



Detrital zircon provenance and paleogeography of the Pahrump Group and overlying strata, Death Valley, California



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ABSTRACT

The Mesoproterozoic and Neoproterozoic Pahrump Group of Death Valley, California spans ca. 1300–635 Ma and provides a >500 million-year record of geologic events in southwestern Laurentia. The strata analyzed include preserved sequences separated by unconformities recording syn-Rodinia basin development (Crystal Spring Formation); Rodinia stability; regional extension culminating in Neoproterozoic rifting of the Laurentian margin of Rodinia (Horse Thief Springs through Johnnie Formations); and multiple phases of glacial sedimentation and subsequent cap carbonate deposition (Kingston Peak Formation and Noonday Dolomite). U-Pb detrital zircon analyses were conducted on samples from the entire Pahrump Group and the Noonday Dolomite in the southeastern Death Valley region (20 samples, 1945 grains) to further constrain hypotheses for regional basin development during the development of the southwestern Laurentian margin.

Our interpretation of provenance data expands upon and clarifies previous models defining a series of tectonostratigraphic units including: (A) the <1400 Ma basal conglomerate of the Crystal Spring Formation, comprised of metasedimentary quartzite clasts, and exhibiting a unimodal detrital zircon sample distribution at 1690 Ma with northerly source; (B) the ca. 1320–1080 Ma Crystal Spring Formation exhibiting unimodal zircon distributions derived from southerly, local Paleoproterozoic basement sources punctuated by a ca. 300 Ma duration unconformity; (C) the ca. 780–740 Ma sequence of the Horse Thief Springs Formation, Beck Spring Dolomite, and KP1 unit of Kingston Peak Formation deposited in a marine basin with mixed southwestern Laurentian provenance; (D) a ca. 710–635 Ma glaciogenic sequence (KP2-KP4 members of Kingston Peak Formation), recording the onset of Rodinia rifting, and Sturtian and Marinoan “Snowball Earth” intervals with provenance data suggesting derivation from erosion and recycling of older Pahrump Group strata; (E) the ca. 635 Ma cap dolostone of the Sentinel Peak Member of the Noonday Dolomite, representing post-glacial drainage reorganization with more regional provenance; followed by (F) the <635 Ma strata of the Radcliff Member of the Noonday Dolomite, showing a marked shift to bimodal age distributions, indicating derivation from local basement sources. These data synthesize and complement previous provenance studies from overlying units and result in the addition of ca. 500 Ma of new provenance analysis for the southwestern Laurentian margin.

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1. Introduction

Many questions remain unanswered with respect to paleocontinental reconstructions during the ‘life cycle’ of the supercontinent Rodinia (ca. 1200–600 Ma; e.g. Li et al., 2008), including a lack of well-defined piercing points and an incomplete understanding of the paleogeographic evolution of rifted margins (e.g. Sears and Price, 1978, 2003; Rainbird et al., 1996; Karlstrom et al., 2001; Piper, 2011). Links between the breakup of Rodinia and

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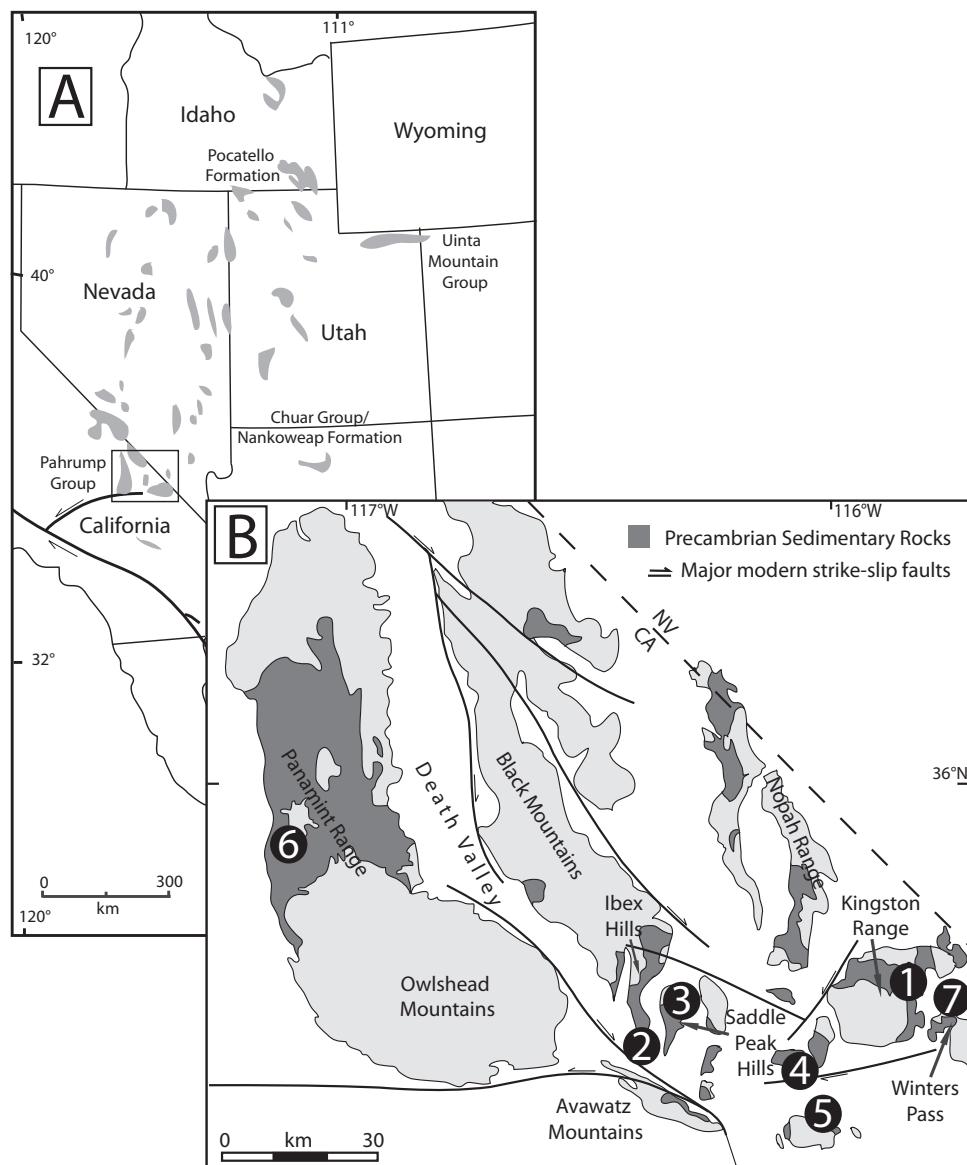


Fig. 1. (A) Map of the southwestern United States showing location and extent of Neoproterozoic sedimentary successions (in gray; modified after Stewart et al., 2001; Lund, 2008). (B) Distribution of Proterozoic sedimentary rocks (dark gray) of the Pahrump Group through Zabriskie Quartzite in the southern Death Valley region. Geology modified from Jennings et al. (1962), Workman et al. (2002) and Petterson (2009). Localities sampled and discussed in text indicated by numbers: 1 – Kingston Range; 2 – southern Ibex Hills/Saratoga Spring; 3 – Saddle Peak Hills; 4 – Alexander Hills; 5 – Silurian Hills; 6 – Redlands Canyon in the southern Panamint Range; 7 – Winters Pass in the Mesquite Mountains.

development of low-latitude glaciations of the late Neoproterozoic also remain uncertain (e.g. Prave, 1999; MacDonald et al., 2013). The Pahrump Group and overlying strata of the Death Valley, California region (Fig. 1) preserve a rich Mesoproterozoic to Cambrian stratigraphic record (see Fig. 2), which captures the time period spanning the growth and decay of Rodinia (Heaman and Grotzinger, 1992; Li et al., 2008; Mahon et al., 2014), and two potentially low-latitude glacial-cap carbonate cycles (Miller, 1985; Link et al., 1994; Prave, 1999; Abolins et al., 2000; Corsetti and Kaufman, 2003).

In this paper, we present new detrital zircon data (20 samples, 1945 grains) from the Pahrump Group (Crystal Spring and Horse Thief Springs Formations, Beck Spring Dolomite, and Kingston Peak Formation) and the overlying Noonday Dolomite, and integrate these data with previously reported zircon ages from underlying basement and overlying Ediacaran and Early Cambrian strata. In light of recent lithostratigraphic, tectonostratigraphic

and chronologic investigations (e.g. Mrofka and Kennedy, 2011; Petterson et al., 2011a, 2011b; Verdel et al., 2011; MacDonald et al., 2013; Mahon et al., 2014), our data provide a detailed record of the chronology, provenance and paleogeographic evolution of the ca. 1300–650 Ma time represented (as both preserved sedimentary rock and unconformities) by the Pahrump Group and Noonday Dolomite. The result is the new view that the Pahrump Group records several discrete sedimentation episodes separated by major unconformities, documenting the tectonic evolution within intracratonic Laurentia.

2. Geologic setting

The Pahrump Group (~3 km average thickness) is exposed in numerous ranges across the central and southern Death Valley region, and sits unconformably on 1800–1200 Ma crystalline basement (Wasserburg et al., 1959; Labotka et al., 1980; Barth

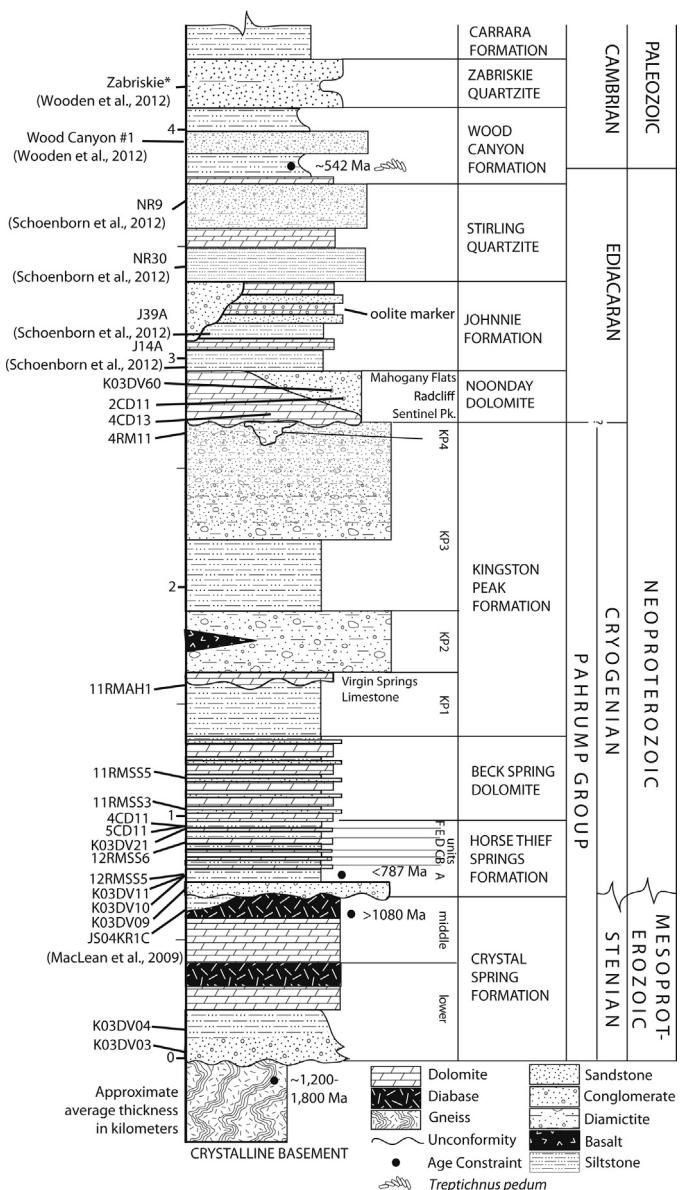


Fig. 2. Generalized stratigraphy of the Mesoproterozoic to lower Cambrian sedimentary sequence in the Death Valley region. Sample numbers indicate stratigraphic position of samples discussed in this study. Radiometric age constraints for the lower and middle Crystal Spring Formation from Heaman and Grotzinger (1992). Maximum depositional age and revised nomenclature for the Horse Thief Springs Formation from Mahon et al. (2014). Informal units A–F for Horse Thief Springs Formation from Maud (1979, 1983) and Mahon et al. (2014). Informal units KP1–KP4 from Prave, 1999; MacDonald et al. (2013). Basement age constraints from Lanphere et al. (1964), Labotka et al. (1980), Barth et al. (2001, 2009), and Iriondo et al. (2004). Ediacaran–Cambrian boundary from Corsetti and Hagadorn (2000). Asterisk on Zabriskie sample (from Wooden et al., 2012) indicates this sample is from the San Bernardino Range, CA.

et al., 2001, 2009; see Figs. 1 and 2). The Pahrump Group consists of four formations; a lower siliciclastic–carbonate unit, the Crystal Spring Formation, commonly intruded by diabase sills; an overlying siliciclastic–carbonate unit, the Horse Thief Springs Formation (formerly the upper member of the Crystal Spring Formation, revised in Mahon et al., 2014); a carbonate-dominated unit, the Beck Spring Dolomite; and an upper siliciclastic-dominated unit, the Kingston Peak Formation. Overlying the Pahrump Group is the carbonate-dominated Noonday Dolomite (see Fig. 2).

2.1. Stratigraphy and depositional setting

2.1.1. Lower and middle members of the Crystal Spring Formation

The lower and middle members of the Crystal Spring Formation are lithologically variable. The lower member of the Crystal Spring Formation (210–656 m thick; Roberts, 1982) comprises a basal conglomerate that unconformably overlies metamorphic basement, and fines upward into arkose. South directed paleocurrents in the lowermost arkosic fluvial unit are consistent with northward coarsening grain-size trends. This suggests a northern upland with south-flowing alluvial fans that fed a tidal-dominated sea (Roberts, 1982).

The remaining fluvial to marine lower Crystal Spring Formation fines upward into feldspathic sandstone and ultimately mudstone. Paleocurrent indicators suggest a drainage reversal occurs between south-directed flow in the basal Crystal Spring Formation to north-directed flow in the remaining lower and middle Crystal Spring Formation (Roberts, 1982). The middle member of the Crystal Spring Formation (136–397 m thick excluding diabase sills) comprises algal and dolomitic limestone overlain by clastic strata (the “cherty sub-member”), with the limestone units dominating in the north and clastic strata prominent in the south (Roberts, 1982). Paleocurrent indicators and thickness trends indicate the presence of a southern upland that shed clastic sediment northward onto a carbonate shelf, which was ultimately buried with northward-prograding clastic sediment (Roberts, 1982).

2.1.2. Horse Thief Springs Formation (previously the upper Crystal Spring Formation)

The Horse Thief Springs Formation (<787 Ma; ≤650 m thick; stratigraphic revision in Mahon et al., 2014) lies unconformably on the Crystal Spring Formation. This unconformity records a ca. 300 million year hiatus. The basal deposits comprise several sub-meter-scale cycles of clast-supported conglomerate/sedimentary breccia and siltstone; with clasts derived from the underlying Crystal Springs Formation (Maud, 1983). The Horse Thief Springs Formation comprises six regionally traceable, marine units of siliciclastic strata overlain by dolostone (see Fig. 3B); these units are defined by Maud (1979, 1983), from base to top as the “A through F units”. They range in thickness from 10s to 100s of meters. The siliciclastic units dramatically thicken eastward, but coarsen to the south-southwest. This suggests an upland to the southwest and maximum subsidence rate in the east-northeast (Maud, 1979, 1983). Northeast paleocurrent indicators predominate, however, some sediment was derived from or reworked by currents flowing to the east, west and south.

Carbonate units are relatively thin (a few decimeters to several meters thickness) when compared to the siliciclastic intervals, and display varying textural characteristics including microbial laminations, stromatolite beds, oncrolite, massive micrite, and occasional grainstone. Carbonate units, while variable in thickness, do not show similar consistent, dramatic thickness changes as siliciclastic units across the exposure area (Maud, 1979, 1983). The carbonates thus indicate times of both decreased siliciclastic input and more spatially uniform, if slower, subsidence (Maud, 1979, 1983). A favored depositional model of Maud (1983) is an “open clastic shoreline” whereby siliciclastic facies represent shoreline to offshore shoreface deposition, and the overlying transgressive carbonate facies indicate a shallow platform that was amenable to microbial productivity. Enterolithic folding of fine-grained sandstone and siltstone in the A–C units of the Horse Thief Springs Formation (Fig. 4B) indicates deposition of primary evaporites (subsequently dissolved) in a sabkha or a restricted basin depositional environment (Mahon et al., 2014).

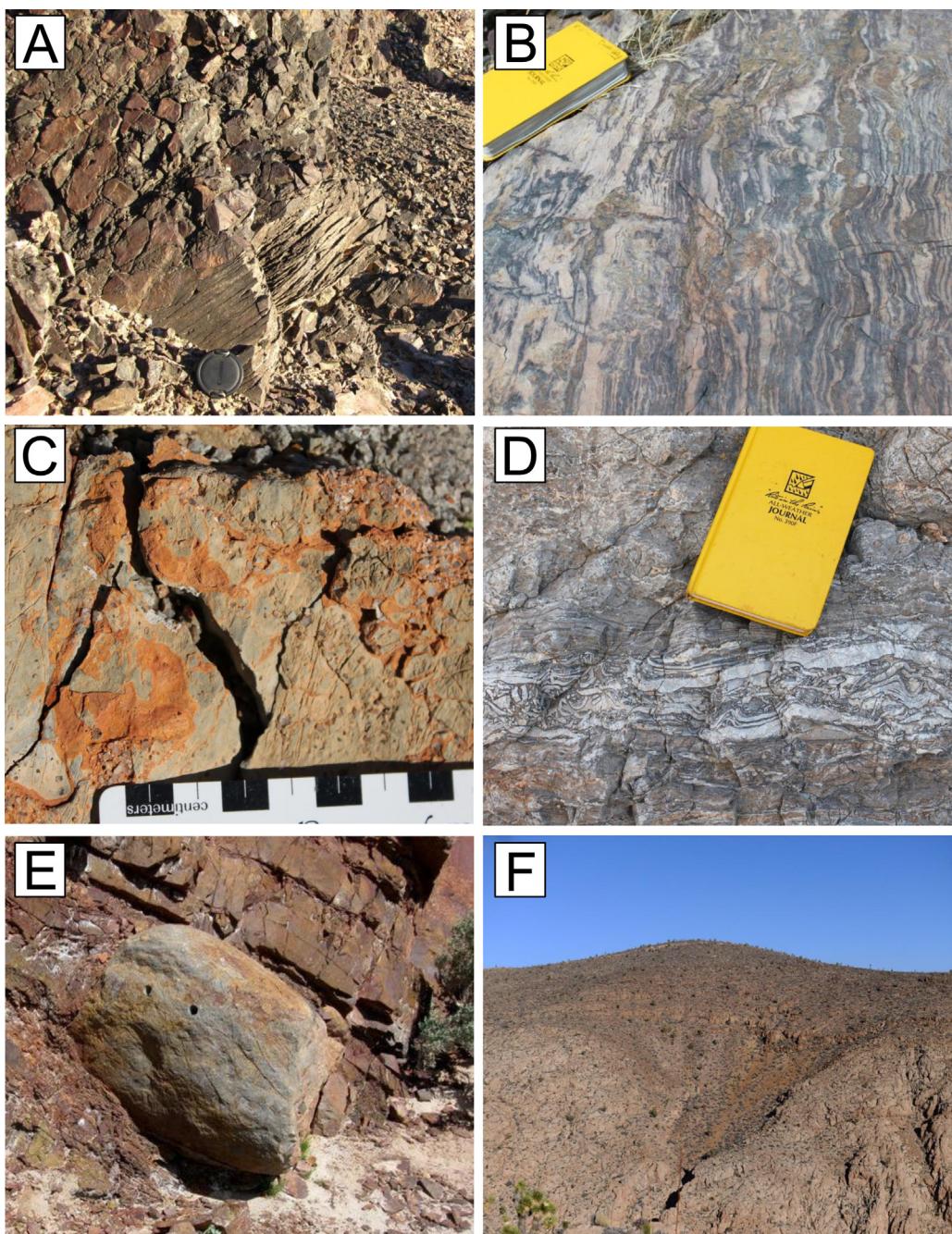


Fig. 3. Outcrop photographs of (A) unconformity at the base of the Horse Thief Springs Formation from the southern Ibex Hills with middle Crystal Spring Formation siltstone to the lower left, Horse Thief Springs Formation conglomerate above (lens cap for scale is 6.7 cm in diameter); (B) enterolithic folding in the Horse Thief Springs Formation, A-unit from Beck Canyon in the Kingston Range (field notebook for scale is 19 cm by 12 cm); (C) paleokarst horizon in the Beck Spring Dolomite from the southern Ibex Hills – note the orange, irregularly shaped clastic detritus-filled wedges and stringers developing from the upper surface of the gray dolomite bed; (D) soft sediment deformation structures interpreted as seismites in the Beck Spring Dolomite from the southern Black Mountains – evidence for seismic origin includes confinement of deformation to laterally continuous, thin layers, and lack of preferred orientation of soft sediment folds; (E) Dropstone in the Kingston Peak Formation (KP3 unit) in Sperry Wash (paleomag boreholes are 3 cm diameter for scale – photo courtesy of Jessica Nichols); and (F) Erosional fill between the top of the Sentinel Peak Member and base of the Radcliff Member of the Noonday Dolomite. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.1.3. Beck Spring Dolomite

The Beck Spring Dolomite (~350 m thick) is a carbonate-dominated unit, which conformably overlies the Horse Thief Springs Formation (Zempolich, 1989). Predominantly composed of gray to variegated gray-orange dolomite (see Fig. 3C), the Beck Spring Dolomite is commonly stromatolitic or microbially laminated (including roll-up structures), and contains oncoidal beds. In exposures to the southwest it contains paleokarst, molar tooth structures, soft-sediment deformation features, giant oolite

(ooliths >5 mm diameter), and significant siliciclastic components (Marian, 1979; Tucker, 1983; Zempolich et al., 1988; Zempolich, 1989; Harwood and Sumner, 2011; Mahon and Link, 2011). These indicate deposition in a shallow, platform environment (Gutstadt, 1968; Cloud et al., 1969; Marian, 1979; Zempolich et al., 1988; Zempolich, 1989; Harwood and Sumner, 2011), although the clastic facies indicate nearshore higher energy environments. Seismically induced soft-sediment deformation structures and syn-depositional normal faults observed in the Horse Thief Springs

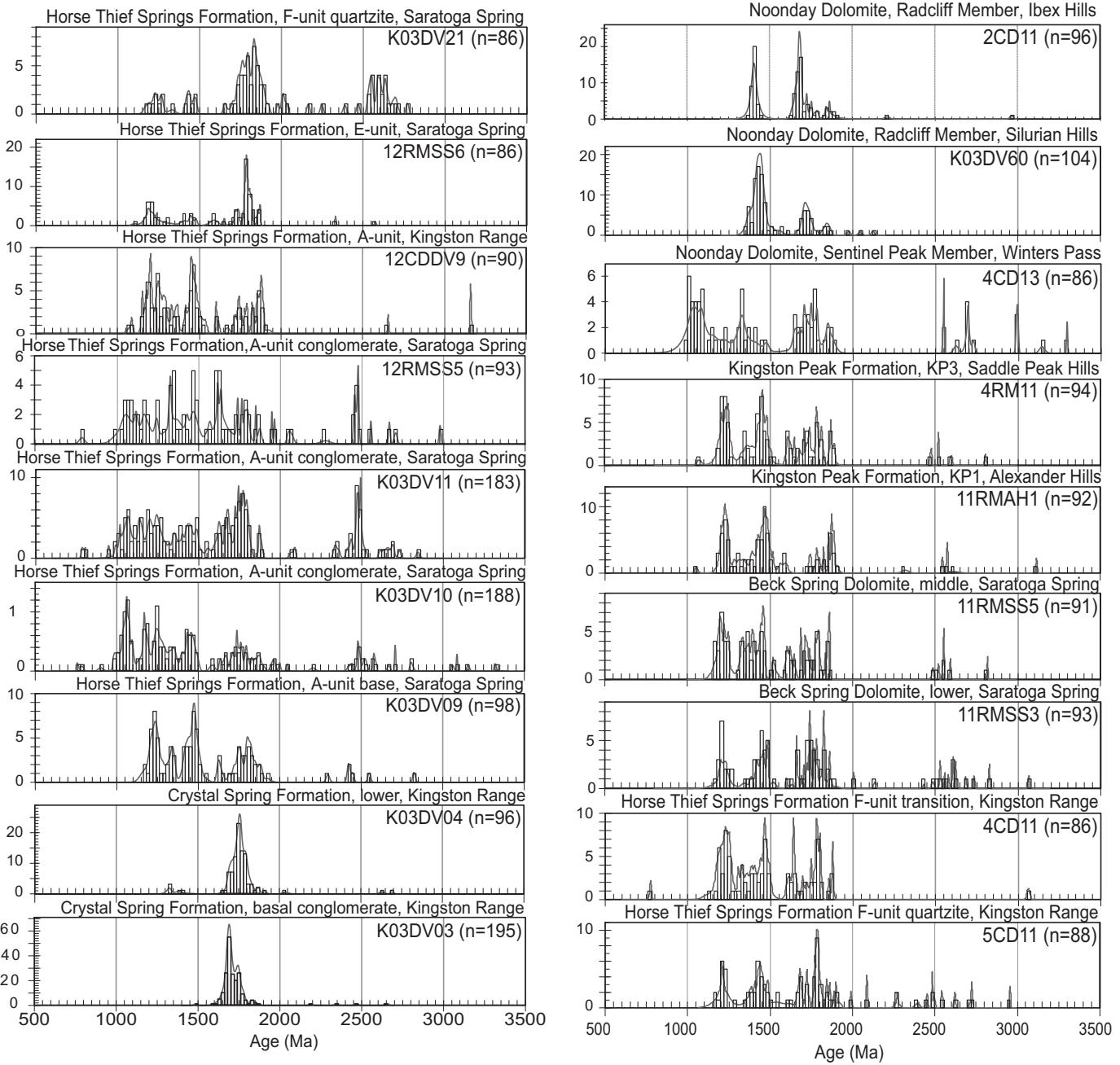


Fig. 4. Detrital zircon age sample distributions with overlaid probability density curves for samples analyzed in this study. Histogram bin size is 20 Ma. Minor axis ticks at 50 Ma intervals. See Table DR6 (Supplementary material) and Section 3 for description of methods used to analyze and prepare sample distributions.

Formation and in the Beck Spring Dolomite indicate the basin was undergoing extensional tectonism and seismicity during deposition of both units (Fig. 3D; Link et al., 1993; Mahon and Link, 2011; Mahon, 2012).

2.1.4. Kingston Peak Formation

The Kingston Peak Formation (<1800 m thick) is a heterolithic unit; it is informally divided into four stratigraphic units, KP1-KP4, on the basis of internal unconformities (Prave, 1999). The lowermost unit, KP1, comprises calcareous siltstone and fine sand, and is in gradational contact with, and considered to be tectonostratigraphically related to the underlying Beck Spring Dolomite (Prave, 1999; MacDonald et al., 2013; Mahon et al., 2014).

The overlying units in the Kingston Peak Formation (KP2-KP4) are a mixture of cobble-boulder diamictite (see Fig. 3E), sandstone

of varying composition and texture, fine grained siliciclastic units, and subordinate carbonate rock (e.g. Troxel, 1967). The extensive deposits of diamictite are interpreted to be of glacial or glaciomarine origin based on the presence of striated and faceted clasts, limestones, dropstones, and ice rafted debris (e.g. Hazzard, 1939; Troxel, 1982; Miller, 1985; Link et al., 1993; Prave, 1999). Clast-count data show predominantly sedimentary lithic compositions, with many recognizable clasts (specifically including gray oolitic and oncotic dolomite attributable to the Beck Spring Dolomite, and quartzite and diabase attributable to the Crystal Spring Formation) implying that much of the clastic material in KP2-KP4 was derived from the older units of the Pahrump Group, requiring uplift and recycling of underlying units (Miller, 1985; Prave, 1999; Mahon, 2012). Multiple unconformities occur within these units, some of which show angular discordance (Prave, 1999; MacDonald

et al., 2013). These surfaces, along with large-scale buried Proterozoic normal faults in association with tholeiitic basalts and feeder dikes, indicate a rift tectonic setting (Troxel, 1967; Hammond, 1983, 1986; Walker et al., 1986; Prave, 1999). Carbonate facies within the Kingston Peak Formation have variable origins, one of which is considered to be a cap carbonate deposited during deglaciation from a Snowball Earth glacial event (Sourdough Limestone; Prave, 1999).

2.1.5. Noonday Dolomite

The Noonday Dolomite (<400 m thick) sharply, and in some cases unconformably, overlies different units within the Pahrump Group or rests directly on Paleoproterozoic basement rocks (e.g. Petterson et al., 2011b). The lowermost member, the Sentinel Peak Member, is thicker in the northeast (200 m) and thins southward to as little as 2 m (Fig. 3; Petterson et al., 2011b). This dolomite contains unusual features such as 'sheet cracks' and tubestone (see Fig. 3F), which are unique features proposed to have been deposited only during Marinoan (635 Ma) 'cap carbonate' deposition (Prave, 1999; Petterson et al., 2011b). The overlying Radcliff Member (<200 m) is a mixed siliciclastic-carbonate unit consisting of thinly bedded arkosic arenite, arkosic wacke, limestone rhythmite, intraformational breccia, and locally, variegated shale. The uppermost member, the Mahogany Flats Member (<200 m thick), is a thin- to thickly-bedded stromatolitic dolostone. The Noonday depositional system began with microbial build-ups and offshore carbonate deposition (Sentinel Peak Member), with concurrent and later deposition of immature sands filling in topographic lows (Radcliff Member). This was followed by a return to microbially-dominated sedimentation on a carbonate platform (Mahogany Flats Member; Petterson et al., 2011b).

2.2. Tectonic setting

The Pahrump Group was considered by early workers to have accumulated in a differentially subsiding failed rift basin, termed the "Amargosa Aulacogen" (Wright, 1952, 1968; Roberts, 1974a, 1974b, 1976, 1982; Wright et al., 1974). This inference comes from paleogeographic interpretations, which show within the lower Crystal Spring Formation, initial sediment source areas to the north followed by an abrupt shift to source areas to the south (e.g. Wright et al., 1974). This pattern led workers to interpret an east-west-trending, elongate extensional basin whereby different rift shoulders (north versus south) were active at different times. However, this model for the evolution of the Pahrump Group basin did not account for Basin and Range tectonics, and included the assumption that the Pahrump Group was a tectonostratigraphically and chronostratigraphically continuous section, without major internal unconformities.

More recent work has refined the tectonic history of the Pahrump Group (e.g. Prave, 1999; Timmons et al., 2005; Petterson et al., 2011a; Dehler et al., 2012; MacDonald et al., 2013; Mahon et al., 2014). Four unconformity-bounded tectonostratigraphic packages have been previously described. The Crystal Spring Formation represents the oldest package, constrained in age by underlying basement (1760–1400 Ma; Wasserburg et al., 1959; Labotka et al., 1980; Barth et al., 2001, 2009). It is intruded by dia-base sills, which yield U-Pb baddeleyite ages of 1087 ± 3 Ma and 1069 ± 3 Ma (Heaman and Grotzinger, 1992). The unconformably overlying tectonostratigraphic package comprises the Horse Thief Springs Formation and the gradationally overlying Beck Spring Dolomite through lower Kingston Peak Formation (KP1) (Prave, 1999). The basal Horse Thief Springs Formation contains a suite of Neoproterozoic detrital zircons that provide a maximum depositional age of 787 ± 11 Ma (Mahon et al., 2014) for the base of this conformable sequence. Overlying this are two younger diamictite-cap carbonate packages identified in the upper Pahrump Group

and the Sentinel Peak Member of the Noonday Dolomite, interpreted to correlate with Sturtian (~715–670 Ma; KP2-KP3) and Marinoan (~650–635 Ma; KP4 + Noonday) glacial episodes (Prave, 1999; Petterson et al., 2011a). These correlations are based on regional and global lithologic similarities, as well as similarities in carbon isotope values (e.g. Prave, 1999; Petterson et al., 2011a), although no direct age control currently exists, so their assigned ages are speculative.

2.3. Previous detrital zircon studies

MacLean (2007) and MacLean et al. (2009) presented three U-Pb SHRIMP-RG (sensitive high resolution ion microprobe - reverse geometry) detrital zircon samples from the Pahrump Group. Vogel (2004) also presented SHRIMP-RG detrital zircon data from one sample of the Kingston Peak Formation from Redlands Canyon in the Panamint Range and one sample from the Johnnie Formation in the eastern Death Valley region. Overlying Neoproterozoic strata have also been sampled for detrital zircon analyses (Stewart et al., 2001; Schoenborn, 2010; Schoenborn et al., 2012; Wooden et al., 2012) and comparisons to these data will be discussed below. Detailed provenance analysis from early studies was significantly hindered by small datasets and an incomplete understanding now available of the complexity of the surrounding basement provinces (e.g. Barth et al., 2009; Strickland et al., 2013; Holland et al., 2013). Overall, the data presented herein dramatically expand the understanding of the provenance history for Mesoproterozoic through Neoproterozoic time along the southwestern margin of Laurentia, in the period leading to the development of the Cordilleran passive margin (e.g. Gehrels and Pecha, 2014).

3. Methods

3.1. Detrital zircon analysis

3.1.1. Sampling

Samples of fine-to-medium-grained sandstone and quartzite were collected over the course of several years from throughout the Pahrump Group section in the southeastern Death Valley region (see Data Repository Table DR1, Supplementary material). We especially targeted the Horse Thief Springs Formation to test the hypothesis that it is indeed a different and significantly younger unit than the lower-middle Crystal Spring Formation (see Mahon et al., 2014). Overall, two samples from the lower Crystal Spring Formation, nine samples from the Horse Thief Springs Formation, two samples from Beck Spring Dolomite, two from the Kingston Peak Formation, and three from Noonday Dolomite were analyzed as part of this study (stratigraphic positions of samples are shown in Fig. 2).

3.1.2. Preparation

Samples were prepared for analysis using standard crushing and mineral separation techniques at Idaho State University, Boise State University, and University of Arizona mineral separation facilities. Samples were washed and crushed using hammer and steel plate or mechanical chipper, followed by powdering the samples in a disk mill and sieving samples to 60-mesh. Sieved sands were run across a water table for relative density separation and sample was collected at three intervals. The heaviest washed sample was then oven dried and subjected to initial Frantz magnetic separation, and heavy liquid separation using methylene-iodide ($\rho = 3.32$ g/mL) heavy liquid. Heavy mineral separates were then subjected to stepwise Frantz magnetic separation to remove the dense magnetic mineral fraction (e.g. pyrite and hornblende). Separates were mounted in epoxy with several standards of SL (Sri Lanka). Sample mounts were

polished; imaged using reflected light and BSE (back scatter electron microscopy) and cleaned before analyses.

3.1.3. Analysis

20 detrital zircon samples were analyzed for U and Pb isotopes using the LA-MC-ICPMS (Laser ablation multi-collector inductively coupled plasma mass spectrometer) at the Arizona LaserChron facility at University of Arizona in Tucson. Approximately 100 grains were analyzed per sample (using methods outlined in Gehrels et al., 2008). Ablation for samples analyzed prior to May 2011 (samples with label prefixes K03DV-) was conducted using New Wave UP193HE excimer laser; ablation for samples analyzed after May 2011 (all other samples, as well as re-analyses of K03DV10 and K03DV11) was conducted with a Photon Machines Analyte G2 excimer laser. Analyses consist of single 15-second integrations on peaks with the laser off (for backgrounds), 15 one-second integrations with the laser firing, and a 30 second delay to purge the previous sample. The ablation pit is ~15 µm in depth and 30 µm in diameter.

In-run analysis of Sri Lanka standards (known age 563.5 ± 3.2 , 2-sigma standard deviation) were conducted after every fifth unknown grain analysis. Isotope ratios are corrected for $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ instrumental fractionation using fractionation factors determined from in-run analysis of Sri Lanka standards. Uncorrected $^{206}\text{Pb}/^{238}\text{U}$ ages for all runs of Sri Lanka standards from all sample analyses yields a mean age of 564.2 Ma with a 2-sigma standard deviation for all analyses of 10.8 Ma, providing a measure for the reproducibility of the standard runs over the entire suite of sample analyses. $^{206}\text{Pb}/^{238}\text{U}$ ages were used for analyses younger than 1000 Ma while $^{206}\text{Pb}/^{207}\text{Pb}$ ages were used for analyses older than 1000 Ma. Samples with greater than 20% $^{206}\text{Pb}/^{238}\text{U}$ vs. $^{206}\text{Pb}/^{207}\text{Pb}$ discordance and 5% reverse discordance were discarded. A complete discussion of discordance cutoffs for provenance studies is found in Gehrels (2012). Data reductions for sample runs are performed in Isoplot Excel program (Ludwig, 2008).

4. Results

Of 1981 total grains analyzed 1945 detrital zircon grains fell below discordance filters and were used to construct relative probability (Fig. 4; Table DR2, Supplementary material) and concordia plots (see Fig. DR3, Supplementary material). Sampled age distributions include >2500 Ma, ca. 2500–2400 Ma, 1600–1900 Ma, 1500–1600 Ma, 1350–1490 Ma, 950–1350 Ma and ca. 800–760 Ma.

4.1. Stratigraphic trends of age distributions

Detrital zircon spectra obtained in this study reveal three significant shifts in sampled age distributions within the Pahrump Group/Noonday Dolomite. Spectra from the basal conglomerate from the lower Crystal Spring Formation exhibit a strongly unimodal sample distribution with a peak at ca. 1685 Ma. Samples of the lower and middle Crystal Spring Formation also exhibit a unimodal sample distribution with peak at 1745 Ma (see Fig. 4). MacLean et al. (2009)'s data from the middle Crystal Spring Formation show a sample distribution with a unimodal peak at about 1780 Ma.

The 300 m.y. unconformity between the Crystal Spring Formation and the Horse Thief Springs Formation (see Mahon et al., 2014) is recognized in a pronounced shift in provenance. Detrital zircon spectra from the Horse Thief Springs Formation through the Kingston Peak Formation show a mixed suite of Paleoproterozoic to Mesoproterozoic sample ages. The detrital-zircon spectra become increasingly complicated, with many small age-peaks, and

probably resulting from recycling of zircon grains from preexisting sandstones. Significant sample distributions include peaks at ca. 1040, 1180, 1220, 1450, 1730 and 1790 Ma. There is a 2455 Ma peak in the basal Horse Thief Spring Formation samples, as well as variable 2500–2650 Ma age distributions in several samples.

The Horse Thief Springs Formation contains a significant peak at ca. 1040 Ma in the A-unit quartzite (samples K03DV10, K03DV11, 12RMSS5) that does not appear in the overlying samples from the Horse Thief Springs through Kingston Peak Formations. The ca. 1220 Ma age peak persists throughout the Horse Thief Springs Formation and into the Beck Springs and lower Kingston Peak formations. A shift to a greater proportion of Paleoproterozoic grains occurs in the E and F-units of the Horse Thief Springs Formation in the southern Ibex Hills/Saratoga Spring sections (samples 12RMSS6, K03DV21), however this shift is not mirrored by samples from equivalent stratigraphic horizons in the Kingston Range (samples 4CD11, 5CD11).

The Sentinel Peak Member of the Noonday Dolomite (sample 4CD13) shows similar detrital zircon age spectra to the underlying Kingston Peak Formation, however, a significant proportion of ca. 1040–1100 Ma detrital zircons ages are present. This age-range is generally not present or represented by very small numbers of grains in the underlying Kingston Peak Formation, and is only present in the A-unit quartzite of the Horse Thief Springs Formation.

A major shift in detrital zircon age spectra occurs within the Noonday Dolomite. The Radcliff Member of the Noonday Dolomite is strongly bimodal with sample distributions exhibiting peaks at ca. 1400 Ma and 1675 Ma (Fig. 2). The wide distribution of 1040–1220 Ma ages is not present. This suggests a more restricted provenance area.

5. Sources of age populations

5.1. Archean (>2500 Ma)

Grains of ages 2500 Ma and older are present in variable proportions in all but one of the analyzed samples (Radcliff Member of the Noonday Dolomite – K03DV60) (see Fig. 5). The nearest known basement source for grains of these ages is the Wyoming Craton (Whitmeyer and Karlstrom, 2007; Shufeldt et al., 2010; see Fig. 6); however, paragneisses containing significant detrital populations of this age range are common in the more proximal Mojave province (e.g. Barth et al., 2000; Strickland et al., 2009, 2013; Holland et al., 2013). The persistence of grains of this age range throughout the Pahrump Group section as well as other Neoproterozoic successions in southwestern Laurentia (e.g. Doe et al., 2012), and the presence of significant populations in samples from the Horse Thief Springs Formation F-unit quartzite and the Beck Spring Dolomite, suggests that these grains were most likely recycled from paragneisses of the Mojave Province. Paleoflow, and clast and point count data from the Pahrump Group, the simple nature of the detrital-zircon populations, as well as its immediate proximity to known metasedimentary sources of grains of this age range, all suggest recycling from local Mojave Province paragneisses rather than from the distal Wyoming Province.

5.2. Earliest Paleoproterozoic (ca. 2450 Ma)

A significant distribution of earliest Paleoproterozoic (2500–2450 Ma) grains is present in samples from the base of the Horse Thief Springs Formation (samples K03DV10, K03DV11, K03DV09; Fig. 5). Metasedimentary (micaceous gneiss) units in the Mojave Province basement also have grains of this age in varying proportions (Barth et al., 2009; Doe et al., 2012; Strickland et al., 2013; Holland et al., 2013; see Figs. 5 and 6). Paleocurrents from

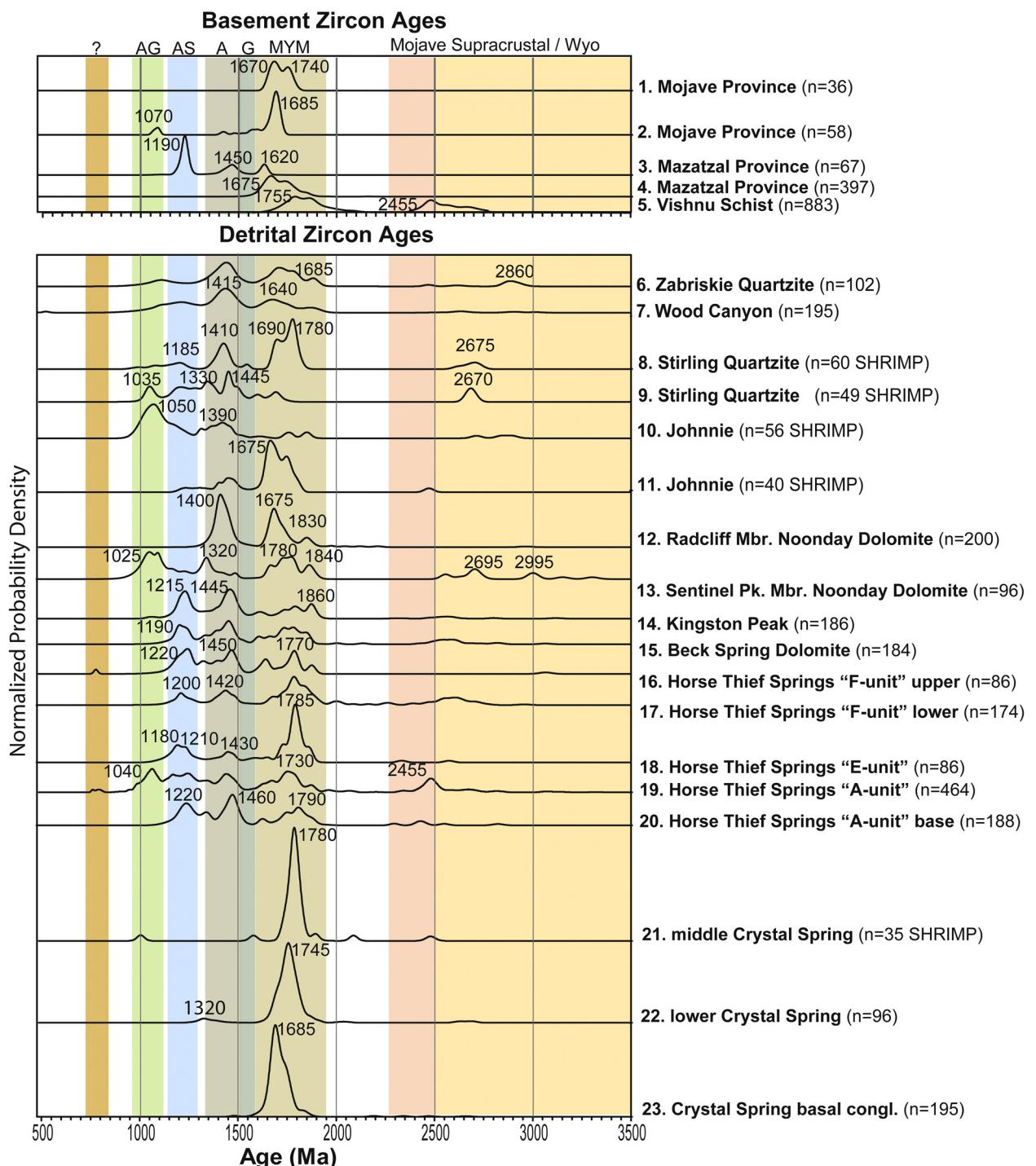


Fig. 5. Combined normalized probability density plot of detrital zircon grains. Colored bars highlight significant population ranges. Age range labels: Wyo – Wyoming Craton, likely recycled; V – Vishnu Schist or equivalent Paleoproterozoic schist; MYM – Mojave, Yavapai and Mazatzal provinces; G – North American magmatic gap; A – A-type granites in S. California and Arizona; AG – Aibo Granite or equivalent; AS – San Gabriel anorthosite-syenite complex or equivalent; ? – unknown provenance. Several samples are combined on the basis of similar spectra and are as follows: (19) Horse Thief Springs A-unit – K03DV10, K03DV11, 12CDDV9; 12RMSS5; (17) Horse Thief Springs F-unit quartzite – K03DV21, 5CD11; (15) Beck Spring Dolomite – 11RMSS3, 11RMSS5; (14) Kingston Peak Formation – 11RMAH1, 4RM11; (12) Radcliff Member, Noonday Dolomite – K03DV60, 2CD11. Samples derived from previous work are as follows: (1) Barth et al. (2009); (2) Iriondo et al. (2004); (3) Rämö et al. (2003); (4) Amato et al. (2008); (5) Shufeldt et al. (2010); (6–7) Wooden et al. (2012); (9–12) Schoenborn et al. (2012); (22) MacLean et al. (2009). Note: sample labeled (6) Zabriskie Quartzite (from Wooden et al., 2012) is from the San Bernardino Mountains. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cross beds within the A-unit of the Horse Thief Springs Formation (from Maud, 1979) suggest sediment transport was primarily from the south. Thus, the source for these grains in the Horse Thief Springs Formation is hypothesized to be from reworked metasedimentary rocks within the Mojave Province (e.g. Vishnu Schist, White Ledges Formation or equivalents).

5.3. Paleoproterozoic (1800–1610 Ma)

Paleoproterozoic grains ranging in age from 1800 to 1610 Ma are present in all samples. Primary magmatic ages in this range are known from local basement sources in the Mojave crustal province (see Figs. 5 and 6) (Wasserburg et al., 1959; Wooden

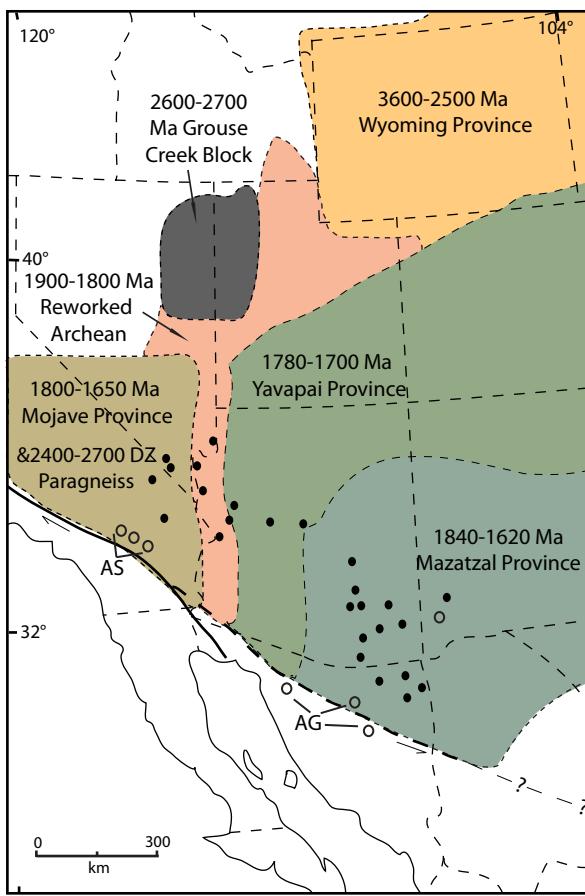


Fig. 6. Geology of southwestern United States showing age ranges of major Precambrian basement provinces illustrating possible sediment source terranes (modified after Whitmeyer and Karlstrom, 2007; with data from Link et al., 2007). Filled black dots represent 1340–1460 Ma A-type granites (from Stewart et al., 2001); open circles represent “Grenville” aged granitic bodies: AS – ca. 1200 Ma San Gabriel Mountains Anorthosite-Syenite complex (Ekstrom et al., 1994; Barth et al., 2001); AG – ca. 1010 Ma Aibo Granite (Farmer et al., 2005). “2400–2700 Ma DZ paragneiss” refers to detrital zircons of this age derived from supracrustal paragneisses (from Barth et al., 2009; Doe et al., 2012; Strickland et al., 2013; Holland et al., 2013).

and Miller, 1990; Karlstrom and Humphreys, 1998; Barth et al., 2000; Bryant et al., 2001; Coleman et al., 2002; Barth et al., 2009; Nelson et al., 2011; Karlstrom and Williams, 2012; Strickland et al., 2013). Similar ages are known from both the Yavapai and Mazatzal crustal provinces (see Fig. 5) with narrower age ranges than those known for the Mojave Province (Karlstrom and Humphreys, 1998; Duebendorfer et al., 2001; Cox et al., 2002; Rämö et al., 2003; Iriondo et al., 2004; Amato et al., 2008; Shufeldt et al., 2010). Ultimately, using the U-Pb age alone to determine the specific basement sources of these grains is problematic due to the widespread distribution of this age range in basement throughout the Southwest. However, location of the Pahrump Group within the Mojave crustal province, which contains granitic sources of this entire age range, as well as associated north-directed paleocurrents (e.g. Maud, 1979, 1983), make the southern Mojave the most likely source region.

5.4. Mesoproterozoic (1600–1500 Ma)

This period of time represents a period in which basement zircon ages are unknown in southwestern Laurentia (“North American magmatic gap” of Ross and Villeneuve, 2003). A few grains of this age are present in some samples of the Pahrump Group, notably as discrete minor peaks (up to 4 grains; see Figs. 4 and 5) in the

Horse Thief Springs Formation and Beck Spring Dolomite. Sources for these grain ages are missing from Laurentian basement rocks with the exception of the Pinware Terrain of northeastern Canada (Rainbird et al., 1997), but detrital grains of this age are known from Mesoproterozoic and Neoproterozoic basins to the north (e.g. Belt Supergroup, Ross and Villeneuve, 2003; Uinta Mountain Group, Dehler et al., 2010; Kingsbury-Stewart et al., 2013) and southeast (e.g. Yankee Joe Formation; Doe et al., 2012). As such, we infer these grains reflect reworking of regional metasedimentary rocks.

5.5. Mesoproterozoic (1490–1350 Ma)

A significant distribution of grains ranging in age from 1490 to 1330 Ma is present in all samples from the Pahrump Group above the unconformity at the base of the Horse Thief Springs Formation. These grains were likely to have been derived locally, considering the presence of A-type granites of this age in southeastern California and western Arizona (Anderson, 1989; Karlstrom and Humphreys, 1998; Stewart et al., 2001; Bryant et al., 2001; Goodge and Vervoort, 2006; see Fig. 6).

5.6. Mesoproterozoic (1350–950 Ma)

“Grenville-aged” detrital zircon grains (1350–950 Ma) are present in a majority of samples above the unconformity at the base of the Horse Thief Springs Formation, with a significant age distribution centered at ca. 1220 Ma. Zircon-bearing igneous rocks of this age are present in southeastern California (San Gabriel Anorthosite-Syenite complex – Barth et al., 1995, 2001; Wooden et al., 2012), and southwestern New Mexico (Rämö et al., 2003). Separate, distinct sample distributions centered at ca. 1060–1080 Ma are also present in samples at the base of the Horse Thief Springs Formation (samples K03DV10, K03DV11, 12CDDV9). Granites of these ages are known from New Mexico, Arizona, Chihuahua, and Sonora (Stewart et al., 2001; Iriondo et al., 2004; Amato et al., 2013; Bright et al., 2014) as well as the Llano uplift in Texas (e.g. Barker and Reed, 2010). Moderate rounding and abrasion to detrital zircon grains of these ages within the Pahrump Group samples supports a less distal source (see Figs. DR1 and DR2, Supplementary material). Thus, we ultimately suggest this age range as indicative of regional transport from similar-age granitic sources in Arizona, New Mexico or Sonora.

In the case of samples from the Pahrump Group and Noonday Dolomite, detrital zircons of later Mesoproterozoic ages appear to be narrowly confined to two discrete age populations as described above, each of which can be directly attributed to felsic magmatism in the vicinity of southwestern Laurentia (see Fig. 5, samples 2 and 3). This contrasts with the broad sample distributions over a wider age range (1350–950 Ma), such as those present in samples from the Johnnie Formation, Stirling Quartzite and the Wood Canyon Formation and Zabriskie Quartzite as shown in Fig. 5 (from Stewart et al., 2001; reanalyzed by Wooden et al., 2012; and Schoenborn et al., 2012; see Fig. 5, samples 6–10). Thus we would interpret age distributions with broad ranges over 950–1350 Ma to (such as those from the upper Johnnie through Wood Canyon Formations) represent more distally-sourced detritus from cratonic sources in the Grenville or Llano uplifts. This is consistent with sedimentologic interpretations of Fedo and Cooper (2001), who attribute the middle Wood Canyon Formation and Zabriskie Quartzite to represent the onset of the mature passive margin – craton cover sequence (Phase III of Fedo and Cooper, 2001) as well as interpretations made by Schoenborn et al. (2012) that these units represent the onset of a passive margin setting, with some contribution of distally derived detritus. This hypothesis warrants further testing using Hf-isotope

geochemistry or other methods to determine the exact sources of these Mesoproterozoic detrital zircon ages.

5.7. Neoproterozoic (800–760 Ma)

Three samples from the Horse Thief Springs Formation contained detrital zircon grains with ages between 800 and 760 Ma. Samples containing this age range show also mixed Mesoproterozoic to Neoproterozoic age populations. A possible western Laurentian source for grains of this age range could include an unrecognized zircon-bearing component of the 780 Ma Gunbarrel Magmatic Event in northwestern Laurentia (Harlan et al., 2003). It is also possible that these zircon grains represent the reworking of one or more ashfall events, sourced either in eastern Laurentia such as the ~760 Ma Mount Rogers Formation and Crossnore Complex (Aleinikoff et al., 1995; Su et al., 1994; respectively) or from a conjugate continent across the Rodinia rift margin such as the 783–770 Ma A-type granites in South China (Wang et al., 2010; Xia et al., 2012), the 777 ± 7 Ma Boucaut Volcanics (rhyolites) in the Nackara Arc of South Australia (Priess, 2000) or the 804–776 Ma continental arc magmatic rocks from West Africa (Handke et al., 1999). Detrital grains of this age are generally small, equant, and subangular-subround and lack significant zoning (see Figs. DR1 and DR2, Supplementary material). The small number of sampled grains of this age does not allow a robust characterization of source type from grain morphologies.

Neoproterozoic (ca. 780–760 Ma) grains also occur in the Nankoweap Formation and Chuar Group of the Grand Canyon Supergroup (Dehler et al., 2012), the Little Willow Formation in Utah (Spencer et al., 2012) and the Uinta Mountain Group (Dehler et al., 2010; Kingsbury-Stewart et al., 2013). Paleocurrent data and the fluvial interpretation for the A-unit quartzite of the Horse Thief Springs Formation (Maud, 1979, 1983), from which five of six detrital zircon grains of this age grouping were obtained, suggests that the most recent transport of these young grains was along fluvial networks from the south.

5.8. Synthesis of detrital zircon sources

Analysis of the potential sources of each individual age distribution can thus be summarized as follows: grains of Archean and earliest Paleoproterozoic ages (3600–2450 Ma) are likely derived from recycling of Paleoproterozoic meta-sedimentary rocks of the Mojave province or adjacent regions (e.g. Vishnu Schist, White Ledges Formation or local equivalents). Grains of Paleoproterozoic (1800–1610 Ma) are likely derived locally from Mojave province basement; however, it is impossible to distinguish between Mojave, Yavapai and Mazatzal crustal provinces based on age alone. Early Mesoproterozoic ages (1600–1500 Ma) are scarce, but present. Their ultimate source is unclear; however, these grains could have been derived via proximal recycling of older sedimentary strata (e.g. Yankee Joe Formation, see Doe et al., 2012). Middle Mesoproterozoic (1490–1350 Ma) ages are likely derived from any of the broadly distributed A-type mid-continent granites, common throughout the western Laurentian crustal provinces and present local to the Death Valley region. Late Mesoproterozoic (1350–950 Ma) detrital zircon grain age spectra, particularly those exhibiting more narrow, discrete distributions at 1080 and 1220 Ma (such as those from the Horse Thief Springs Formation through the Sentinel Peak Member of the Noonday Dolomite), are inferred to have been derived from regional felsic bodies known throughout the Mojave-Yavapai-Mazatzal provinces adjacent and to the east of the Death Valley region. However, where grains of this age range are present in more broad age-distributions (such as those in the upper Johnnie through Wood Canyon Formations), we postulate a more easterly-derived source from the Grenville-Llano orogenic belts

within a continental-scale drainage system. Finally, the provenance of the trace Neoproterozoic detrital zircon grains (800–770 Ma), present in the Horse Thief Springs Formation remains problematic.

6. Discussion

6.1. Paleogeography

Analysis of stratigraphic trends and sources of detrital zircon age sampling distributions, paleocurrent data, sandstone point count and conglomerate clast count data, and the nature of the unconformities within and above of the Pahrump Group results in the recognition of six distinct paleogeographic “time slices” that correspond with and refine previously proposed tectonostratigraphic packages (Prave, 1999; Timmons et al., 2005; MacDonald et al., 2013) (Fig. 7). These include: (A) the basal conglomeratic fluvial member of the Crystal Spring Formation; (B) the remaining fluvial-intertidal lower and middle Crystal Spring Formation; (C) marine Horse Thief Springs Formation-lower Kingston Peak Formation (KP1); (D) glaciomarine middle-upper Kingston Peak Formation (KP2-KP4); (E) the marine Sentinel Peak Member of the Noonday Dolomite; and (F) the marine Radcliff Member of the Noonday Dolomite through the lower Johnnie Formation. The paleogeographic setting and relationship to other tectonostratigraphic frameworks for each of these time-slices is described in detail in the following sections.

6.1.1. Basal Crystal Spring Formation (<1400 Ma)

During the deposition of the basal conglomerate of the lower Crystal Spring Formation, sediment was delivered by a fluvial system flowing to the south (Roberts, 1974a, 1974b, 1982). Detrital zircon ages from the basal sample show a strongly unimodal sample distribution with a peak at ca. 1685 Ma (see Fig. 5). This age is representative of local Mojave Province basement (Wasserburg et al., 1959; Wooden and Miller, 1990; Karlstrom and Humphreys, 1998; Barth et al., 2000; Bryant et al., 2001; Coleman et al., 2002; Barth et al., 2009; Nelson et al., 2011; Karlstrom and Williams, 2012; Strickland et al., 2013), yet this system must have received input from a quartzite unit, as a majority of the clasts present in the basal conglomerate are composed of metasedimentary quartzites. Several quartzite units with similar detrital zircon age-spectra are reported across the Mojave Province (e.g. Jones et al., 2009; queried in Fig. 7A), although identifying the specific source is not deemed possible with this data. The age of the basal Crystal Spring Formation is poorly constrained (<1400 Ma) based on youngest ages of basement in the region; however, deposition of this unit is inferred to have occurred during widespread intracratonic basin development associated with the assembly of the Rodinia supercontinent (Timmons et al., 2005).

6.1.2. Remaining Crystal Spring Formation (ca. 1320–1080 Ma)

While not directly evident from detrital zircon signatures, paleoflow direction, grain size and clast composition (Roberts, 1974a, 1974b, 1976, 1982) indicate a paleoenvironmental and provenance shift between the basal, conglomeratic portion of the lower Crystal Spring and the remainder of the Crystal Spring Formation (see Fig. 7B). Quartzite units interfinger with lower conglomeratic units and north-directed paleoflow within deltaic and tidal settings characterizes the remainder of the formation (Roberts, 1974a, 1974b, 1982). Detrital zircon grains show unimodal sample distributions with peaks at ca. 1760 Ma, representing derivation from local Mojave Province basement (see Fig. 7B).

There is a small ($n = 3$) sub-sample of ca. 1320 Ma detrital zircon grains in the lower Crystal Spring Formation (sample K03DV04) above the basal conglomeratic units which constrains the maximum depositional age for this unit. It is likely that there was

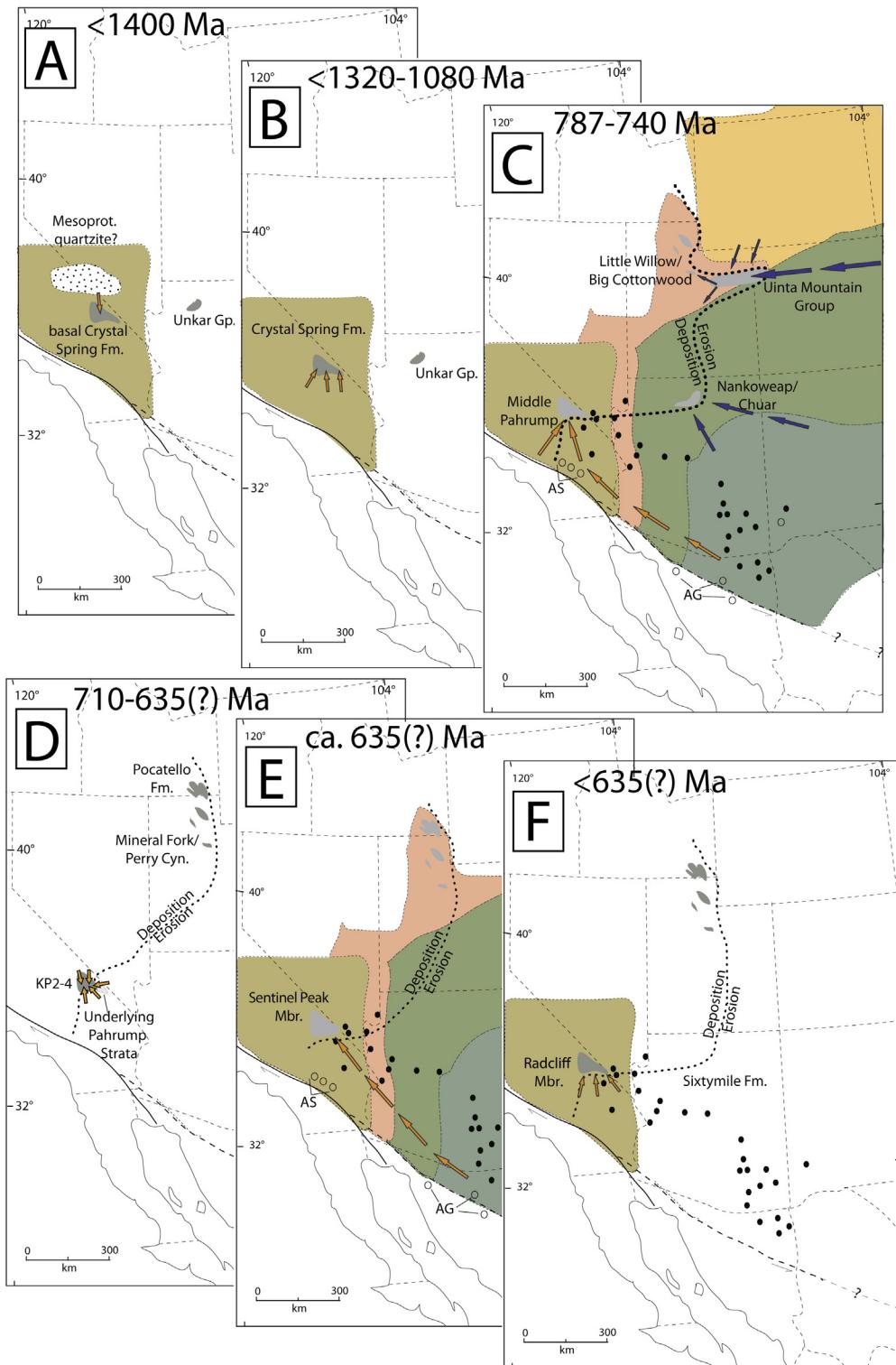


Fig. 7. Inferred paleodrainage (arrows) for six paleogeographic time-slices in the Pahrump Group through Noonday Dolomite: (A) Stenian-Ectasian (?) basal Crystal Spring Formation. Sediment is derived from an unknown Mesoproterozoic quartzite source with a unimodal 1690 Ma detrital zircon population evidenced by abundance of quartzite clasts in the basal Crystal Spring Formation. South-directed paleoflow directions supported by paleocurrent data from Roberts (1974a, 1974b, 1982). (B) Stenian lower and middle Crystal Spring Formation. Strongly unimodal detrital zircon population at 1760 Ma in each sample suggest local sediment source from the Mojave Province. North directed paleoflow directions supported by paleocurrent data from Roberts (1974a, 1974b, 1982). (C) Cryogenian Horse Thief Springs Formation, Beck Spring Dolomite and lower Kingston Peak Formation during incipient rift development. Note regional southwesterly drainage network (orange arrows) inferred from detrital zircon data and paleocurrent analyses (from Maud, 1979, 1983). Blue arrows indicate paleocurrent and drainage patterns for the Chuar Group from Timmons et al. (2001, 2005) and the Uinta Mountain Group from Dehler et al. (2010). (D) The Cryogenian middle and upper Kingston Peak Formation. Note localized reworking of uplifted earlier Pahrump Group strata. (E) The Ediacaran (?) Sentinel Peak Member of the Noonday Dolomite. Note the regional drainage network. (F) The Ediacaran (?) Radcliff Member of the Noonday Dolomite. Note local drainage network evidenced by exclusively Mojave Province derived detrital zircon spectra. For ages and descriptions of basement provinces and igneous bodies presented on maps, see Fig. 6. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

some drainage reorganization between basal Crystal Spring Formation depositional time and the remainder of the overlying Crystal Spring Formation as evidenced by paleocurrent and facies analysis (Roberts, 1974a, 1974b, 1982). The majority of the Crystal Spring Formation correlates with Unkar Group-age basin formation of the southwestern U.S. (1250–1100 Ma; Timmons et al., 2005). This is consistent with the similarity of the stratigraphy and mafic intrusive-determined minimum depositional ages between the Crystal Spring Formation and the Unkar Group (Heaman and Grotzinger, 1992; Timmons et al., 2005). The Crystal Spring Formation is inferred to represent deposition during a period of active tectonism, and this is evident in the local sourcing of detritus, the presence of mafic sills with geochemistry indicative of an extensional setting (Hammond, 1986), as well as depositional age coincident with the amalgamation of the Rodinia supercontinent (e.g. Li et al., 2008).

6.1.3. Horse Thief Springs Formation through KP1 (<787–740 Ma)

Little is known directly about tectonic activity in the region during the time period between ca. 1080 Ma and 787 Ma. No depositional record is preserved in the Death Valley region, and this time period is represented by a major unconformity. On the largest scale, this time period is coincident with the stability of the supercontinent Rodinia (e.g. Li et al., 2008). Following this protracted period of non-deposition/erosion, the basal Horse Thief Springs Formation marks the return to deposition in a tectonically active basin after about 787 Ma. A shift from locally-derived detrital zircon populations to regionally derived populations occurs across this unconformity (see Fig. 7C).

Detrital zircon spectra are relatively consistent from the Horse Thief Springs Formation through the lower Kingston Peak Formation (KP1) and show zircon grains of mixed Laurentian age populations. We hypothesize regional sources from the south-southwest and the southeast as shown in Fig. 7B. There are local variations of paleoflow, facies associations (Maud, 1979, 1983) and detrital zircon spectra throughout these stratigraphic units indicating that transport of detritus into the region occurred via dynamic drainage networks (e.g. Fig. 4 – sample K03DV10 vs. sample 12RMSS6).

The Horse Thief Springs Formation, Beck Spring Dolomite and lower Kingston Peak Formation represent deposition within an intracratonic extensional basin from <787 Ma through ~740 Ma (Prave, 1999; Mahon and Link, 2011; Mahon et al., 2014). This marine basin likely reflects regional-scale southwestern Laurentian drainage and ocean current patterns (Fig. 7B).

6.1.4. Kingston Peak Formation KP2-KP4 (~710–635 Ma)

An unconformity is present between the top of KP1 and the base of the KP2 in eastern Death Valley. The unconformity is interpreted to represent incision resulting from glacioeustatic drawdown, and the overlying diamictites of KP2-KP4 record two glacial and volcanic-bearing intervals ("diamictite and volcanic succession" of Link et al., 1993, 1994) deposited concurrent with initial rifting of Laurentia (Troxel, 1967, 1982; Miller, 1985; Prave, 1999). Regional detrital zircon sample distributions remain consistent from the Horse Thief Springs Formation through the Kingston Peak Formation. Complementary petrographic analysis of sandstones and clast-count analysis of diamictites in KP2-KP4 (Miller, 1985; Mahon, 2012; see Tables DR3 and DR4, Supplementary material) show primarily sedimentary lithic composition, with clasts attributable to underlying Pahrump Group units (see Fig. 7D). This suggests that sediments in the middle and upper Kingston Peak Formation were derived from local recycling of previously deposited sedimentary rock units, rather than from primary basement sources.

The detrital zircon data do not change across the KP1-KP2 unconformity. However clast and point count data are consistent with the model of Prave (1999) that suggests major drainage reorganization during rifting and glaciation, with sediment sourcing accomplished by erosion of uplifted local horsts exposing previously deposited sedimentary rock units (Fig. 7D). The details of unconformities within the KP2-KP4 units cannot be discerned from our data set—it is possible that an unroofing sequence could be noted in detrital zircon age populations if a systematic stratigraphic/detrital zircon study was performed on these KP units. This is seen in the Neoproterozoic diamictite successions of northern Utah and southern Idaho (Balgord, 2011; Balgord et al., 2013).

6.1.5. Sentinel Peak Member of the Noonday Dolomite

Overlying the Kingston Peak Formation, the Sentinel Peak Member of the Noonday Dolomite records postglacial marine transgression, and deposition of "cap dolostone" (Prave, 1999; Peterson et al., 2011b). Detrital zircon age spectra from this member are similar to underlying units, however, it contains a significant late Mesoproterozoic (~1040–1100 Ma) suite of detrital zircon ages, not present in underlying strata (see Fig. 4, sample 4CD13). We interpret this age range to have been derived medially from similar-aged granitic rocks in Arizona-New Mexico-Sonora region (as discussed in Section 5.6). This unit is seen to represent a major drainage reorganization associated with post-glacial retreat, resulting in a regional, southeasterly-derived sedimentary provenance (see Fig. 7E).

6.1.6. Radcliff Member of the Noonday Dolomite (~635 Ma?)

A major detrital zircon population shift occurs between the Sentinel Peak and Radcliff Members of the Noonday Dolomite, from mixed Paleoproterozoic and Mesoproterozoic strongly bimodal ages at ca. 1420 Ma and 1720 Ma, both of which are represented within the local Mojave Province basement. This shift in provenance is interpreted to represent post-glacial drainage reorganization, following cap-carbonate deposition. Detritus was likely delivered to the basin from local, basement derived sediment sources (see Fig. 7F). This shift in provenance may support the presence of a major unconformity at the base of the Radcliff Member (e.g. Summa, 1993).

6.2. "Amargosa Aulacogen" revisited

Detrital zircon provenance data presented herein, as well as age constraints on an unconformity within the Pahrump Group (from Mahon et al., 2014) and tectonostratigraphic distinctions made in MacDonald et al. (2013) provide evidence for major depositional hiatuses and several episodes of drainage reorganization across the >500 million-year record spanned by the Pahrump Group. Individual paleogeographic "time-slices", as presented above (Fig. 7), show punctuated intervals of basin development related to tectonic and climatic events rather than deposition during development of a single short-lived basin. In light of this new understanding, the aulacogen model for the entire Pahrump Group (as proposed by Wright et al., 1974; Roberts, 1974a, 1974b, 1976, 1982) is no longer considered reasonable. Rather, the Pahrump Group is interpreted to represent a series of intracratonic basins developed along the margin of western Laurentia during discrete yet significant periods of tectonic activity (cf. MacDonald et al., 2013). Palinspastic reconstructions (e.g. Levy and Christie-Blick, 1991; Topping, 1993) also call into question the elongate, east-west oriented basin geometry for the Pahrump Group, a key component of the aulacogen model.

6.3. Regional correlations

The Pahrump Group is correlative to other Mesoproterozoic to Neoproterozoic units in the region. The correlation of the Crystal Spring Formation with the Unkar Group of the Grand Canyon Supergroup is robust: both are mixed siliciclastic-carbonate units, rest on 1700–1400 Ma crystalline basement, and are intruded by ca. 1080 Ma mafic bodies (Heaman and Grotzinger, 1992; Timmons et al., 2005). The Horse Thief Springs Formation, Beck Spring Dolomite, and KP1 unit are correlated with the Chuar Group of Grand Canyon (Dehler et al., 2001; Dehler, 2008; Mahon et al., 2014). The Chuar Group sedimentary rocks were deposited in a syn-extensional intracratonic marine basin that may have extended as far as Death Valley (Timmons et al., 2001; Dehler et al., 2001). The Kingston Peak Formation is generally similar, though different in detail to other Late Neoproterozoic diamictite and volcanic-bearing successions along the western Cordillera (Link et al., 1993, 1994; Prave, 1999). The KP2-KP4 sequence and correlatives represent deposition during rifting of the western Laurentian margin (Prave, 1999; Li et al., 2008). Strata above the Kingston Peak Formation, including the Noonday Dolomite through the Cambrian Wood Canyon Formation, record onset of thermal subsidence and early development of the passive margin (e.g. Stewart, 1970; Levy and Christie-Blick, 1991; Fedo and Cooper, 2001).

6.4. Rodinia's imprint on southwestern Laurentia

The data presented herein provide significant insight into the tectonic history of the southwestern Laurentian region. Basin development across the region accompanied the assembly of Rodinia from <1360 Ma through ca. 1080 Ma (Crystal Spring Formation and the Unkar Group in the Grand Canyon). While the Unkar Group sedimentary basin was sourced by farther-traveled detritus from the Grenville–Llano orogenic belts (Timmons et al., 2005), the majority of the Crystal Spring Formation appears to have only sources from local basement. A period of tectonic stability from ca. 1080 through 787 Ma may have followed the deposition of the Crystal Spring Formation, however, the unconformity at the top of the Crystal Spring Formation shows 0–20 degrees of angular discordance as well as some tens of meters of erosional relief, thus implying some tectonic activity within that time period (Mbuyi and Prave, 1993; Mahon et al., 2014).

Following this period, deposition commenced in extensional basins across the region (Horse Thief Springs Formation through lower Kingston Peak Formation; Nankoweap Formation and Chuar Group in the Grand Canyon; Uinta Mountain Group and Little Willow/Big Cottonwood Formations in Utah) associated with organization of regional to continental drainage networks (e.g. Karlstrom et al., 2000; Timmons et al., 2005; Dehler et al., 2010; Spencer et al., 2012; Kingsbury-Stewart et al., 2013). This ca. 780–740 Ma basin development is likely the result of incipient rifting associated with onset of breakup of the Rodinia Supercontinent. Further extensional basin development occurred during the period 715–660 Ma (Kingston Peak Formation; Pocatello Formation in Idaho; Perry Canyon and Mineral Fork formations in Utah), associated with the main stages of rifting of Rodinia (Prave, 1999; Fanning and Link, 2004; Keeley et al., 2012; Pettersson et al., 2011a; Balgord et al., 2013). Extensional tectonic activity likely continued through the Noonday Dolomite and lower Johnnie Formation, (correlative to the Sixtymile Formation in the Grand Canyon; Brigham Group in Idaho and Utah) as shown by local sourcing of detrital zircon populations, as well as sedimentologic observations (e.g. Fedo and Cooper, 2001; Schoenborn et al., 2012). Finally, completion of continental separation and thermal subsidence followed at ca. 650–580 Ma (e.g. Stewart, 1970; Levy and Christie-Blick, 1991; Fedo and Cooper, 2001; Keeley et al., 2012; Balgord et al., 2013) and

development of the stable passive margin/cratonal cover sequence the latest Neoproterozoic (e.g. Fedo and Cooper, 2001; Schoenborn et al., 2012).

7. Conclusions

Detailed provenance analysis from the Mesoproterozoic and Neoproterozoic Pahrump Group strata in eastern Death Valley can be described using six sequential paleogeographic maps. These show: (A) local sediment sourcing of recycled Mojave Province basement grains from the north, followed by (B) drainage reorganization and paleoflow from the south, (C) a pronounced detrital zircon provenance shift occurs across a major unconformity at the base of the newly named Horse Thief Springs Formation showing a transition to regional southwestern Laurentian (<1000 km) sediment sources, coincident with arrival of farther-traveled detritus and possibly the earliest expression of Rodinia supercontinent break-up along the western Laurentian margin; (D) major drainage reorganization between the Lower Kingston Peak Formation (KP1) and the middle-to-upper Kingston Peak Formation (KP2-KP4; Prave, 1999), although detrital zircon data alone did not detect this major change due to the reworking of underlying older Pahrump Group strata during KP2-KP4 time; (E) a shift to regional provenance immediately following deglaciation in the Sentinel Peak Member of the Noonday Dolomite; and (F) an initial shift in paleodrainage to locally-derived basement sources coincident with post-glacial marine transgression in the Radcliff Member and overlying units, followed by a return to eastern-derived regional and continental provenance upper Johnnie through the Wood Canyon Formation.

Strata of the Pahrump Group and Noonday Dolomite in the Death Valley region are punctuated by major unconformity representing up to 300 m.y. of hiatus and several smaller regional unconformities, rather than being deposited during continuous basin development. These new analyses clarify the provenance trends for a large period of southwestern Laurentian history. When taken in conjunction with the provenance and paleogeographic trends presented for the remainder of Neoproterozoic–Phanerozoic time, a more complete understanding of the evolution of the western margin of Laurentia is now possible.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.precamres.2014.06.005>.

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