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Constraining the timing and provenance of the Neoproterozoic Little Willow and Big Cottonwood Formations, Utah: Expanding the sedimentary record for early rifting of Rodinia

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ABSTRACT

U–Pb ages of detrital zircon spectra indicate that the Little Willow Formation in the Wasatch Range, Utah, is not a part of a Paleoproterozoic basement complex (~1700–1800 Ma) as previously thought, but is a metamorphosed part of the Big Cottonwood Formation (~750 Ma). The youngest detrital zircon grains in the metamorphic Little Willow and unmetamorphic Big Cottonwood Formations are 750–850 Ma. These young zircons form a small, but persistent population possibly from Rodinia rift-related magmatism. The majority of the zircons are Grenville-age with other smaller populations derived from the Laurentian anorogenic granites, Mazatzal/Yavapai terranes, and Wyoming Craton. The distribution of new U–Pb detrital zircon ages from the Little Willow Formation has a high statistical probability of similarity to the detrital zircon spectra previously reported from both the Big Cottonwood Formation and the Uinta Mountain Group. Based on these similarities, we propose that the Little Willow Formation represents some of the earliest sediment shed into the Uinta rift basin during the earliest-known phases of Rodina break-up in western Laurentia. The Little Willow is not, therefore of Paleoproterozoic or Archean age as is shown on existing geologic maps.

Lu–Hf isotopes in detrital zircons from the Little Willow and Big Cottonwood Formations compared with potential source regions provide evidence that the sediment could have been derived from eastern Laurentia and thus requiring a transcontinental river to transport the sediment ~2000 km. The U–Pb and Lu–Hf values from the Little Willow and Big Cottonwood Formations correspond well with the ~1.0 Ga Grenvillian basement, 1.4 Ga A-type Granites intruding the Central and Western Yavapai, evolved portion of the 1.7–1.8 Ga Santaquin Complex, and the 1.6–3.0 Ga Farmington Canyon Complex (Wyoming Craton).

1. Introduction

The purpose of this paper is to resolve a long-standing debate about the age and provenance of a key metamorphic complex (Little Willow Formation), which helps reconstruct the Pre-Cambrian geology of Rodinia and initiation of its breakup. The approach is two fold: (1) use U–Pb zircon geochronology to determine the age of the Little Willow Formation, and (2) use Lu–Hf isotopes in zircon to identify its potential source region and its relation to the overlying Big Cottonwood Formation.

The Little Willow Formation is exposed in the central Wasatch Range east of Salt Lake City (Fig. 1a). Because of the metamorphic character, the 40th Parallel Survey party of the USGS first classified the Little Willow Formation as Archean in age and unconformably overlain by unmetamorphosed Big Cottonwood Formation (King, 1871). More recent researchers group the Little Willow Formation with other Paleoproterozoic basement rocks in Utah (e.g. Farmington Canyon and Santaquin Canyon Complexes), which is the standard interpretation in local and regional geologic maps (Paris, 1935; Birch, 1940; Neff, 1962; Crittenden, 1965; Kohlmann, 1980; Bryant, 1988, 1992; Hintze and Kowallis, 2009). The contact with the overlying Big Cottonwood Formation is mapped as a nonconformity by Crittenden (1965) and the basal contact is not exposed. Since its discovery, the Little Willow Formation has remained an enigmatic rock body in reconstructions of the metamorphic basement of central-western North America. For example, Bryant (1988)

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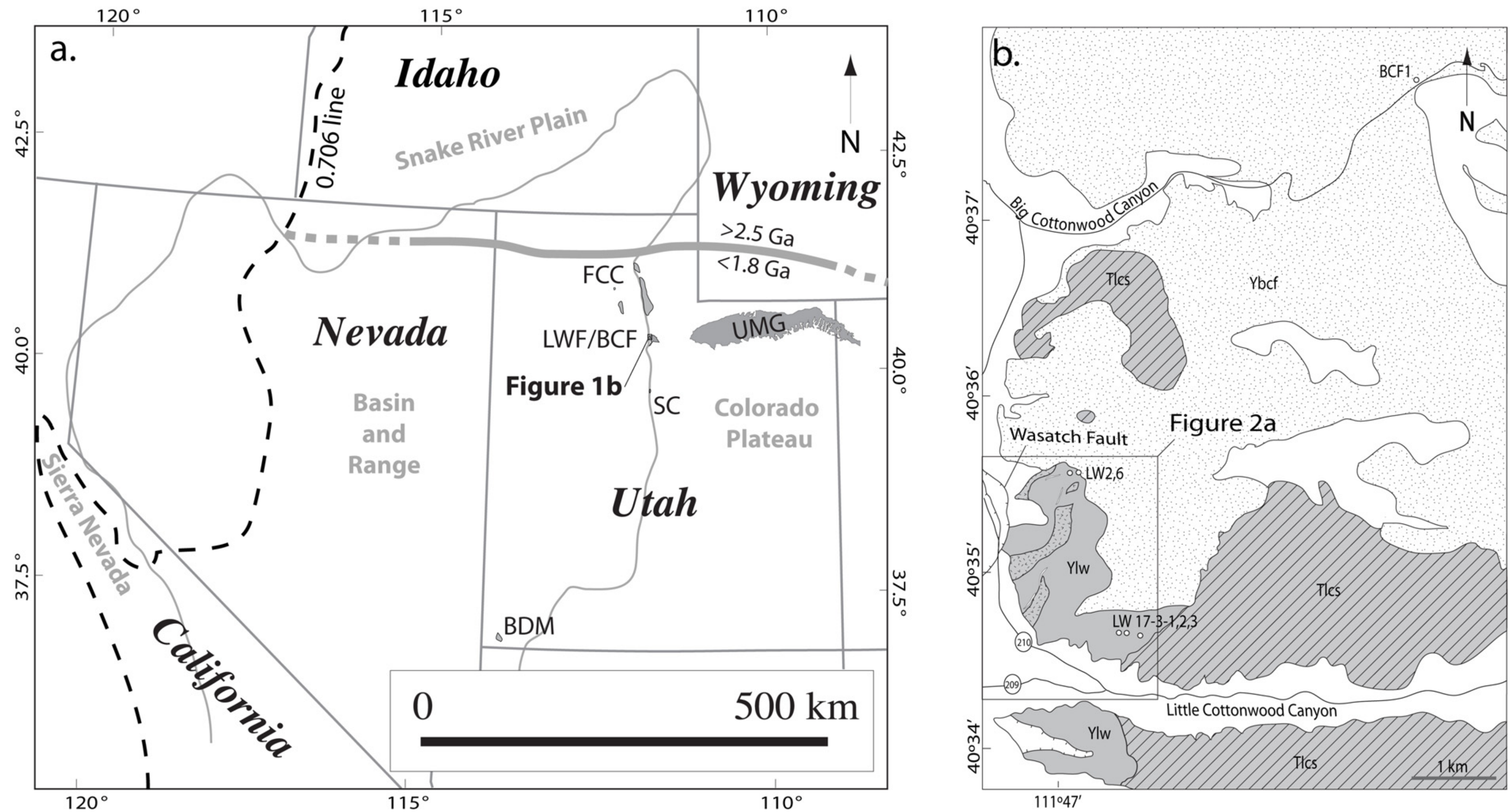

Fig. 1. (a) Map of Utah showing the distribution of Precambrian crystalline exposures and Archean/Paleoproterozoic boundary after Nelson et al. (2011) and the Neoproterozoic Uinta Mountain Group, Big Cottonwood Formation, and Little Willow Formation (Dehler et al., 2010). (b) Generalized geologic map and sample locations of the Little Willow Formation and surrounding area. (c) Close up generalized geologic map of Fig. 1b and sample locations of the Little Willow Formation and surrounding area. Line A-A′ and B-B′ represents lines of cross section in Fig. 2 (after Crittenden, 1965; Kohlmann, 1980). White bands within the metasedimentary units represents thin metaconglomerate beds found throughout the complex. Ylw: Little Willow Complex, Ybcf: Big Cottonwood Formation, Tlcs: Little Cottonwood Stock.

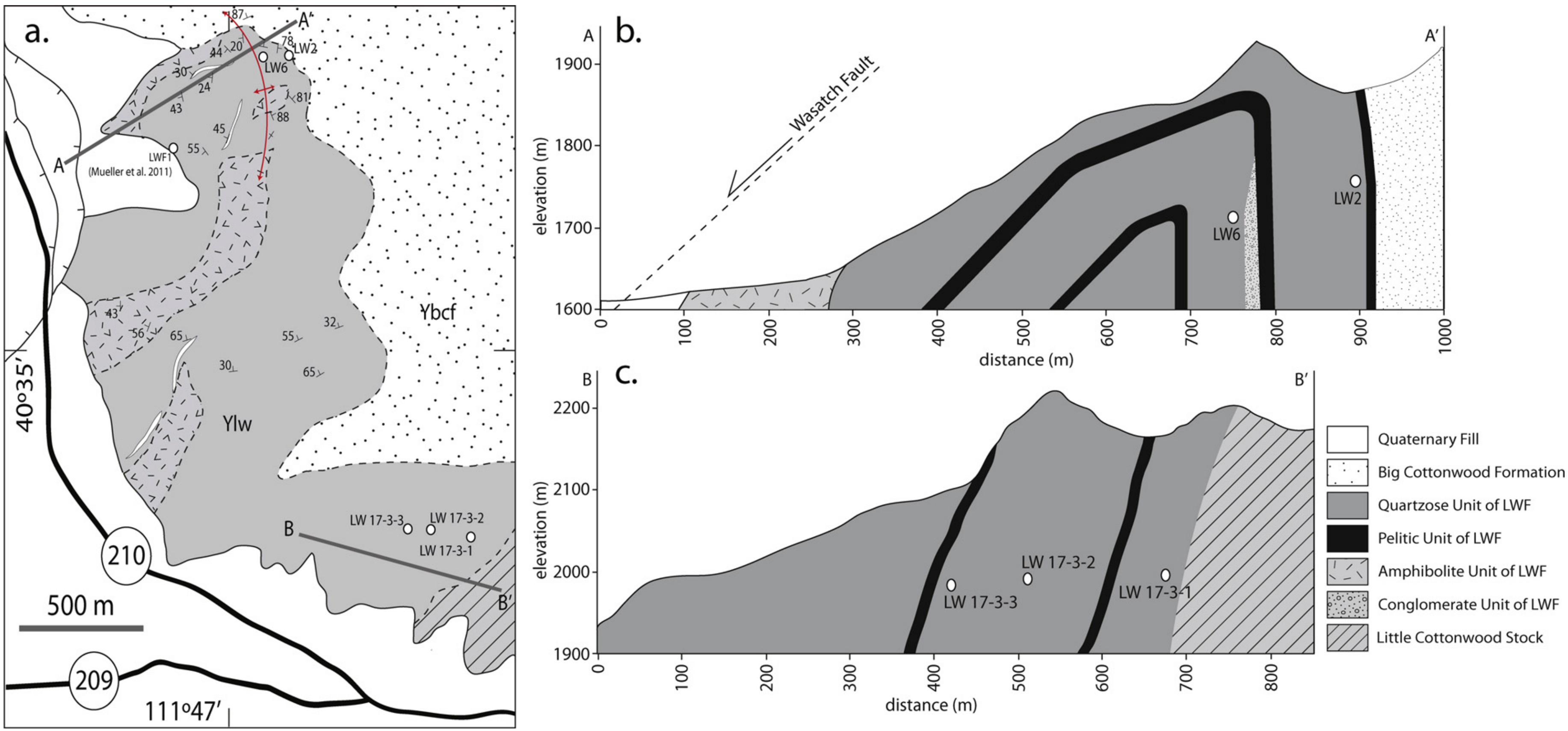

Fig. 2. (A-A′) Schematic cross section through the northern portion of the Little Willow Formation. Overall structure is an eastward verging asymmetrical anticline (Sevier/Laramide age?). (B-B′) Schematic cross section through the southern portion of the Little Willow Formation.

projects the Archean/Proterozoic boundary (the western extension of the Cheyenne Belt) to the south of the Little Willow Formation, whereas more recent correlations interpret the Little Willow Formation as Paleoproterozoic-age and south of the Archean/Proterozoic boundary (Bryant, 1992; Nelson et al., 2000). However, none of these constraints are based upon geochronological data.

The Little Willow Formation (Fig. 1b and c) consists of a succession of greenschist to middle amphibolite grade quartzofeldspathic gneiss, mica schist, amphibolite, quartzite, and pebble metaconglomerate and is exposed directly below the fluvio-tidal strata mapped as part of the Big Cottonwood Formation on the west front of the Wasatch Range near the mouth of Little Cottonwood Canyon. Both the Little Willow Formation and the overlying Big Cottonwood Formation are folded into a north-eastward verging anticline (Fig. 2) during Sevier/Laramide deformation and was subsequently exhumed by Neogene uplift on the footwall of the Wasatch fault.

The Little Willow Formation is intruded by the Little Cottonwood Stock (Figs. 1c and 2), which yields a zircon U–Pb crystallization age of 30.5 ± 0.5 Ma (Vogel et al., 2002). The extent of the metamorphic aureole of the Little Cottonwood Stock remains poorly constrained. However, the stock may not be far beneath the Little Willow Formation as indicated by the presence of a finger of the intrusion exposed in the middle of the formation. Furthermore, metamorphic grade increases from post-kinematic andalusite furthest from the stock and increasing above the first (andalusite derived sillimanite) and second (muscovite/quartz derived potassium feldspar and sillimanite) sillimanite isograds towards the stock (Kohlmann, 1980). Our mapping revealed differences from the geologic map of Crittenden (1965) including the remapping of the contact between the Little Willow Formation and the Big Cottonwood Formation as the uppermost contact of the metamorphic aureole of the Little Cottonwood Stock. Furthermore the metamorphic rocks closest to the Little Cottonwood Stock were previously mapped as migmatite. However, petrographic studies reveal the supposed melanosomes and leucosomes were merely pelitic and psammitic interlayers.

Detrital zircon analyses (Dehler et al., 2010) on the Big Cottonwood Formation and correlative Uinta Mountain Group suggests that these thick successions of fluvial-deltaic and tidal sedimentary rocks have a maximum age of <766 ± 5 Ma (the age of the youngest detrital zircon population). These ages correlate with the Chuar Group of the Grand Canyon, which contains an ash bed near the top dated by U–Pb in zircon at 742 ± 6 Ma (Karlstrom et al., 2000).

Dehler et al. (2010) suggest the sediments of the Big Cottonwood Formation and Uinta Mountain Group were derived from an eastern Laurentian source thus requiring a transcontinental river (>2000 km) to transport the sediment. This study uses Hf isotopes in zircon to establish an isotopic connection (rather than an age-only approach) between the sediments and prospective sources.

2. Sample descriptions and localities

Five samples from the Little Willow Formation were collected for detrital zircon geochronology. Two samples (LW2 and LW6) were collected from the middle and upper Little Willow Formation. Both samples are medium to course grained sedimentary quartzite with minor amounts of secondary biotite, muscovite, chlorite, andalusite, and Fe–Ti oxides (Fig. 2 and Appendix A2 photograph 1 for field photo). The other three samples were collected in a quartzofeldspathic paragneiss progressively further from the contact of the Little Willow Formation and the Little Cottonwood Stock (LW 17-3-1, LW 17-3-2, LW 17-3-3). The mineralogy of the quartzofeldspathic paragneiss includes quartz + K-feldspar + biotite + muscovite + Fe–Ti oxides ± sphene ± chlorite. Despite the metamorphism in the Little Willow Formation, high-angle crossbeds and a thin pebble conglomerate are still preserved in this paragneiss giving further evidence this has a sedimentary origin (see Appendix A2 photographs 2 and 3 for field photo). Narrow discontinuous bands (1–2 m wide) of schist intercalated with banded and ptygmatic folded gneiss are also found. One course grained sandstone sample was collected from the middle Big Cottonwood Formation. See Supplementary Materials for sample locations.

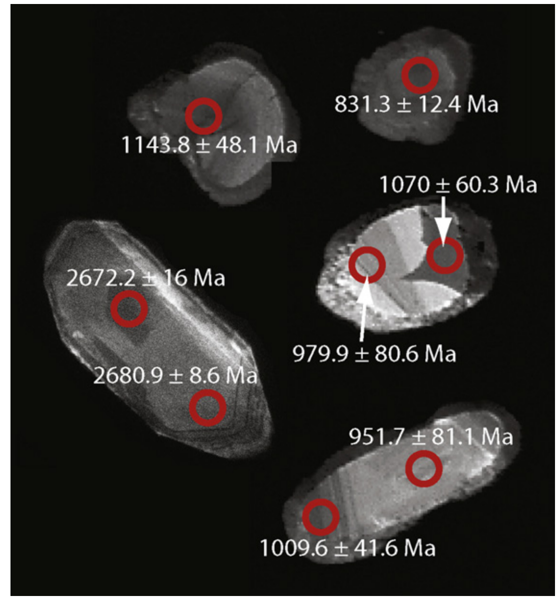

Fig. 3. CL images of zircon grains for sample 08LW06.

3. Detrital zircon U–Pb age analysis

3.1. U–Pb methods

All samples were processed using a roll crusher, magnetic separator, wilfley table, and TBE heavy liquid. Zircons were extracted from the resulting heavy mineral separates. Cathode luminescence images were acquired using a Hitachi 3400 N SEM equipped with a Gatan Chroma CL system at the University of Arizona. In situ U–Pb isotope analyses for individual grains were performed using a Nu Plasma HR MC-ICPMS with ablation done in a He carrier gas using a 40 μm diameter spot size. More detailed U–Pb analytical procedures have been described in detail by Gehrels et al. (2008). Discordant grains (<90% concordance) that do not lie along a well defined discordia were rejected. Concordia diagrams, TuffZirc age determination, and probability density distribution plots were generated using Isoplot (version 3.0) software (Ludwig, 2000). Samples were analyzed in sets of 7 analyses, which include 5 unknown spots, bracketed beginning and end by a pair of analyses of the Sri Lanka zircon standard. The R33 zircon standard was also analyzed at the beginning and end of each sample set as an independent control on reproducibility and instrument stability.

3.2. U–Pb results

Nearly all the zircon grains analyzed are inclusion-free and show normal magmatic zonation (Fig. 3). We interpret the zircon grains as igneous in origin based on average U/Th ratios

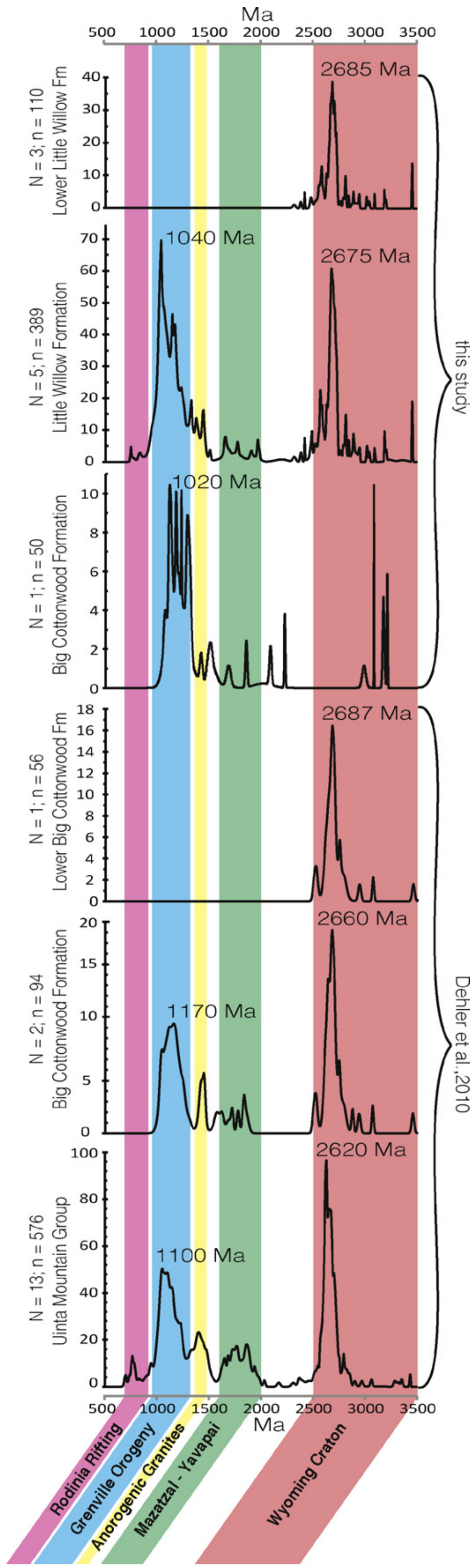

Fig. 4. Normalized distribution of detrital zircon populations from the Little Willow Formation (this study), the Big Cottonwood Formation (Dehler et al., 2010), the Uinta Mountain Group (Mueller et al., 2007), Yavapai and Mazatzal Terrains (Shufeldt et al., 2010), and igneous zircon crystals from bimodal igneous terranes from the rifting of Rodinia (Southern China: Wu et al., 2007; Li et al., 2008; Wang et al., 2008; Zhu et al., 2008; Laurentia: Li et al., 1995; Karlstrom et al., 2000). Ages of nearby provinces compiled from Rahl et al. (2003) and Dickinson and Gehrels (2009). Zircons from samples LW17-3-1, LW17-3-2, LW17-3-3 are combined into the Lower Little Willow Formation and zircons from samples LW2 and LW6 are combined into the Little Willow Formation.

of 2.9, where a U/Th ratio less than 10 is considered a magmatic zircon (Rubatto, 2002; Hartman and Santos, 2004). The rounded shape of the grains (Fig. 3) demonstrates they experienced surface transport and are detrital, which is also consistent with the scatter of ages. Ages range from ~3450 to 750 Ma, with five populations identified. These are, from oldest to youngest, and with the interpreted source area in parentheses: (A) >2500 Ma, 30% of total (Wyoming and/or Superior Craton), (B) 2200–1600 Ma: 8% of total (Mazatzal/Yavapai Terranes), (C)1500–1400 Ma: 9% of total (Laurentian A-type granites and/or Belt Basin), (D) 1200–900 Ma, 51% of total ("Grevillean-age" orogenic belts), and (E) 900–700 Ma, 1% of total (Rodinia volcanism?) (Figs. 4 and 5). These are the same populations found in the Big Cottonwood Formation and Uinta Mountain Group (Dehler et al., 2010; Mueller et al., 2007). The samples collected at the base of the Little Willow Formation are distinct in that they only contain zircons of the oldest population (>2500 Ma). Using Isoplot v3.0 (Ludwig, 2003), a youngest grain analysis of all the zircons analyzed yielded an age of 755 +55, -12 Ma (age of the second youngest grain at 95% confidence).

The detrital zircon patterns from the composite Little Willow Formation are compared with the composite Big Cottonwood Formation and composite Uinta Mountain Group using the degree of similarity and overlap, which compares the proportions of similar and overlapping ages of two relative age-probability curves (after Gehrels et al., 2000). Values of 1.0 indicate a perfect match between the age and relative abundances of ages in two samples, and a value of 0.0 indicates that there is no correlation of ages. The Little Willow Formation and the Big Cottonwood Formation have a similarity value of 0.89 and an overlap value of 0.79. The Little Willow Formation and the Uinta Mountain Group have a similarity value of 0.89 and an overlap value of 0.91. The Big Cottonwood Formation and the Uinta Mountain Group have a similarity value of 0.88 and an overlap value of 0.80. From these values, it is apparent that the Little Willow Formation, Big Cottonwood Formation, and Uinta Mountain Group have a high probability of correlation.

4. Detrital zircon Hf analysis

4.1. Hf methods

In situ Hf isotope data were acquired at the Laserchron Center at the University of Arizona using a 40 μm diameter spot size and a laser pulse frequency of 7 Hz. Blocks of unknown analyses were paired with analyses of zircon standards (Mud Tank, Temora-2, FC-52 (similar to FC-1), 91500, Plesovice, R33, and Sri Lanka) every 10–15 analyzed unknowns (described in detail by Gehrels, 2010).

The isotope 176Hf is the daughter of radioactive 176Lu. 177Hf is a stable isotope of Hf that is present in the solar nebula. When zircon crystallizes it extracts Hf from the fluid in which it forms, but excludes Lu. Therefore the measured 176Hf/177Hf ratio in zircon reflects the composition of the magma from which it crystallized. Hf values were obtained from two samples of the Little Willow and one sample of the Big Cottonwood Formations.

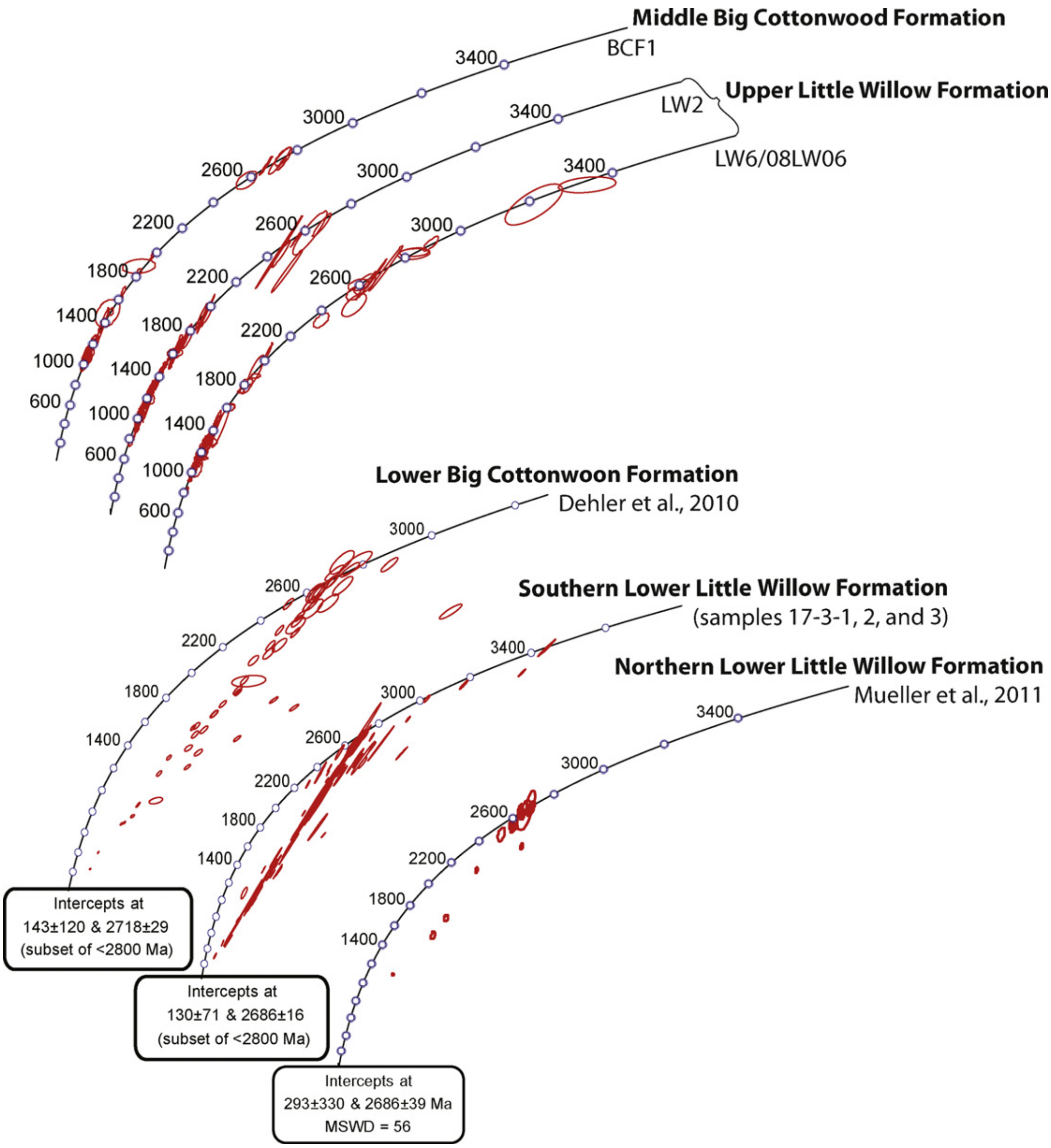

Fig. 5. Concordia plot for detrital zircons from (a) lower Little Willow and (b) upper and lower Big Cottonwood Formations (lower Big Cottonwood Formation from Dehler et al., 2010).

4.2. Hf results

Hf analyses from zircons in the Little Willow Formation and Big Cottonwood Formation are paired with U–Pb analyses from the same ($n = 59$). εHf within the Little Willow Formation ranges from −14.6 to 11.1 (mean = 1.1) with U–Pb ages of 952–3451 Ma. εHf values from zircon in the Big Cottonwood Formation ($n = 34$) range from −17.7 to 7.2 (mean = −1.8) with U–Pb ages of 979–2766 Ma.

5. Discussion

5.1. Provenance of the Little Willow Formation

The samples collected at the base of the Little Willow Formation only contain zircons with an Archean signature (samples 17-3-1, 17-3-2, and 17-3-3). This is the same relationship found in the basal Big Cottonwood Formation and the Uinta Mountain Group (Mueller et al., 2007; Dehler et al., 2010). This implies that the Little Willow Formation, Big Cottonwood Formation, and the Uinta Mountain Group were initially sourced from south-flowing rivers shed off of the Wyoming Craton (>2500 Ma) followed by west or north-flowing rivers with sources found throughout the rest of Laurentia (Dehler et al., 2010). The zircon U–Pb concordia of the lower portion the Little Willow Formation yields a discordia with an lower and upper intercepts of 130 ± 71 Ma and 2686 ± 16 Ma, respectively (Fig. 5). Mueller et al. (2011) also analyzed a quartzite sample from the northern lower Little Willow Formation. This sample also yielded similar results to that of the southern lower Little Willow Formation (this study) and the lower Big Cottonwood Formation (Dehler et al., 2010) with upper and lower intercepts of 293 ± 330 Ma and 2686 ± 39 Ma, respectively ($n = 18$). Mueller et al. (2011) assumes this sample is representative of the Little Willow Formation and thus represents part of a Paleoproterozoic passive margin similar to that of the Farmington Canyon Complex. However, in light of the samples from the upper Little Willow Formation, we place Mueller et al.'s sample in a similar context as our lower Little Willow Formation samples.

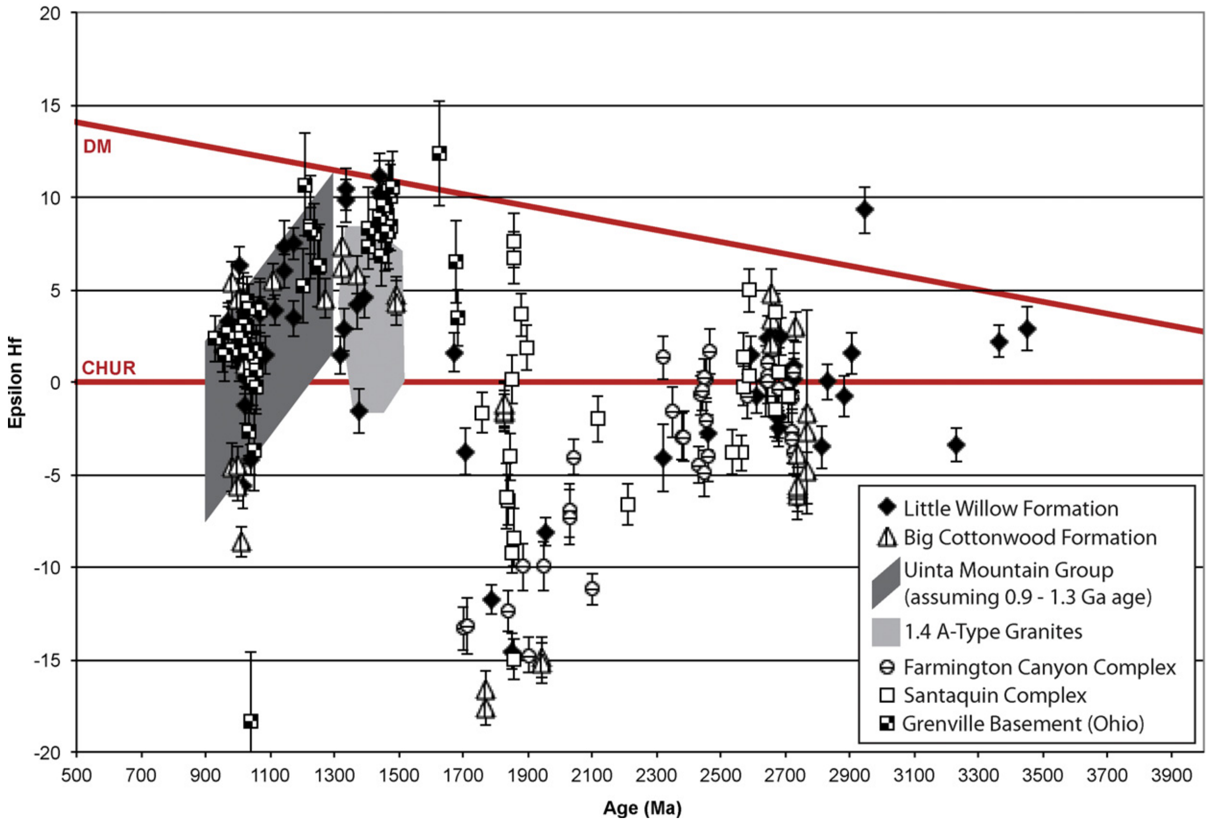

Fig. 6. Epsilon Hf vs U–Pb age. Uinta Mountain Group values recalculated from Mueller et al. (2007) assuming a 0.9–1.3 Ga age. 1.4 Ga A-type granite values from Goodge and Vervoort (2006). Grenville basement values from Petersson (2010).

Using the U–Pb and Hf values of zircons from Grenvillian basement (Petersson, 2010), 1.4 Ga A-type granites (Goodge and Vervoort, 2006), Santaquin Complex (Yavapai Province), and Farmington Canyon Complex (Wyoming Craton) (Spencer, unpublished data) the U–Pb and Hf isotopes of the Little Willow and Big Cottonwood Formations show considerable overlap with those of potential source regions (Grenvillian basement, 1.4 Ga anorogenic granites, Yavapai Province, and Wyoming Craton) (Fig. 6). Although the 1.4 Ga granites, Santaquin Complex, and Farmington Canyon Complex are considered proximal sources (<500 km), detritus derived from the Grenville orogeny must have traveled from much greater distances as the nearest Grenville related rocks are >2000 km away from the Uinta-Cottonwood depocenter. Dehler et al. (2010) uses this as evidence for trans-Laurentian rivers deriving Grenville age material from the east coast of Laurentia. However, a more likely scenario is that the Grenville age detritus was derived from the most proximal Grenville related rocks found in the Franklin Mountains, Van Horn region, and Llano Uplift of west and central Texas.

Detrital zircon geochronology from other Neoproterozoic sedimentary basins located along the western margin of Laurentia now exposed in northern Canada, Nevada, Arizona, Utah, and northern Mexico, yielded detrital zircons with Grenville detritus (Rainbird et al., 1992, 1997; Stewart et al., 2001; Timmons et al., 2005; Dehler et al., 2010; Rainbird et al., 2012). These observations lead to the possibility that these sedimentary basins were the remnants of large river systems draining off the Grenville orogenic belt >2000 km from the site of deposition (Fraser et al., 1970; Rainbird et al., 1992, 1997; Rainbird et al., 2012).

5.2. Maximum depositional age of Rodina rift-related sediments

Four post-Grenville grains were found in the Little Willow Formation (>75% concordance) ranging from 748 ± 6 to 851 ± 23 Ma. Although, this small number of grains does not form a significant enough population to constrain a precise lower limit on the age of deposition, we assume that the protolith of the Little Willow Formation is at least as young as Grenville (900 Ma) and the presence of post-Grenville grains could place the depositional age even younger (<748 Ma), which overlaps with age of Chuar Group in Grand Canyon (Karlstrom et al., 2000). There are potentially several sources for the youngest grains, including volcanic rocks of this age found in South China and Australia (Fanning et al., 1986; Preiss, 2000; Wu et al., 2007; Li et al., 2008; Wang et al., 2008, 2010; Zhu et al., 2008). During widespread magmatism in these areas, Antarctica and/or Australia rifted away from southern Laurentia between 830 and 650 Ma (Preiss, 2000; Goodge et al., 2008). Some eastern Laurentian sources for this population are also possible, such as the rhyolite of the Mount Rogers Formation of Virginia (~760 Ma) (Aleinikoff et al., 1995) and some plutonic rocks of the Crossnore Formation in the North Carolina Blue Ridge (750–760 Ma) (Su et al., 1994).

During a concerted search for the freshest magmatic grains, Dehler et al. (2010) also found twelve zircons from the Uinta Mountain Group (n = 470 total) that have post-Grenville ages (between 840 and 690 Ma) similar to the post-Grenville grains in the upper Little Willow Formation. This similarity suggests that the Little Willow Formation and the Uinta Mountain Group have nearly the same maximum depositional age (~766 ± 5 Ma). Similarly, the Chuar Group of the Grand Canyon also has zircons as young as

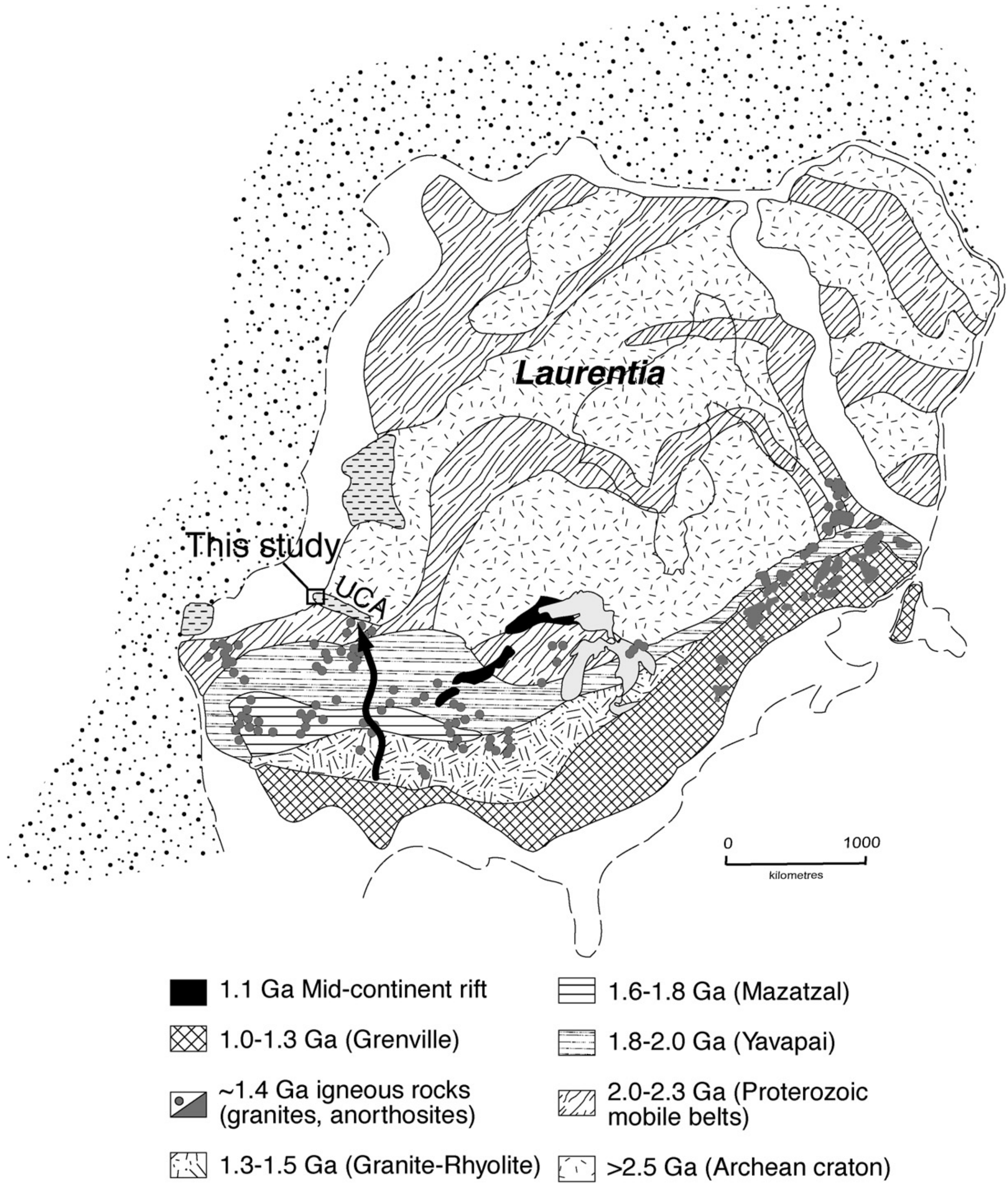

Fig. 7. Paleotectonic reconstruction at ~750 Ma modified from Goodge et al. (2008) and Rainbird et al. (2012) showing hypothetical river system tapping the most proximal Grenvillian sources of west- and central-Texas, delivering Grenvillian sediments into the Uinta Cottonwood Rift and other western Laurentia basins (black arrows).

742 Ma (Karlstrom et al., 2000). The similarity in detrital zircon assemblages between the Uinta Mountain Group, Big Cottonwood Formation and Little Willow Formation suggests a depositional general age for the Little Willow Formation at < 770 Ma. This new maximum depositional age of the Little Willow Formation is nearly one billion years younger than its previously assumed Paleoproterozoic age (e.g. Hintze and Kowallis, 2009).

The depocenter that is now comprised by the Little Willow and Big Cottonwood Formations as well as the Uinta Mountain Group was supplied from the Grenville orogen by a large series of rivers. These river systems produced huge volumes of Grenville-derived detritus that were dispersed throughout the western margin of Laurentia and the proto-Pacific (Rainbird et al., 2012) (Fig. 7).

6. Conclusion

U–Pb analysis of detailed zircon grains from the Little Willow Formation suggests that it represents some of the earliest known rift deposits of Rodinia at <770 Ma. Because the depositional age and detrital zircon spectra of the Little Willow Formation are the same as the Big Cottonwood Formation, the contact between the Little Willow Formation and the overlying Big Cottonwood Formation is redefined here as the uppermost level of metamorphosed Big Cottonwood Formation as opposed to a nonconformity and/or thrust contact as shown by previous investigators.

U–Pb and Hf isotopes in detrital zircons from the Little Willow and Big Cottonwood Formations compared with potential source regions provide evidence that the sediment was likely derived locally from Paleoproterozoic and Archean provinces (e.g. Yavapai/Mazatal and Wyoming, respectively). It is also more likely that the 1.0 Ga zircons were derived from the Grenvillian basement in west and central Texas rather than eastern Laurentia.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2012.02.009.

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