb}/^{207}\text{Pb}$ ages for such discordant analyses are not considered to reflect the crystallization age of the zircon, and so they were excluded from the relative probability plots.

SCUMG-9 Sample from Outlaw Trail formation

As with the other samples, zircon grains (n = 50) from sample SCUMG-9 (Swallow Canyon-UMG-9) were first analyzed in a random manner in order to determine the detrital zircon age distribution (Fig. 3). Within these 50 randomly selected grains, one had a concordant age of ~770 Ma, and we analyzed a second area on this sectioned grain to confirm the notable young age. For the other 49 grains analyzed in this session, five failed to yield meaningful data, and the remaining 44 grains had U-Pb ages ≥880 Ma, with most ≥1000 Ma. It must be noted, and in fact stressed very strongly, that a single grain cannot truly define the maximum age of deposition. There are many variables, not the least of which includes the potential for the youngest grain being a contaminant of the laboratory processing. We hand selected additional grains from that first mineral separation and collected a second sample suite from the same stratigraphic interval; we then carried out another complete mineral separation. Zircon grains from both samplings were hand selected on the basis of similar physical characteristics—least rounded, subhedral to euhedral grains, with zoned igneous internal structure on the basis of the CL imaging (Fig. 4). From a population of many hundreds of grains (combined from two field samplings), and an additional 78 SHRIMP U-Pb analyses, three more young grains with the same ~770 Ma age were identified (Fig. 4; Table DR2 [see footnote 1]). The four grains have widely different morphologies, ranging from subrounded, more equant grains (grains 1 and 38) to elongate, to subhedral grains (grains 12 and 41) (Fig. 4). It is notable that grain 12 has internal cavities consistent with rapid crystallization in a volcanic to subvolcanic setting. The style of internal CL zoning is consistent with a felsic igneous paragenesis; the zircons are not from a mafic igneous source where broader or subdued CL structure would be present (Corfu et al., 2003).

RESULTS

Maximum Depositional Age of the Uinta Mountain Group

After analyzing a total of ~128 zircon grains (Table DR2 [see footnote 1]) in sample SCUMG-9, we identified the four youngest analyses that are within analytical uncertainty of each other, and these give a concordia age at 766.4 ± 4.8 Ma (Figs. 4 and 5). Similar single-grain U-Pb dates are recorded in the Jesse Ewing Canyon Formation sample (91PL05) and the Moosehorn Lake formation sample (73PL05) (Fig. 3). Unfortunately, these are isolated single-grain analyses and so individually are not yet considered to be depositional age constraints. Nevertheless, the presence of grains less than 800 Ma in three samples from the lower-middle Uinta Mountain Group in both the eastern and western parts of the range, in different stratigraphic levels, including the very basaltic formation, adds further support to a general age assignment for the Uinta Mountain Group at <770 Ma.

The fact that there are only four out of 128 grains analyzed (3.1%) in SCUMG-9 that provide the ~766 Ma date in the Uinta Mountain Group demonstrates the difficulty of recognizing small but important detrital zircon populations in detrital zircon studies. This is in general agreement with Vermeesch (2004), who calculated that in the worst case scenario, at least 117 grains are required in order to have 95% confidence that one has identified a group of ages that comprises 5% of the total population (cf. Stewart et al., 2001; Mueller et al., 2007).

From the initial analyses of sample 31PL06, grain 8 gave a slightly discordant age of just less than 700 Ma ($^{206}\text{Pb}/^{207}\text{Pb}$ date of 697 ± 9 Ma, ~5% discordant). This is anomalously young, because the other 56 grains analyzed are Grenvillian or older (Fig. 3; Table DR2 [see footnote 1]). A replicate analysis of this grain confirms the original date. In the course of this replication, a further 15 grains were targeted in an attempt to find another similarly young grain, but only Grenvillian or older were recorded. Grain 8 is not a simple euhedral grain that might be expected for a volcaniclastic zircon dating the youngest deposition. The grain is dark colored and high in U (~1780 and 2645 ppm, respectively, for the two analyses) and

Figure 4. Combined transmitted light photomicrographs and cathodoluminescence (CL) scanning electron microscope images of the young grains (766 Ma) analyzed from the SCUMG sample, Outlaw Trail formation. Grains labeled as per Table DR2.4 [see footnote 1]. The areas analyzed are shown on the CL image.
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has likely lost radiogenic Pb. This single grain is the only one of this age that was found out of the overall total of 704 grains analyzed and, while interesting, no geological significance is placed on this single grain. Indeed, many geological data sets indicate that the Uinta Mountain Group is ~740–770 Ma, including correlations with the Big Cottonwood Formation (which is overlain by presumed Sturtian Mineral Fork Formation) and the Chuar Group (~740–~770 Ma) (Figs. 2A and 2B).

Detrital Zircon Age Populations

Overall, from a total of 704 grains analyzed, 565 are considered significant in terms of concordance and/or have meaningful $^{207}$Pb/$^{206}$Pb ages, and these have been used to construct relative probability plots (Fig. 3; Table DR2 [see footnote 1]). Peaks are identified at ~2700, 1650–1850 Ma, 1500–1600 Ma, 1400–1450 Ma, and 930–1200 Ma, in addition to the small population of ~766 Ma grains. Archean and Grenvillian grains occur in about equal proportions, with ~32% of the total grains analyzed in the age range 2500–2755 Ma, whereas ~36.5% are between 930 and 1300 Ma.

Archean Detrital Zircon Age Populations (2.5–2.8 Ga)

All 12 samples contain some Archean grains with a dominance of grains at 2600–2700 Ma (see Fig. 3). Three samples (lower Big Cottonwood, lower Red Pine Shale, and lower Red Castle formations) contain solely Archean grains. Two of these are feldspathic samples from the Uinta Mountain Group (76PL05 and 69PL05), and one is a quartz arenite from the basal Big Cottonwood Formation (90PL05) (Figs. 3 and 6; Tables DR2 and DR3 [see footnote 1]). Those from the BCF have suffered significant radiogenic Pb loss, but still define a prominent $^{207}$Pb/$^{206}$Pb age peak at ~2685 Ma. Concordant grains in the lower Red Castle Formation define a single peak at 2600 Ma, whereas zircons from the lower Red Pine Shale have a more dispersed age spectrum with prominent peaks at ~2645 Ma and 2710 Ma (Fig. 3). All three samples have few to no grains older than 2800 Ma.

We infer that the source for the Uinta Mountain Group feldspathic deposits was on the southern margin of the Wyoming province (SAT—Southern Accreted Terranes of Mueller and Frost, 2006). Petrographic, facies, paleocurrent, and detrital zircon data together indicate that first-cycle sediment was derived from igneous and/or metageneous sources exposed along the southern part of the Wyoming Craton and deposited in deltaic systems on the northern side of the Uinta Mountain Group basin (Table 1; Table DR3 [see footnote 1]). The strong Archean peak in the Red Pine Shale, the youngest unit of the Uinta Mountain Group, and in the lower Red Castle formation, one of the oldest units in the western Uinta Mountain Group, and the presence of similar Archean peaks in all other samples, indicates that local northern source area(s) continuously contributed immature sediment throughout deposition of the Uinta Mountain Group (Figs. 2A and 3; Table 1).

Unlike the Uinta Mountain Group feldspathic samples mentioned above, the basal Big
Cottonwood Formation sample with the unimodal Archean-age population is a texturally mature, fine-grained quartz arenite of fluvial-tidal origin (Ehlers and Chan, 1999) (Fig. 6, Table DR3 [see footnote 1]). The textural composition, petrography, and detrital zircon provenance of this sample suggest that quartz-rich sands were produced from fluviatile and tidal reworking of feldspathic sands similar to those represented in the Uinta Mountain Group samples with unimodal Archean grain-age populations. This does not appear to be the case in the Uinta Mountain Group, however, where quartz arenite samples show a mixture of Archean and Proterozoic grain-age populations (Table 1). The westerly and northerly paleoflow directions in the Big Cottonwood Formation are supportive of reworking by longitudinal rivers or tides (by comparison to facies and paleoflow in the Uinta Mountain Group, Table 1). Alternatively, these grains could have been derived from a quartz-rich source on the Wyoming craton, now eroded or covered, that supplied sediment to the incipient basin in the Big Cottonwood area (Fig. 6; Table DR3 [see footnote 1]). The wide range in sandstone composition of these three Uinta Mountain Group–Big Cottonwood Formation samples with unimodal Archean grain populations shows that composition is not necessarily a reflection of provenance, as has been the general model for UMG provenance (Fig. 6).

Whole rock Nd-isotope data from Big Cottonwood Formation, Red Pine Shale, and Red Castle shale samples (Condie et al., 2001; sample locations not reported) suggest a dominantly Paleoproterozoic or mixed Paleoproterozoic–Archean source rather than the Archean provenance shown in our detrital zircon data. Because unimodal Archean detrital zircon populations were found in coarse- and fine-grained sandstone samples, grain size alone does not explain the differences in zircon provenance, at least in the sand fraction (Fig. 6; Table DR3 [see footnote 1]). As our understanding of the complex sourcing of the Uinta Mountain Group and Big Cottonwood Formation basin unfolds, it may be that the shale deposits sampled by Condie et al. (2001) were derived from Paleoproterozoic or mixed sources. In any case, the whole rock Nd analyses, because they are a composite average analysis of the total rock samples, record different chemical systematics than the more resilient single zircon data presented herein.

**Paleoproterozoic Detrital Zircon Age Populations (1.65–1.85 Ga)**

Paleoproterozoic detrital zircons are present in nine of the samples. They range in age from 1650 to 1850 Ma and were derived from source areas in the juvenile Paleoproterozoic crust of the Mojave, Yavapai, and Mazatzal–Central Plains provinces. Most of these grains, like other Proterozoic grains in this study, were transported from the east, northeast, and southeast via fluviatile, tidal, and/or long shore currents (Table 1; Fig. 1B). The presence of the mixture of Archean and Paleoproterozoic detrital zircon grains typically coincides with a change in textures and demonstrates a trend seen on many stratigraphic scales. For example, the basal Red Pine Shale (sample 69PL05) is a delta-front deposit with a unimodal Archean zircon age population (Figs. 2A and 3; Table 1). Above this interval, the Red Pine Shale (sample RP03B) shows transgression to a distal prodelta setting with mixed Archean and dominantly Paleoproterozoic detrital zircon grains (Dehler et al., 2007; Brehm, 2008). The Paleoproterozoic provenance signature is consistent with Nd-isotope values from many of the Uinta Mountain Group and Big Cottonwood Formation shale samples analyzed by Condie et al. (2001). Petrographic results from these nine samples again show that sandstone composition does not consistently correlate with a specific source area (Fig. 6).

**Early Mesoproterozoic (1.5–1.6 Ga) Detrital Zircon Age Population**

There is a minor but significant 1500–1600 Ma age peak in four of the samples from the Uinta Mountain Group and Big Cottonwood Formation (Fig. 3). The ultimate source for these grains may be from Australia (e.g., Gawler Range Volcanics), but a more proximal and likely source could be reworked lower Belt Supergroup equivalents (e.g., Ross and Villeneuve, 2003; Link et al., 2007) and/or the Pinware terrane in northeastern Canada (Rainbird et al., 1997; Heaman et al., 2004). This grain-age population has thus far only been found in the middle part of the two successions (Uinta Mountain Group and Big Cottonwood Formation) and is associated with very prominent Grenvillian peaks; further analyses could reveal that this is a significant detrital zircon stratigraphic-marker interval, perhaps indicating a regional paleogeographic change. This idea is consistent with the proposed correlation between the Uinta Mountain Group and Big Cottonwood Formation in Figure 2A.

**Early-Middle Mesoproterozoic (1.4–1.45 Ga) Detrital Zircon Age Populations**

Seven of the samples yielded an age population of 1.4 to 1.45 Ga. These zircons probably were ultimately sourced from A-type igneous rocks that were emplaced across Laurentia between 1330 and 1480 Ma (Van Schmus et al., 1993) or reworked from the Belt basin to the north (Link et al., 2007).

**Middle-Late Mesoproterozoic (9.3–1.2 Ga) Detrital Zircon Age Populations**

Nine samples contain grains ultimately derived from the 930–1200 Ma Grenville-age terrane. The large proportion of Grenvillian grains reaffirms the “Grenville flood” as reported by Mueller et al. (2007), and extensively noted previously in similar age rocks elsewhere in Laurentia, Baltica, and Siberia (Rainbird et al., 1992, 1997; Maclean et al. 2006; Cawood et al., 2007). The Grenvillian grains are associated with the Paleoproterozoic and other Mesoproterozoic grain-age populations and a wide range of paleoflow directions indicating a mixing of populations from multiple source areas. On the other hand, some samples show a correlation between large populations of Grenvillian grains and overall westerly paleoflow (Table 1), suggesting derivation from the Grenville orogen and its foreland to the east (e.g., Link et al., 1993; Mueller et al., 2007; Baranoski et al., 2009). The river system that flowed through and/or into the Uinta Mountain Group–Big Cottonwood Formation basin supplied major numbers of Great Basin zircons to the western margin of Laurentia and the proto-Pacific (Fig. 7).

The Big Cottonwood Formation tidal rhythmite sample (122PL20) is dominated by a Grenvillian detrital zircon population (Fig. 3A). This is in stark contrast to the other sample from the basal BCF, which has only Archean zircon grains. This is another good example (like the Red Pine Shale samples) of what is likely causing the provenance change in the Big Cottonwood Formation–Uinta Mountain Group strata: the marine or relatively distal depofacies have mixed populations, and the fluvial-influenced or more proximal (northern) depofacies are dominated by Archean grains.

**Neooproterozoic (~766 Ma) Detrital Zircon Age Population**

Three samples contain detrital zircons derived from a 760–770 Ma source. The morphology and internal CL structure of the grains indicate a felsic volcanic source for these zircons (Fig. 4). These younger grains are from samples that have mixed provenance, and come from subarkosic and/or quartz-rich sandstone and shale from similar marine depofacies (Table 1; Figs. 3B and 6). Sampled intervals of the Outlaw Trail (SCUMG-9), Jesse Ewing Canyon (91PL05), and Moosehorn Lake (73PL05) formations show north-northwesterly paleoflow indicating final transport was by marine currents coming from the south-southeast (Table 1).

There are several possible sources for the ~760–770 Ma grains. In eastern Laurentia, rhyolite in the Mount Rogers Formation is ~760 Ma (Aleinikoff et al., 1995), and some...
plutonic rocks of the Crossnore Complex in the North Carolina Blue Ridge are between 750 and 760 Ma (Su et al., 1994). There are no known felsic sources of this age in western Laurentia. Considering the paucity of ~766 Ma grains in the Uinta Mountain Group, it is possible that the zircons were the product of an ashfall event from eastern Laurentia or the proximal conjugate Rodinia rift margin, such as from the 777 ± 7 Ma Boucaut Volcanics of the Nacara Arc in South Australia (Preiss, 2000). Regardless of the primary source, the 766 Ma grains appear to be unique to marine depofacies and were ultimately carried via marine currents during transgressions.

**DISCUSSION**

**Paleogeography and Tectonics**

The maximum depositional age of the Outlaw Trail formation, which, along with the Jesse Ewing Canyon and Moosehorn Lake formations, hosts the 760–770 Ma zircon grains, refines previously proposed correlations within Succession B of western North America. Detrital zircon age populations from the Big Cottonwood Formation are nearly identical to those units were deposited after ~770 Ma, in a series of coeval, and possibly connected marine basins in southwestern Laurentia (the ChUMP Interior Seaway; Dehler, 2008). This age range is consistent with constraints on Succession B strata in Canada, which also record intracratonic basin development at this general time (>723 Ma to <1070 Ma; Rainbird et al., 1996, and references therein).

Correlations with strata farther afield suggest that the transgressions documented in the Uinta Mountain Group–Big Cottonwood Formation basin were eustatically driven. In addition to the development of marine intracratonic basins in Laurentia at ~740–770 Ma, major marine inundation also commenced at ~760–770 Ma in the Adelaide rift complex of Australia (Preiss, 2000) and is coincident with the development of other marine intracratonic basins of this general age (e.g., Akademikerbreen Group, northeast Svalbard and Eleonore Bay Group, east Greenland [Knoll et al., 1986; Halverson et al., 2007]). These correlations suggest a pre-Sturtian and/or early Cryogenian interval of high global sea level that was likely caused by increased seafloor spreading rates as Rodinia rifted apart (e.g., Asmerom et al., 1991; Preiss, 2000; Li et al., 2003; Li et al., 2008).

The Uinta Mountain Group, Big Cottonwood Formation, and Chuar Group together record intracratonic extension and sedimentation in southwestern Laurentia at ~740–770 Ma that was likely related to the breakup of Rodinia (Dehler et al., 2001a; Timmons et al., 2001; this paper). This would have taken place prior to bi-modal volcanism and normal faulting recorded in the ~680–720 Ma formations along the Cordilleran margin (e.g., Pocatello, Kingston Peak, Mineral Fork, Perry Canyon, and Edwardsburg formations) and subsequent formation of a west-facing passive margin after 650 Ma (Christie-Blick, 1997; Lund et al., 2003; Fanning and Link, 2004, 2008). The Adelaide rift complex (~777 Ma) and rift basins in southern China (745–780 Ma) and Namibia (758.5 ± 3.5 Ma) are roughly coeval with the ~740–770 Ma Laurentian intracratonic basins, supporting the idea of a time-transgressive breakup of Rodinia (Hoffman and Halverson, 1996; Hoffman et al., 1998; Preiss, 2000; Eyles and Januszczak, 2003; Li et al., 2003).

**Provenance**

The detrital zircon age populations presented in this paper generally reaffirm the interpretations of Condie et al. (2001), among others, that sediment was sourced both from the north, from the Archean Wyoming province, and from the east, from a major river parallel with the strike of the Cheyenne Belt and the fabric of the Paleoproterozoic accreted crust of Colorado (Fig. 1B). This large west-flowing fluvial system contained detrital zircons from 1650 to 1850 Ma juvenile Paleoproterozoic crust of the Mojave, Yavapai, and Central Plains provinces, 1450 Ma A-type granites of Colorado, and 930–1200 Ma Grenvillian terranes (Fig. 1B). In addition to derivation from the Wyoming Province to the north, Archean detrital zircons were also likely delivered from the Superior craton to the northeast (Fig. 1B), which is consistent with a common southwestern paleoflow associated with the alluvial and fluvial depofacies of the eastern Uinta Mountain Group (Table 1; Sanderson and Wiley, 1986; De Grey and Dehler, 2005; Rybczynski, 2009).

A minor, but significant, number of previously unrecognized mid-Neoproterozoic zircon grains (~760–770 Ma) were derived from an unknown source and finally transported in a north-northwesterly direction within the Uinta Mountain Group–Big Cottonwood Formation system during marine transgressions. The provenance change associated with these marine units, defined by detrital zircon populations, paleocurrent data, and detepofacies, suggest that during transgressive episodes, young grains were reworked, and/or different sources were tapped to the south-southeast and integrated with sediment continuously derived from the north and east via deltaic and/or fluvial systems (Fig. 1B; Table 1). During regressions there was less mixing of grain populations, especially proximal to the basin edges.
The Fate of Grenvillian Sediment Downstream of the Uinta Mountain Group—Big Cottonwood Formation River System

The Uinta Mountain Group—Big Cottonwood Formation river system was a continental-scale river system that transported Laurentian zircons, in particular the abundant 930–1300 Ma grains derived from the Grenville province, to western Laurentia and ultimately to the incipient marine basin formed by the early rifting of Rodinia (Fig. 7) (cf. Mueller et al., 2007). This river system may have been coeval with other pan-continental river systems in northern Laurentia that were also tapping the Grenville orogen (Young et al., 1979; Rainbird et al., 1992, 1997). Limited geochronologic control on the Shaler and Mackenzie Mountain supergroups (>723 Ma and <1070 Ma), which record these northern fluvial systems, makes this paleogeographic interpretation uncertain.

Though Rodinia reconstructions are under debate, the configuration shown by Goode et al. (2008) places the Uinta Mountain Group—Big Cottonwood Formation basin such that it may have been an avenue for Grenvillian zircons to reach not only the western Laurentian margin but also peri-Gondwanan Neoproterozoic continental margins. This may have provided a way for large quantities of Grenvillian zircons to be reworked into latest Neoproterozoic sands on several continental margins of eastern Gondwana (Ireland et al., 1998) that otherwise have no known viable Grenvillian source. This idea requires that the proto-Pacific Ocean separating Laurentia from Antarctica and Australia maintained subdued topography and, hence, rifting had not yet commenced in this part of the ocean basin.

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REFERENCES CITED


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