

# Late Triassic Texas uplift preceding Jurassic opening of the Gulf of Mexico: Evidence from U-Pb ages of detrital zircons

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## ABSTRACT

We use U-Pb ages for 2655 individual detrital zircon grains in 30 samples of Upper Triassic (Carnian–Norian) sandstones of the southwestern USA (our data) and northern Mexico (other data) to infer regional Late Triassic provenance relations and tectonic features, which included a prerift uplift in Texas precursory to Jurassic opening of the Gulf of Mexico. Detrital zircons in sandstones from central paleorivers of the Chinle-Dockum fluvial system on the High Plains (USA) and Colorado Plateau, and from the marine terminus of the fluvial system along the eastern flank of the Auld Lang Syne backarc basin in the Great Basin, reflect regional dispersal of sediment from the Ouachita orogen and adjacent Mesoproterozoic basement exposed on the northern flank of the rift uplift. The composite grain population of Ouachita-derived sands displays dominant U-Pb age peaks at 1100–1050 Ma (Grenvillian) and subordinate Neoproterozoic (630–550 Ma) and Paleozoic (475–400 Ma) age peaks inferred to document recycling of sand grains from the Ouachita system. The Ouachita detritus was supplemented by contributions from Mesoproterozoic basement rocks of southwest Laurentia (compound 1805–1655 Ma and unitary 1440 Ma age peaks) and from Permian–Triassic arc assemblages of northeastern Mexico (composite 285–215 Ma age peak). Master Chinle-Dockum paleodrainages extended east-southeast–west-northwest for 2000 km from Texas to Nevada, flowing along the axis of a backarc trough formed by

dynamic subsidence behind the Cordilleran magmatic arc, from headwaters in the Texas prerift uplift to the sediment trap of the backarc marine basin where the Auld Lang Syne Group accumulated.

Sandstones from peripheries of the linked fluvial and marine depositional systems contain contrasting populations of detrital zircons derived either from the relict Amarillo-Wichita uplift, which fed abundant Cambrian zircons derived from an uplifted aulacogen-floor igneous assemblage, to selected basal units of the fluvial system, or from the Cordilleran arc assemblage to the south and west. The youngest Dockum sample from the Ouachita foreland on the High Plains contains abundant Devonian zircons probably derived from the Ouachita metamorphic core zone now present only in the Texas subsurface. Sandstones along the southern flank of the Chinle backarc basin on the southern Colorado Plateau contain populations of detrital zircons similar to those in sandstones of the Antimonio-Barranca forearc basin (Sonora) that was farther south beyond the arc axis. Sediment transported longitudinally from the Texas uplift to the El Alamar paleoriver and Potosí subsea fan of northeastern Mexico contains populations of detrital zircons similar but not identical to those in Chinle-Dockum fluvial strata of the High Plains shed transversely from the rift uplift.

## INTRODUCTION

U-Pb ages of detrital zircons from Mesozoic strata of the Colorado Plateau and adjoining areas have provided fresh insights into the paleogeographic and paleotectonic evolution

of North America by indicating the nature and probable locations of changing sediment provenances over Mesozoic time (Dickinson and Gehrels, 2010). In this paper we discuss evidence from U-Pb ages of detrital zircons for Late Triassic transport of voluminous sediment across southwest Laurentia from an uplift in central Texas interpreted as a thermal precursor to Middle Jurassic opening of the Gulf of Mexico (Stern et al., 2008). Our focus is on patterns of Carnian and Norian sedimentation, with minimal attention to Rhaetian (latest Triassic) deposits that typically formed in close association with overlying eolian Lower Jurassic successions. The sedimentary record of detritus from the Triassic uplift in Texas elucidates an important facet of the evolution of the southern margin of Laurentia.

Detrital zircons in Chinle-Dockum fluvial sandstones of the High Plains and Colorado Plateau were discussed in detail in Dickinson and Gehrels (2008). U-Pb analytical data, concordia diagrams, age-bin histograms, and multiple age-probability plots for 19 Chinle-Dockum sandstones and two sandstones from the correlative marine Auld Lang Syne Group, exposed farther west in the Great Basin of Nevada, are included as Supplemental File 1<sup>1</sup> for this paper. The Auld Lang Syne data supplant preliminary data in Gehrels and Dickinson (1995) and Manuszak et al. (2000) for the same two samples. We also compare, with our Chinle-Dockum and Auld

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Lang Syne data, detrital zircon populations from the western flank of the Auld Lang Syne basin adjacent to the Cordilleran magmatic arc in California (Manuszak et al., 2000), the Antimonio-Barranca forearc basin of northwestern Mexico (González-León et al., 2009), and the El Alamar paleoriver–Potosí subsea fan system of north-eastern Mexico (Barboza-Gudiño et al., 2010).

## DATA ACQUISITION AND MANIPULATION

Procedures for sample collection and preparation, and for U-Pb analyses of individual detrital zircon grains by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) methodology (Gehrels et al., 2008), were described in detail in Dickinson and Gehrels (2008). In brief, zircon grains separated from 22–24 kg samples were incorporated into epoxy mounts (typically 1000–2000 zircon grains each), and sanded down to a depth of 20  $\mu\text{m}$  to expose grain interiors. U-Pb ages were then determined for ~100 randomly selected grains in each sample mount, but only concordant and nearly concordant ages (Dickinson and Gehrels, 2008) were retained for further consideration. Discordant U-Pb ages for detrital zircons cannot be interpreted because each zircon grain potentially had a different history, and discordia chords cannot be defined for detrital zircons. An average of 91 grain ages per sample were retained for provenance analysis and included in Supplemental File 1 (see footnote 1).

Of the grain ages retained for provenance analysis, >95% have ovals of age uncertainty (at  $1\sigma$  for  $^{206}\text{Pb}/^{238}\text{U}$  and  $^{206}\text{Pb}/^{207}\text{Pb}$  ages) that overlap concordia. The remaining slightly discordant grains (all older than 1000 Ma) were filtered for <30% discordance and <5% reverse discordance, and retained because they represent ~30% of all grain ages older than 2000 Ma, which include ~5% of all grains. Potentially important provenance information would have been lost had the slightly discordant grain ages been rejected, because no lead loss could make grains appear younger than their slightly discordant ages imply. For this study,  $^{206}\text{Pb}/^{238}\text{U}$  ages are used for grains younger than 1000 Ma and  $^{206}\text{Pb}/^{207}\text{Pb}$  ages for grains older than 1000 Ma, except that the exact cutoff age is adjusted to avoid breaking up clusters of grain ages. Note, however, that U-Pb systematics are inherently least accurate for 1000–1250 Ma (Grenvillian) ages. Because of differing U-Pb decay constants,  $^{206}\text{Pb}/^{238}\text{U}$  ages are more accurate for younger grains and  $^{206}\text{Pb}/^{207}\text{Pb}$  ages are more accurate for older grains, but neither are comparably accurate, and age uncertainties tend to be greatest, for Mesoproterozoic grains (Gehrels et al., 2008).

Age spectra of detrital zircon populations are presented as age-distribution curves in the form of relative age-probability plots derived from the probability density function (Ludwig 2003). For the age-distribution curves presented here,  $N$  denotes the number of samples composited and  $n$  is the number of U-Pb ages from those samples (see figure captions herein). The plots incorporate each age and its analytical uncertainty as a normal distribution. The individual normal distributions are then stacked into a single compound curve. For visual comparison, the age-distribution curves are normalized to equal areas beneath each curve. Visual inspection of the age-distribution curves allows qualitative comparison of detrital zircon populations or subpopulations.

Age-bin histograms for detrital zircon ages are useful for evaluating individual samples (Supplemental File 1; see footnote 1) because they allow age peaks on age-probability curves controlled only by isolated individual detrital zircon grains to be discounted relative to age peaks controlled by multiple grain ages. Age-bin histograms are selective presentations of U-Pb analytical data, however, and are not statistically valid because they are based exclusively on best estimates of grain age without taking age uncertainties into account. No matter how age bins are selected, some grain ages in each bin will have age uncertainties that overlap with at least one adjacent age bin. For the age-probability curves of this paper composited from multiple samples, we do not include age-bin histograms, which would lack statistical validity and might be misleading.

Specific age peaks on an age-probability plot depend in part upon random selection of grains for analysis, and do not in all cases faithfully reflect the actual age distribution of detrital zircons present in a sample. Andersen (2005) showed by synthetic experiment that multiple random selections of grains from a detrital zircon population will yield age-probability plots with different age peaks, none of which exactly match the age peaks for the parent detrital zircon population that is sampled. We accordingly regard detrital zircon analysis on a regional scale as a reconnaissance provenance tool unsuited to detect subtle shifts in sediment sources or transport patterns, and regard only robust contrasts in detrital zircon age spectra as significant for provenance relations. However, we freely compare detrital zircon populations from diverse sedimentological facies (fluvial, eolian, shallow marine, deep marine) because U-Pb zircon ages are unaffected by diagenetic processes, and sedimentary processes do not sort zircon grains by age.

To supplement visual comparisons of plotted age spectra, Kolmogorov-Smirnov (K-S) sta-

tistics (Press et al., 1986) were used to test for congruence or incongruence of comparative age spectra. The K-S test mathematically compares two age spectra, taking analytical uncertainties of each grain age into account, and determines a probability ( $P$ ) assessing the likelihood that differences between two age spectra could be due to random choice of grains during analysis. Where  $P > 0.05$ , there is <95% confidence that two age populations were not selected randomly from the same parent population (with  $P = 1.0$  indicating identical age spectra). We infer that comparative age spectra yielding  $P > 0.05$  from the K-S test reflect statistically indistinguishable zircon sources, but note that the K-S test cannot establish that two detrital zircon populations actually had the same sources.

The K-S test is stringent, however; for example, if a detrital zircon population is composed of just two age subpopulations in proportions of 40:60 and 60:40, then  $P$  is <0.05. This  $P$  value seemingly implies distinctly different provenances, but geological insight might suggest that the two grain populations were derived from the same source rocks in somewhat different proportions. For assessing provenance relations, qualitative visual comparisons of detrital zircon age spectra are useful in addition to quantitative K-S tests because geological affinities of two detrital zircon populations are not necessarily revealed properly by a strictly statistical comparison of grain ages.

## LATE TRIASSIC PALEOGEOGRAPHY

Figure 1 is a reconstruction of the Late Triassic (Carnian–Norian) paleogeography and paleotectonics of southwest Laurentia showing the spatial relations of the well-known Chinle-Dockum fluvial system (Dickinson and Gehrels, 2008) to coeval depocenters farther to the west and south, and to inferred provenances, including the prerift Texas uplift. Only the axis of the uplift is shown because the site of the uplift is now buried beneath younger sediment flanking the Gulf of Mexico, and its full extent is unknown. Note the different symbols for sandstone samples containing detrital zircon populations of contrasting provenance, and for directions of paleoriver flow derived from paleocurrent studies (Dickinson and Gehrels, 2008).

Regional relationships important for analysis of sediment dispersal from the Texas uplift include: (1) the close juxtaposition of the Yucatán-Campeche block against the southern margin of Laurentia in Texas before Jurassic opening of the Gulf of Mexico; (2) the position of the late Paleozoic Ouachita orogenic belt on the northern flank of the Texas uplift; (3) the restriction of Eagle Mills rift basins as potential

sediment traps to areas east of the Llano uplift on the northern flank of the Texas uplift; (4) the position of the Tehuantepec paleotransform, active during opening of the Gulf of Mexico, extending southward from the western end of the Texas uplift and bounding the associated Yucatán-Campeche block on the west; (5) the location of the Permian–Triassic East Mexico magmatic arc built on Gondwanan crust after Pennsylvanian–Permian attachment of Gondwana to Laurentia along the Ouachita suture belt; (6) the distribution of isolated Permian arc plutons (marked schematically by asterisks) along the southwest margin of Laurentia to the northwest of the East Mexico arc assemblage; (7) the position of the Potosí subsea fan that prograded to the southwest over oceanic crust west of the Permian–Triassic East Mexico arc; (8) the trend of the diachronously initiated Cordilleran magmatic arc from California across the Jurassic site of the deformed Potosí subsea fan; (9) the courses of Chinle–Dockum paleorivers (Shinarump trunk paleoriver, Cottonwood paleovalley) with headwaters in the Ouachita foreland flanking the Texas uplift; (10) the terminus of the Chinle–Dockum fluvial system in the Auld Lang Syne backarc marine basin of the western Great Basin; (11) the course of the Eagle paleoriver (Gartra Formation) with dominant sources in Cambrian igneous rocks of the Amarillo–Wichita uplift of the Ancestral Rocky Mountains; (12) the location of the El Alamar paleoriver (Barboza-Gudiño, 2009; Barboza-Gudiño et al., 2010) delivering sediment to the Potosí subsea fan from the Texas uplift (headwater reaches unknown); and (13) the forearc position of sediment accumulations forming the Antimonio and Barranca Groups of northwestern Mexico.

### Regional Stratigraphy

Upper Triassic (Carnian–Norian) strata of southwest Laurentia (Fig. 1) were deposited by multiple depositional systems having differing relationships to regional paleotectonics.

1. The Eagle Mills Formation is known only in subcrop from multiple rift troughs located in northeast Texas and eastward where it reaches subsurface thicknesses of 2000 m or more, penetrated by drillholes (Salvador, 1991). Sediment delivery into Eagle Mills redbed troughs was probably from bounding highlands, including exposures of the Ouachita orogenic belt on the north, uplifts to the south (Sabine, Monroe) now buried in the subsurface, and perhaps a buried segment of the Ouachita system on the west; however, no detrital zircon data are available to constrain sediment sources. Eagle Mills rift basins developed within the continental fringe

along a largely amagmatic rifted margin that was to the east of the volcanic rifted margin of central Texas (Mickus et al., 2009).

2. The Gartra Formation, with a maximum thickness of <25 m (McCormick and Picard, 1969; Dubiel, 1992), is exposed along the southern flank of the Uinta Mountains in northern Utah, and eastward into Colorado. Gartra sandstones were deposited along the lower reaches of the Eagle paleoriver (no relation to Eagle Mills rift troughs) with headwaters in the Amarillo–Wichita uplift of the Ancestral Rocky Mountains where the floor of the southern Oklahoma aulacogen was everted in Pennsylvanian time (Dickinson and Gehrels, 2010). Gartra strata are commonly regarded as an outlier segment of the Chinle depositional system (Stewart et al., 1972; Dubiel, 1992), and correlate with basal Chinle–Dockum strata, but Gartra outcrops are separated from other Chinle exposures by a belt where younger units overstep both Chinle and Gartra strata across residual uplands of the Pennsylvanian Ute uplift (Dickinson and Gehrels, 2008).

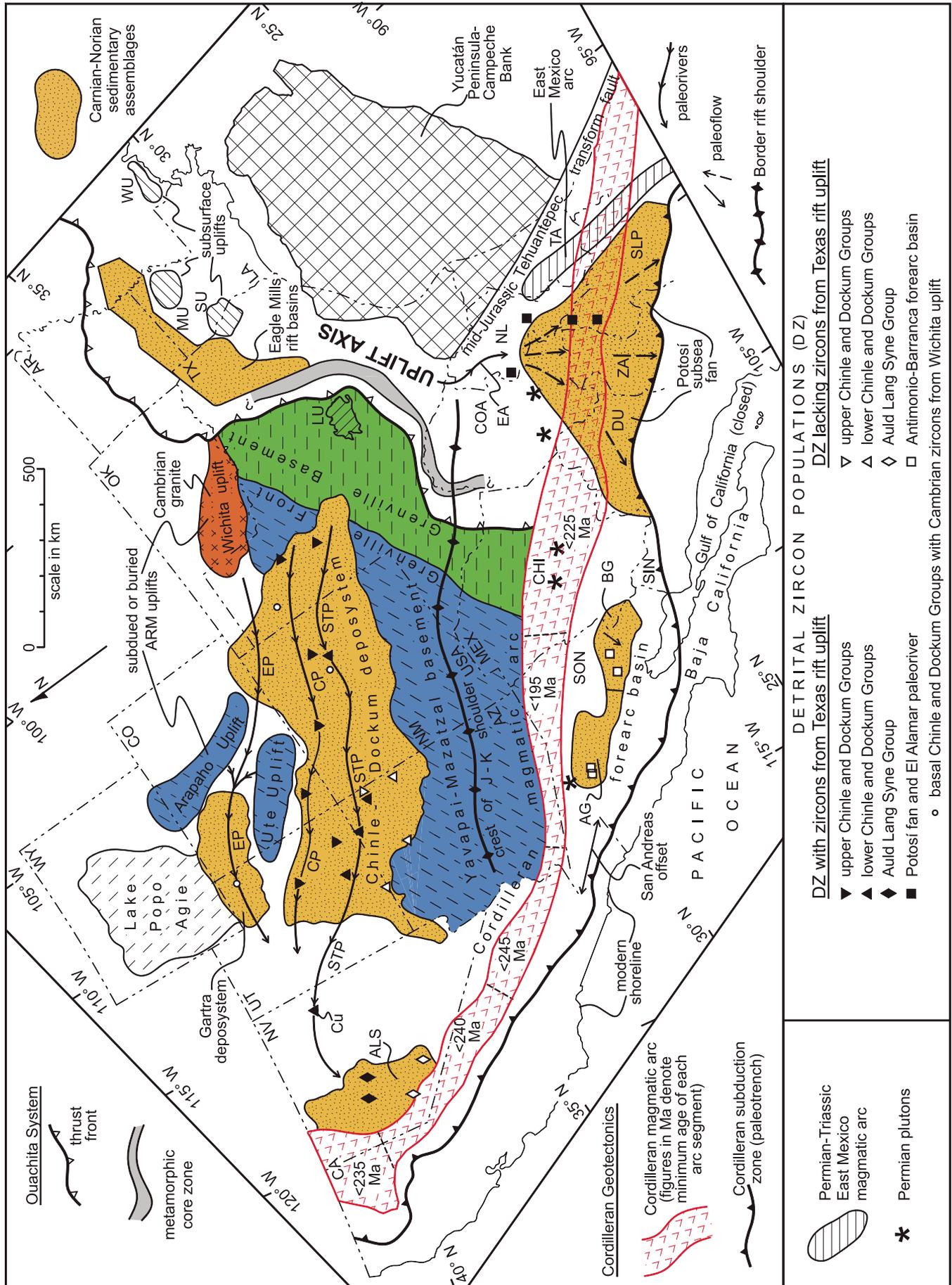
3. Outcrop and subcrop of the Chinle–Dockum fluvial system extend continuously from the Colorado Plateau of Utah on the northwest (Stewart et al., 1972) across northern New Mexico (Lucas, 1995, 2004) to the Llano Estacado of northwest Texas (Lucas et al., 2001). Dominant paleocurrent trends from southeast to northwest indicate dispersal of sediment from the Ouachita foreland of west Texas toward the Cordilleran margin of North America. Stratal thicknesses vary, but commonly exceed 100 m and reach 300 m or more at a depocenter in northeastern Arizona (Dickinson and Gehrels, 2008). The locus of Chinle–Dockum sedimentation was the structural axis of a backarc trough controlled by dynamic subsidence of the continental surface in response to subduction of a dense slab of oceanic lithosphere beneath the Cordilleran magmatic arc and backarc (Dickinson and Gehrels, 2008, 2010). Local stratal terminology is confused by alternate usage of the term group or formation for Chinle strata (thereby divided into either formations or members from place to place), and by designation of correlative strata in Texas as Dockum Group (constituent formations are thereby assigned alternately to either Chinle or Dockum Group on opposite sides of the Texas–New Mexico border). An outlier of fluvial Chinle strata is locally preserved near Currie in northeastern Nevada (Fig. 1) west of the Colorado Plateau (Stewart, 1980; Lucas and Orchard, 2007).

4. The marine terminus of the Chinle–Dockum fluvial system was the Auld Lang Syne basin, named here for the Auld Lang Syne Group (Burke and Silberling, 1973) of largely

shelfal and deltaic strata, but also including more distal turbidite facies (Heck and Speed, 1987). The Auld Lang Syne Group was deposited in the Mesozoic marine province of the western Great Basin (Speed, 1978; Oldow et al., 1993; Wyld, 2000). Chronostratigraphic correlation of marine strata in the Auld Lang Syne basin with terrestrial strata in the Chinle–Dockum fluvial system is well established (Lupe and Silberling, 1985; Lucas and Marzolf, 1993), and the Currie outlier of Chinle strata links Chinle fluvial outcrops on the Colorado Plateau with the marine Auld Lang Syne Group farther west. The Auld Lang Syne basin was apparently formed by extension behind the Cordilleran magmatic arc (Wyld, 2000; Dickinson, 2006), and volcanoclastic strata derived from the arc along the western flank of the basin interfinger eastward with basin fill (Stewart, 1997; Dickinson and Gehrels, 2000). The thickness of Upper Triassic strata within the basin depocenter exceeds 5000 m, but their full original geometry is difficult to reconstruct because basinal facies were thrust eastward over shelfal facies along multiple strands of the Middle Jurassic Luning–Fencemaker thrust system (Wyld, 2002).

5. In northwestern Sonora, successions of Triassic terrestrial and marine strata of the Barranca Group (Stewart and Roldán-Quintana, 1991) and the Antimonio Group (González-León et al., 2005), which also includes Jurassic strata, are each 3500 m thick (González-León et al., 2009), and accumulated in the Cordilleran forearc 400–600 km southwest of the closest remnants of Chinle–Dockum strata (Fig. 1). The Barranca Group is interpreted as fluviodeltaic strata marginal to marine deposits of the Antimonio Group (González-León et al., 2009), and the areal distributions of the two stratal assemblages jointly define the trend of an elongate forearc basin (Fig. 1), although only disconnected erosional remnants of the basin are preserved. Varied sandstone petrofacies in both groups (Stewart and Roldán-Quintana, 1991; Cojan and Potter, 1991; Stanley and González-León, 1995) suggest derivation of sediment from varied source rocks exposed in nearby uplifts (González-León et al., 2009).

6. In central Mexico, the Potosí subsea fan fed by the El Alamar paleoriver (Barboza-Gudiño, 2009; Barboza-Gudiño et al., 2010) was deposited on oceanic crust of the Mezcalera plate (Dickinson and Lawton, 2001a), west of the East Mexico arc. The fan sediments are now incorporated into the Meseta Central subduction complex (Centeno-García et al., 2008), which has been overprinted by the Nazas segment of the Cordilleran arc (Barboza-Gudiño et al., 1998, 2008). Strata of the Potosí fan have been assigned variously to the Carretas,



La Ballena, Taray, and Zacatecas Formations (Centeno-García and Silva-Romo, 1997; Silva-Romo et al., 2000); the latter name is preferred as the best umbrella term for the succession as a whole (Barboza-Gudiño et al., 1999). The original dimensions of the subsea fan and areal variations in sediment thickness are uncertain because of disconnected outcrops beneath widespread younger volcanic and sedimentary cover, and strong postdepositional deformation. Local successions at least 1000 m thick have been reported, however, and its maximum thickness is thought to have reached 2500 m (Bartolini et al., 2001).

### Chronostratigraphic Relations

Regional chronostratigraphy is uncertain for the following reasons.

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**Figure 1. Late Triassic paleogeography of southwest Laurentia (before opening of the Gulf of Mexico by Jurassic seafloor spreading) adapted after Dickinson and Gehrels (2008, 2010); principal sediment accumulations are stippled in orange. Asterisks denote isolated Permian plutons northwest of the Permian–Triassic East Mexico magmatic arc (after Torres et al., 1999; Iriondo and Arvizu, 2009; Arvizu et al., 2009). Other regional geologic relations are after Barth and Wooden (2006), Barboza-Gudiño et al. (2010), Centeno-García (2005), Centeno-García and Silva-Romo (1997), Dickinson (2006), Dickinson and Lawton (2001a), González-Léon et al. (2005, 2009), Jones et al. (1995), Nesse (2007), Picard (1993), Riggs et al. (1996), Salvador (1991), Schweickert and Lahren (1993), Silva-Romo et al. (2000), and Thomas (1989). Abbreviations: J–K—Jurassic–Cretaceous; AG—Antimonio Group; ALS—Auld Lang Syne Group; ARM—Ancestral Rocky Mountains; BG—Barranca Group; CP—Cottonwood paleovalley; Cu—Currie outlier of Chinle strata; EA—El Alamar paleoriver; EP—Eagle paleoriver; LU—Llano uplift; MU—Monroe uplift; STP—Shinarump trunk paleoriver; SU—Sabine uplift; WU—Wiggins uplift. States: AR—Arkansas; AZ—Arizona; CA—California; CHI—Chihuahua; CO—Colorado; COA—Coahuila; DU—Durango; LA—Louisiana; NL—Nuevo Leon; NM—New Mexico; NV—Nevada; OK—Oklahoma; SIN—Sinaloa; SLP—San Luis Potosí; SON—Sonora; TA—Tamaulipas; TX—Texas; UT—Utah; WY—Wyoming; ZA—Zacatecas.**

1. The Triassic time scale (Ogg, 2004) of the geologic time scale of Gradstein et al. (2004) is known to be faulty (Dickinson and Gehrels, 2009b), and the Geological Society of America 2009 time scale (Walker and Geissman, 2009a, 2009b) is accordingly adopted here. Rapid adjustments to the Triassic time scale over the past decade imply that further revision in the near future cannot be precluded.

2. The traditional correlations (e.g., Lucas, 2004) of terrestrial Chinle–Dockum strata with global marine stages have recently been questioned on the basis of magnetostratigraphic data and isotopic dating of key horizons (Zeigler et al., 2008). Alternate chronostratigraphic correlations (Dickinson and Gehrels, 2009b) can thus be entertained for the Chinle–Dockum depositional system, from which most of our detrital zircon U–Pb ages derive.

3. The available biochronology for some voluminous sediment accumulations (e.g., Eagle Mills Formation, Barranca Group, Potosí fan succession) is sketchy, and full spans of deposition are not well constrained.

4. The sedimentation of some Upper Triassic successions (e.g., Antimonio Group, Auld Lang Syne Group) continued unbroken by unconformity or notable hiatus into Early Jurassic time. The boundary between Triassic and Jurassic components of these assemblages is not everywhere well controlled by fossil collections.

With those caveats in mind, Figure 2 is an appraisal of regional chronostratigraphy as understood at present, and shows the approximate stratigraphic positions of detrital zircon samples considered in this paper. Note that traditional interpretations posit a late Carnian age for lower Chinle–Dockum strata, but that provisional revised interpretations regard Chinle–Dockum strata as entirely Norian in age. The latter interpretation is compatible with the entirely Norian and younger age of the Auld Lang Syne Group (Lupe and Silberling, 1985). In this paper we focus our arguments on the Carnian–Norian interval as a whole, and our conclusions are not dependent upon more detailed chronostratigraphic correlations. The unsampled Eagle Mills succession of the subsurface is not shown in Figure 2, but is known to span the Carnian–Norian interval (Byerly, 1991; Salvador, 1991).

### OUACHITA RECYCLING

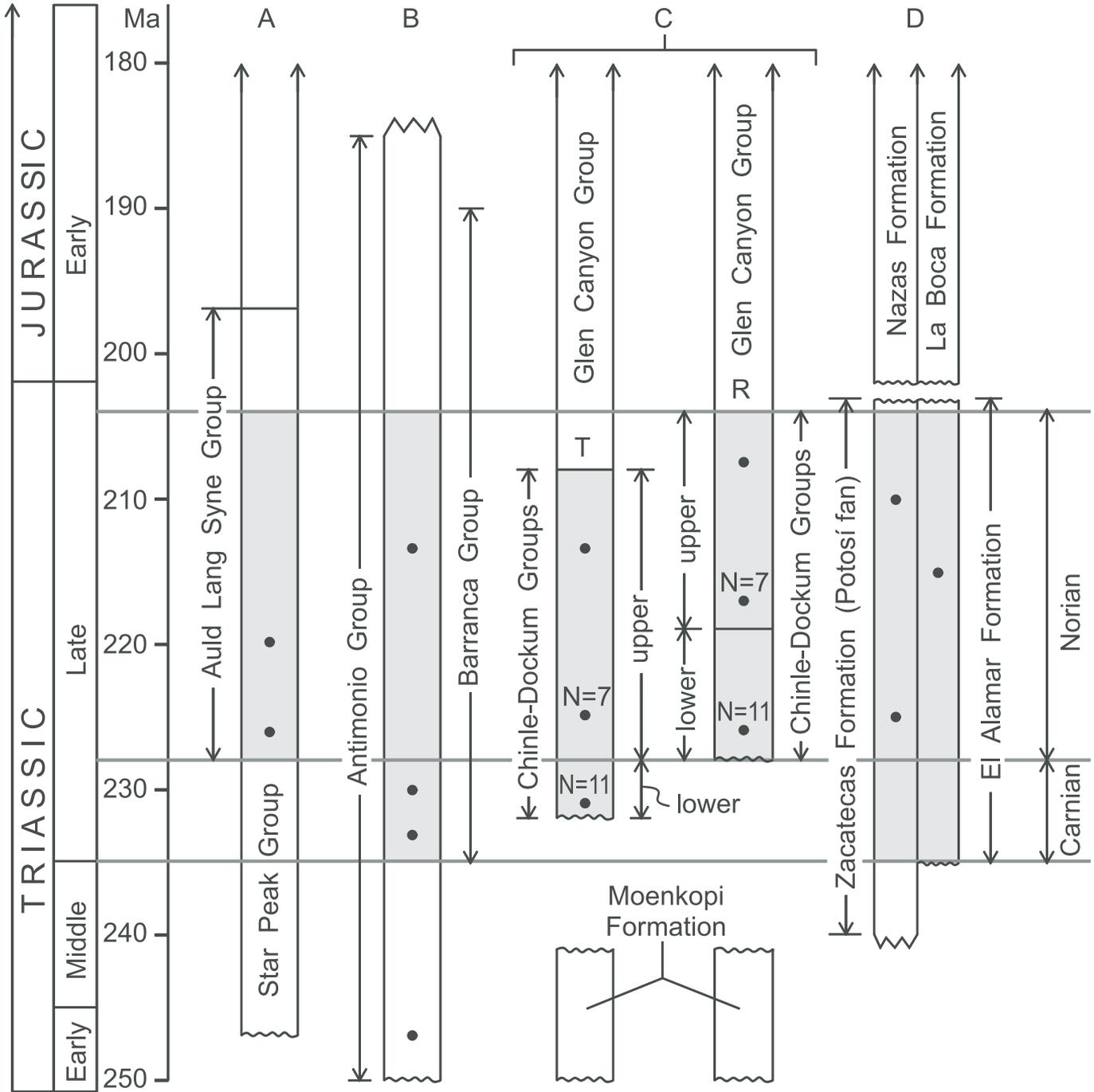
With one exception, our fluvial Chinle–Dockum samples were collected either from basal sandstone units deposited along the Shinarump trunk paleoriver and its tributaries, similar basal sandstone (Gartra Formation) from the course of the Eagle paleoriver, or medial sandstone units deposited along the thalweg of the younger Cot-

tonwood paleovalley and its headwater tributaries (Fig. 1). Other Chinle–Dockum intervals are composed dominantly of finer grained strata that are not as attractive for separation of detrital zircons of the sand size most suitable for U–Pb dating of individual zircon grains. The exception is a sample from the finer grained Cooper Canyon Formation, exposed near the top of the Dockum Group in Texas (Dickinson and Gehrels, 2008). Our sampling strategy produced a database that divides into discrete lower and upper Chinle–Dockum data sets collected from the Shinarump trunk paleoriver and the Cottonwood paleovalley of the Colorado Plateau, and a third data set from headwater reaches of those two paleorivers on the High Plains where thalwegs are less well defined.

The Chinle–Dockum data sets are supplemented by two samples from the Auld Lang Syne Group at the marine terminus of the Chinle–Dockum fluvial system. Both Auld Lang Syne samples were collected from lower Norian strata; one from the shallow-marine Osobb Formation (Burke and Silberling, 1973), and one from the deep-marine Hollywood Formation (Oldow et al., 1990) in the basinal Lovelock sequence (Manuszak et al., 2000). From K–S analysis of the detrital zircon age spectra for the two Auld Lang Syne samples,  $P = 0.205$ , indicating that they are not statistically distinguishable with confidence.

### Detrital Zircon Populations

Upper and lower Chinle–Dockum Groups and the Auld Lang Syne Group all contain pre-Pennsylvanian (older than 318 Ma) detrital zircon populations that resemble those in deltaic and turbidite sandstones of the Pennsylvanian Haymond Formation (Gleason et al., 2007) where exposed in the Marathon segment of the Ouachita system in west Texas (Fig. 3). In the absence of other detrital zircon data from the Ouachita orogen, we assume that the detrital zircon population in the Haymond Formation is representative of Carboniferous flysch and related strata that form the major part of the overthrust Ouachita system. Because of similar age spectra for Chinle–Dockum, Auld Lang Syne, and Haymond populations of detrital zircons, we infer that detrital zircon populations along the central paleodrainages of the Chinle–Dockum fluvial system, and in marine counterparts within the Auld Lang Syne basin, were largely reworked from deformed strata of the Ouachita orogenic belt. Other studies have shown that detrital zircon populations can be reworked without any modification of detrital zircon age-distribution curves (Dickinson et al., 2009b; Kolodner et al., 2009).



**Figure 2.** Stratigraphic context of key Carnian–Norian (Upper Triassic) clastic sedimentary assemblages (shaded intervals of columns) from west to east (see Fig. 1) in southwestern North America (chronostratigraphic time scale after Walker and Geissman, 2009a): A—Auld Lang Syne marine basin of western Nevada; B—Antimonio-Barranca forearc basin of northern Sonora; C—Chinle-Dockum depositional system (fluvial) on the Colorado Plateau and High Plains; D—Potosí subsea fan and El Alamar paleoriver of northeastern Mexico. Dots in columns indicate approximate positions of detrital zircon samples treated in this paper (N indicates number of samples where multiple samples are denoted by single dots). For the Auld Lang Syne assemblage (A), the underlying Star Peak Group is largely carbonate strata. For the Chinle-Dockum assemblage (C), T denotes the traditional correlation (Lucas, 2004), R denotes an alternate revised correlation (Zeigler et al., 2008), and the Glen Canyon Group includes the Church Rock–Rock Point interval after Dickinson and Gehrels (2009a, 2009b, 2010). Sources of data: A—Burke and Silberling (1973), Nichols and Silberling (1977), Lupe and Silberling (1985). B—Stewart and Roldán-Quintana (1991), Gehrels and Stewart (1998), González-Léon et al. (2005, 2009). C—Dickinson and Gehrels (2008, 2010). D—Barboza-Gudiño et al. (1999, 2010), Bartolini et al. (2001).

Non-Ouachita sediment sources must also have contributed sand to the combined fluvial and marine depositional system. For example, the detrital zircon populations (Fig. 3) include minor post-Mississippian (younger than 318 Ma) components derived from Mesozoic arc assemblages (225–240 Ma age peaks) rather than from Ouachita sources (see following discussion). Table 1 provides a census of the 1260 detrital zircon grains in central Chinle-Dockum paleodrainages and correlative marine strata of the Auld Lang Syne basin. Note that nearly two-thirds of the detrital zircon population is composed of Archean, Grenvillian, Neoproterozoic, and pre-Permian Paleozoic grains for which ultimate bedrock sources are absent or rare in the southwestern United States.

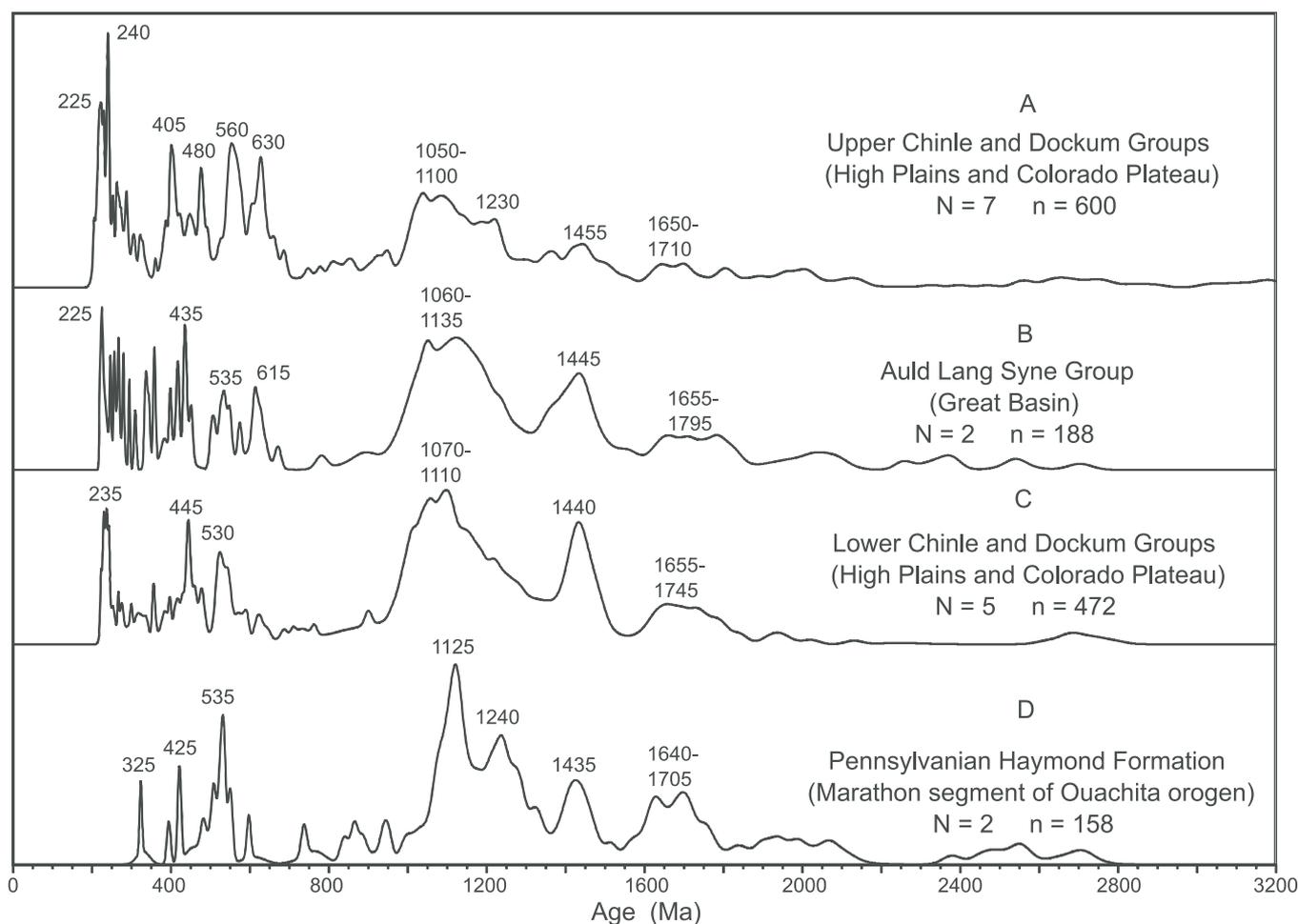
The age-distribution curves (Fig. 3) of pre-Pennsylvanian subpopulations in Auld Lang

Syne, Chinle-Dockum, and Haymond detrital zircon populations display several common features, including a dominance of Grenvillian grains (U-Pb age peaks at 1240–1050 Ma) over older Precambrian grains. The latter are principally in the same two general age brackets (1795–1640 Ma and 1455–1435 Ma age peaks), and subordinate Neoproterozoic–Cambrian (630–530 Ma) and Ordovician–Silurian (480–405 Ma) age peaks are also similar. Figure 1 implies that Grenvillian basement of central and west Texas may have contributed some detritus to sands derived largely from the Ouachita system, but that basement was largely masked by Paleozoic sediment cover that protected it from Mesozoic erosion (Frenzel et al., 1988; Johnson et al., 1988). Locally exposed unconformities between Precambrian rocks and overlying Cretaceous strata in westernmost Texas, on the

Llano uplift (Fig. 1), and in southern Oklahoma suggest, however, that Precambrian basement rocks were locally exposed to Late Triassic erosion within the Ouachita foreland region.

The age-distribution curves of Figure 3 are not identical for pre-Pennsylvanian (older than 318 Ma) grains, and the following factors may account for differences.

1. Detrital zircons of post-Cambrian Paleozoic ages are comparatively sparse in the early Pennsylvanian (Atokan to Desmoinesian) Haymond Formation (Fig. 3D), which contains detritus largely derived from the southern Appalachian belt and the adjacent craton (Gleason et al., 2007). The Haymond Formation was deposited, however, before the culminating Alleghanian event of the Appalachian orogen at a time when many potential Appalachian sources of Paleozoic detritus may not have been



**Figure 3.** Comparative detrital zircon populations (age-probability plots of U-Pb ages) in Pennsylvanian strata of the Marathon segment of the Ouachita system (D after Gleason et al., 2007), and in Upper Triassic sedimentary successions deposited both along central Chinle-Dockum paleodrainages (lower Chinle-Dockum Shinarump trunk paleoriver for C and upper Chinle-Dockum Cottonwood paleovalley for A), including their headwaters in the Ouachita foreland, and in the Auld Lang Syne backarc marine basin (B). N denotes the number of samples and n the number of detrital zircon ages composited for each curve. Numbers denote salient age peaks to the nearest 5 m.y.

TABLE 1. AGE CLUSTERS OF DETRITAL ZIRCONS IN SANDSTONES OF CENTRAL CHINLE-DOCKUM PALEODRAINAGES AND MARINE AULD LANG SYNE GROUP

Grain group	Age range (Ma)	Age peaks (Ma)	Number of grains	Percentage of grains
Arc-derived	203–290	215–240, 265–285	110	8.7
Pre-arc Paleozoic	295–543	360, 400, 445, 475	184	14.6
Neoproterozoic	545–709	550, 630	122	9.7
Null bracket	727–908	—	53	4.2
Grenvillian orogenic	918–1291	1055, 1105	439	34.9
Anorogenic granite	1297–1562	1440	169	13.4
Yavapai-Mazatzal	1579–1861	1655, 1705, 1805	95	7.6
Paleoproterozoic	1892–2398	1965, 2020	46	3.7
Archean	2471–3451	2695, 3175	42	3.3

*Note:* Arc-derived cluster is inferred to derive from East Mexico and Cordilleran magmatic arcs.

fully exposed. By contrast, Chinle-Dockum and Auld Lang Syne sands were derived from the fully developed late Paleozoic (Pennsylvanian–Permian) Ouachita orogen.

2. The prominence of 1445–1440 Ma age peaks for the Auld Lang Syne (Fig. 3B) and

lower Chinle-Dockum (Fig. 3C) detrital zircon populations may reflect dilution of Ouachita detritus with contributions from anorogenic granite plutons intrusive into Yavapai-Mazatzal Precambrian basement (1800–1600 Ma) south of Chinle-Dockum exposures (Fig. 1). Detri-

tus from the anorogenic granite sources may have reached the Shinarump trunk paleoriver of lower Chinle-Dockum age through southern tributaries in much larger proportions than could reach the upper Chinle-Dockum Cottonwood paleovalley farther to the northeast (Fig. 1).

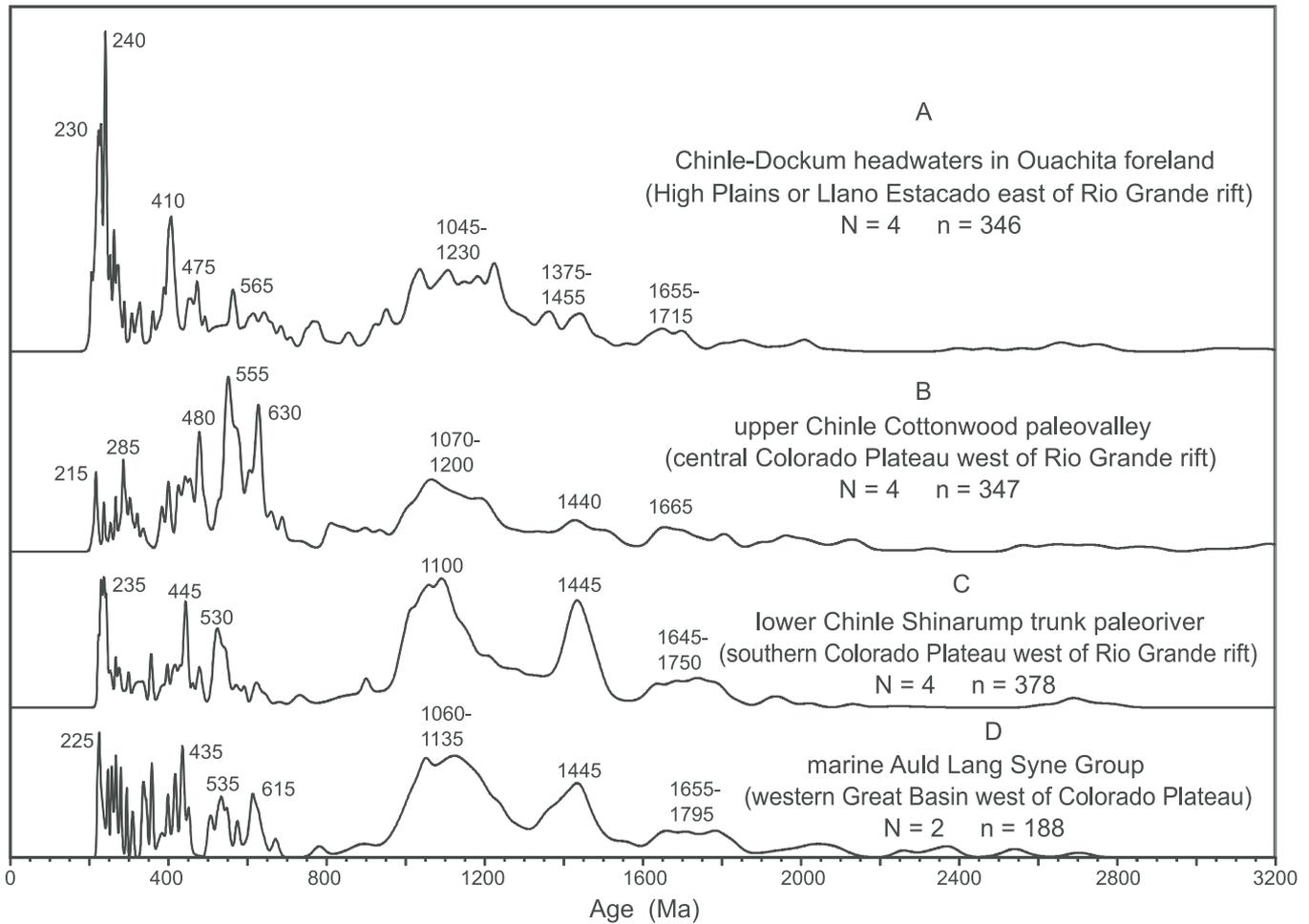


Figure 4. Comparative detrital zircon populations (age-probability plots of U-Pb ages) in Upper Triassic sandstones from headwater reaches (A) of the Chinle-Dockum fluvial system in the Ouachita foreland, paleoriver courses crossing the Colorado Plateau (upper Chinle Cottonwood paleovalley for B and lower Chinle Shinarump trunk paleoriver for C), and the Auld Lang Syne backarc marine basin (D). N denotes the number of samples and n the number of detrital zircon ages composited for each curve. Numbers denote salient age peaks to the nearest 5 m.y.

3. A sharp 630 Ma Neoproterozoic age peak for detrital zircons in the upper Chinle-Dockum assemblage (Fig. 3A) is not seen on the other curves, and may reflect derivation of some detritus from the Yucatán-Campeche block, south of the crest of the Texas uplift (Fig. 1). Florida basement rocks of Gondwanan affinity include components of appropriate Pan-African age (Heatherington and Mueller, 1997), and probably extended westward into the Yucatán-Campeche block (Murphy et al., 2004). Chinle-Dockum headwaters may have eroded headward into Yucatán-Campeche sources as drainage integration brought a progressively wider expanse of the Texas uplift into the Chinle-Dockum paleodrainage system over time.

### Upstream-Downstream Variations

Figure 4 assesses the degree of upstream-downstream variation (top to bottom) in detri-

tal zircon populations from headwaters of the Chinle-Dockum fluvial system through the principal Chinle-Dockum paleorivers to the Auld Lang Syne marine terminus of the fluvial system. The prominence of 1445–1440 Ma age peaks for samples from the lower Chinle Shinarump trunk paleoriver (Fig. 4C) and the Auld Lang Syne Group (Fig. 4D), as compared to samples from the upper Chinle Cottonwood paleovalley (Fig. 4B) and Chinle-Dockum headwaters (Fig. 4A), reinforces the interpretation that Ouachita detritus was diluted downstream by contributions from Precambrian bedrock exposed to the south of Chinle-Dockum exposures. In other respects, the comparative curves show that the detrital zircon signal of Ouachita sources was persistent from headwaters to terminus of the fluvial system. Age peaks are broadly comparable, although with considerable variation in detail for Neoproterozoic and

Paleozoic subpopulations (630–555 Ma and 535–410 Ma age peaks, respectively). Notable is the consistent dominance of Grenvillian grains (1230–1045 Ma age peaks) over older Mesoproterozoic grains (1455–1440 Ma and 1750–1655 Ma age peaks) of ages represented in widespread Precambrian basement of southwest Laurentia (Fig. 1).

Table 2 lists P values from K-S analysis for the comparative detrital zircon populations of individual Chinle-Dockum and Auld Lang Syne samples. As indicated, the samples are spaced at intervals along a regional pathway of sediment dispersal from the upstream thrust front of the Ouachita orogen to the downstream Auld Lang Syne basin over a transport distance of 475–2025 km (mean spacing of sample sites is  $120 \pm 100$  km). Because the content of grains derived from the East Mexico and Cordilleran magmatic arcs is highly variable (0%–24%)

TABLE 2. PROBABILITY (P) VALUES FROM KOLMOGOROV-SMIRNOFF (K-S) ANALYSIS FOR TOTAL DETRITAL ZIRCON (DZ) POPULATIONS OF CENTRAL CHINLE-DOCKUM PALEODRAINAGES AND THE AULD LANG SYNE GROUP

Sample	COO	TRU	CP6	CP5	CP26	CP50	CP48
Total DZ grains	79	83	94	90	72	104	98
Arc-derived DZ grains (%)	24%	18%	0%	24%	3%	5%	7%
Transport distance (km)	475	555	785	790	985	1175	1185
TRU	0	x	-	-	-	-	-
CP6	0	<b>0.07</b>	x	-	-	-	-
CP5	<b>0.15</b>	0.04	0	x	-	-	-
CP26	0	0.04	0	0.04	x	-	-
CP50	0	<b>0.27</b>	0.03	0.01	<b>0.14</b>	x	-
CP48	0	<b>0.54</b>	<b>0.39</b>	0	0.01	<b>0.37</b>	x
CP47	0	0.04	<b>0.27</b>	0	0	0.01	<b>0.20</b>
CP17	0	<b>0.30</b>	0	<b>0.09</b>	<b>0.38</b>	<b>0.10</b>	0
CP42	0	<b>0.23</b>	<b>0.16</b>	0	0	<b>0.20</b>	<b>0.87</b>
CP44	0	<b>0.24</b>	<b>0.13</b>	0	0	<b>0.09</b>	<b>0.24</b>
Currie	0	<b>0.40</b>	0.01	0	0	0.03	0.04
Osobb	0	<b>0.29</b>	<b>0.43</b>	0	0	0	<b>0.09</b>
Lovelock	0	<b>0.76</b>	<b>0.11</b>	0	0.01	<b>0.56</b>	<b>0.49</b>
Sample	CP47	CP17	CP42	CP44	Currie	Osobb	Lovelock
Total DZ grains	98	74	88	97	94	89	99
Arc-derived DZ grains (%)	2%	8%	8%	4%	10%	4%	9%
Transport distance (km)	1280	1305	1400	1430	1785	1975	2025
COO	0	0	0	0	0	0	0
TRU	0.04	<b>0.30</b>	<b>0.23</b>	<b>0.24</b>	<b>0.49</b>	<b>0.20</b>	<b>0.76</b>
CP6	<b>0.27</b>	0	<b>0.16</b>	<b>0.13</b>	0.01	<b>0.43</b>	<b>0.11</b>
CP5	0	<b>0.09</b>	0	0	0	0	0
CP26	0	<b>0.38</b>	0	0	0	0	0.01
CP50	0.01	<b>0.10</b>	<b>0.20</b>	<b>0.09</b>	0.03	0	<b>0.56</b>
CP48	<b>0.20</b>	0	<b>0.87</b>	<b>0.24</b>	0.04	<b>0.09</b>	<b>0.49</b>
CP47	x	0	<b>0.13</b>	<b>0.06</b>	<b>0.33</b>	<b>0.88</b>	<b>0.21</b>
CP17	-	x	0	0.01	0	0	0
CP42	-	-	x	<b>0.12</b>	0	0.04	<b>0.19</b>
CP44	-	-	-	x	<b>0.35</b>	<b>0.14</b>	<b>0.45</b>
Currie	-	-	-	-	x	<b>0.39</b>	<b>0.31</b>
Osobb	-	-	-	-	-	x	<b>0.20</b>
Lovelock	-	-	-	-	-	-	x

Note: Arc-derived DZ grains are younger than 300 Ma. Transport distance is measured from the Ouachita thrust front in Texas. P values in bold are >0.05. Sample localities (full U-Pb analytical data in Supplemental File 1; see text footnote 1): Chinle-Dockum headwaters on the High Plains (COO, TRU, CP5, CP6), lower Chinle Shinarump trunk paleoriver (CP48, CP47, CP42, CUR), and upper Chinle Cottonwood paleovalley (CP26, CP50, CP17, CP44) of the Colorado Plateau, Auld Lang Syne Group in the Great Basin (Osobb, Lovelock). x denotes comparison of samples to themselves (for which K-S analysis would yield meaningless P=1).

from sample to sample, Table 3 compares P values for pre-Pennsylvanian (older than 318 Ma) subpopulations of detrital zircons that were derived largely from the Ouachita orogen and its immediate environs. Tables 2 and 3 include four samples from Chinle-Dockum headwaters on the High Plains (transport distances <800 km), seven samples from Chinle paleoriver courses crossing the Colorado Plateau (transport distances 900–1500 km), and three samples from distal reaches of the depositional system in the Great Basin (transport distances >1750 km). A separate (unpublished) K-S analysis comparing subpopulations of pre-Pennsylvanian grains in Chinle-Dockum and Auld Lang Syne samples (Table 3) with the detrital zircon population in the Pennsylvanian Haymond Formation of the Marathon segment of the Ouachita orogen in Texas (Gleason et al., 2007) yields P values of 0.14–0.72 (statistically indistinguishable at the 95% confidence level) for 30% of the tabulated

samples (Tables 2 and 3): TRU from Chinle-Dockum headwaters on the High Plains, CP47 from the Shinarump trunk paleoriver on the Colorado Plateau, Currie and Osobb from the Great Basin. Tables 2 and 3 show that variations in detrital zircon populations are unsystematic in an upstream-downstream direction, but K-S analysis of the 91 overall sample pairs shows that approximately half (46% for total grain populations, 58% for pre-Pennsylvanian subpopulations) yield P > 0.05 (statistically indistinguishable at the 95% confidence level). The proportion of congruent (P > 0.05) grain populations rises to 53% for total grain populations and 65% for pre-Pennsylvanian subpopulations if aberrant sample COO of Tables 1 and 2 (discussed further in the following), is removed from consideration. The proportion of congruent grain populations (P > 0.05) also rises to two-thirds for the pre-Pennsylvanian subpopulations within generic data sets (Chinle-Dockum

headwaters, Shinarump trunk paleoriver, Cottonwood paleovalley). The seemingly random pattern of varying P values illustrates the difficulty of attributing specific changes in detrital zircon populations within an integrated depositional system to definable shifts in drainage network, entry of tributaries, or other sedimentological factors. The acquisition of U-Pb ages necessarily involves a nested sampling strategy: (1) selection of an individual outcrop within a much larger outcrop belt, (2) selection of the bed or beds to collect on outcrop, and (3) selection of specific grains for laser ablation in the laboratory. Each step of the nested procedure entails statistical challenges that perhaps in combination can never be fully overcome. Moreover, each sample may include detritus aggraded mainly during a single flood event, and different flood events may involve different sets of tributaries tapping different combinations of source rocks. Tables 2 and 3 show, nevertheless, that selected samples from all major segments of the regional dispersal system yield congruent P values (>0.05) when compared with some other samples from either the same segment or other segments of the overall dispersal system including 1550 km of net sediment transport.

**Provenance Evaluation**

Whether pre-Pennsylvanian detrital zircons in central paleodrainages of the Chinle-Dockum fluvial system and its terminus in the Auld Lang Syne marine basin were all recycled from Ouachita sedimentary assemblages, or in part were derived from erosion of Paleozoic-Neoproterozoic sources in the Yucatán-Campeche block and bedrock Mesoproterozoic sources in southern Laurentia, or from a combination of those sources, cannot yet be fully resolved. Given the overall similarity of the comparative age-distribution curves (Figs. 3 and 4), common derivation of most of the detritus from the Marathon segment of the Ouachita orogen is the most parsimonious interpretation. Further work to define detrital zircon age spectra for the Ouachita orogen farther east in the Texas subsurface and farther north in Oklahoma and Arkansas is warranted.

The timing of suturing of Gondwana to Laurentia to form the Ouachita orogen varied from middle Pennsylvanian (310 Ma) in Oklahoma to earliest Permian (290 Ma) in west Texas (Dickinson and Lawton, 2003). Residual orogenic highlands are unlikely to have persisted through the ~80 m.y. between peak Ouachita orogeny and Chinle-Dockum sedimentation (Fig. 2). Accordingly, we infer that relief along the Ouachita trend was rejuvenated by thermal uplift in Texas precursory to Gulf of Mexico

TABLE 3. PROBABILITY (P) VALUES FROM KOLMOGOROV-SMIRNOFF (K-S) ANALYSIS OF PRE-PENNSYLVANIAN (OLDER THAN 318 MA) DETRITAL ZIRCON (DZ) SUBPOPULATIONS OF CENTRAL CHINLE-DOCKUM PALEODRAINAGES AND AULD LANG SYNE GROUP

Sample	COO	TRU	CP6	CP5	CP26	CP50	CP48
DZ grains >318 Ma	60	67	93	67	68	99	91
Transport distance (km)	475	555	785	790	985	1175	1185
TRU	0	x	-	-	-	-	-
CP6	0	<b>0.07</b>	x	-	-	-	-
CP5	<b>0.06</b>	<b>0.08</b>	<b>0.10</b>	x	-	-	-
CP26	<b>0.08</b>	0	0	<b>0.47</b>	x	-	-
CP50	0.02	0.04	<b>0.06</b>	<b>0.99</b>	<b>0.13</b>	x	-
CP48	0.04	<b>0.29</b>	<b>0.72</b>	<b>0.19</b>	0	<b>0.21</b>	x
CP47	0	<b>0.88</b>	<b>0.24</b>	0	0	0.01	<b>0.50</b>
CP17	0.01	0	0	<b>0.60</b>	<b>0.26</b>	<b>0.22</b>	0
CP42	0.01	0.05	<b>0.34</b>	0.03	0	<b>0.08</b>	<b>0.78</b>
CP44	0	<b>0.16</b>	<b>0.26</b>	<b>0.23</b>	0	<b>0.07</b>	<b>0.23</b>
Currie	0	<b>0.77</b>	0	0.03	0	0	0.01
Osobb	0	<b>0.94</b>	<b>0.32</b>	0.01	0	0	<b>0.12</b>
Lovelock	0	<b>0.57</b>	<b>0.31</b>	<b>0.10</b>	0	<b>0.28</b>	<b>0.38</b>
Sample	CP47	CP17	CP42	CP44	Currie	Osobb	Lovelock
DZ grains >318 Ma	96	67	81	92	83	85	89
Transport distance (km)	1280	1305	1400	1430	1785	1975	2025
COO	0	0.01	0.01	0	0	0	0
TRU	<b>0.88</b>	0	0.05	<b>0.18</b>	<b>0.77</b>	<b>0.94</b>	<b>0.57</b>
CP6	<b>0.24</b>	0	<b>0.34</b>	<b>0.26</b>	0	<b>0.32</b>	0.01
CP5	0	<b>0.60</b>	0.03	<b>0.28</b>	0.03	0.01	0
CP26	0	<b>0.26</b>	0	0	0	0	0
CP50	0.01	<b>0.22</b>	<b>0.08</b>	<b>0.07</b>	0	0	0.02
CP48	<b>0.50</b>	0	<b>0.78</b>	<b>0.23</b>	0.01	<b>0.12</b>	0.01
CP47	x	0	<b>0.19</b>	<b>0.13</b>	<b>0.22</b>	<b>0.71</b>	<b>0.14</b>
CP17	-	x	0	0.02	0	0	0.01
CP42	-	-	x	<b>0.11</b>	0	<b>0.06</b>	0
CP44	-	-	-	x	0.05	<b>0.14</b>	0
Currie	-	-	-	-	x	<b>0.16</b>	<b>0.56</b>
Osobb	-	-	-	-	-	x	<b>0.18</b>
Lovelock	-	-	-	-	-	-	x

Note: Transport distance is measured from the Ouachita thrust front in Texas. DZ grains younger than 318 Ma are excluded from the table. P values in bold are >0.05. Sample localities (full U-Pb analytical data in Supplemental File 1; see text footnote 1): Chinle-Dockum headwaters on the High Plains (COO, TRU, CP5, CP6), lower Chinle Shinarump trunk paleoriver (CP48, CP47, CP42, CUR) and upper Chinle Cottonwood paleovalley (CP26, CP50, CP17, CP44) of the Colorado Plateau, Auld Lang Syne Group in the Great Basin (Osobb, Lovelock). x denotes comparison of samples to themselves (for which K-S analysis would yield meaningless P=1).

rifting (Fig. 1). Mesozoic thermal uplift along the Texas Gulf Coast is supported by the presence of a volcanic rifted margin, of presumably Jurassic age, forming transitional crust that now underlies the Gulf Coast sediment prism (Mickus et al., 2009), and by the identification of a hotspot track on the seafloor within the Gulf of Mexico (Bird et al., 2005).

**Comparative Petrofacies**

The somewhat different detrital zircon populations in upper (Fig. 3A) and lower (Fig. 3C) Chinle-Dockum strata are matched by a consistent difference in petrofacies (Fig. 5). Although feldspar contents are broadly comparable for the two assemblages, the lower assemblage is more quartzose and less lithic than the upper assemblage. We interpret the contrast to reflect deeper erosion of the Ouachita system during deposition of the upper assemblage. The progressive unroofing of deeper, more indurated, and partly metamorphosed levels of the Ouachita system may have provided a higher proportion of dura-

ble aphanitic lithic fragments (argillite and slate) to derivative sediment, as opposed to quartz and feldspar grains recycled from sandstones interbedded with destructible shale that would not tend to contribute lithic fragments of sand size. Although the ages of our two Auld Lang Syne samples cannot be distinguished with confidence by biostratigraphy, as both are lower Norian (Lupe and Silberling, 1985; Manuszak et al., 2000), the petrofacies of the stratigraphically higher sample of basinal turbidite (Hollywood Formation of Lovelock sequence) and the stratigraphically lower sample of shelfal sandstone (Osobb Formation) display an analogous contrast in petrofacies (Fig. 5).

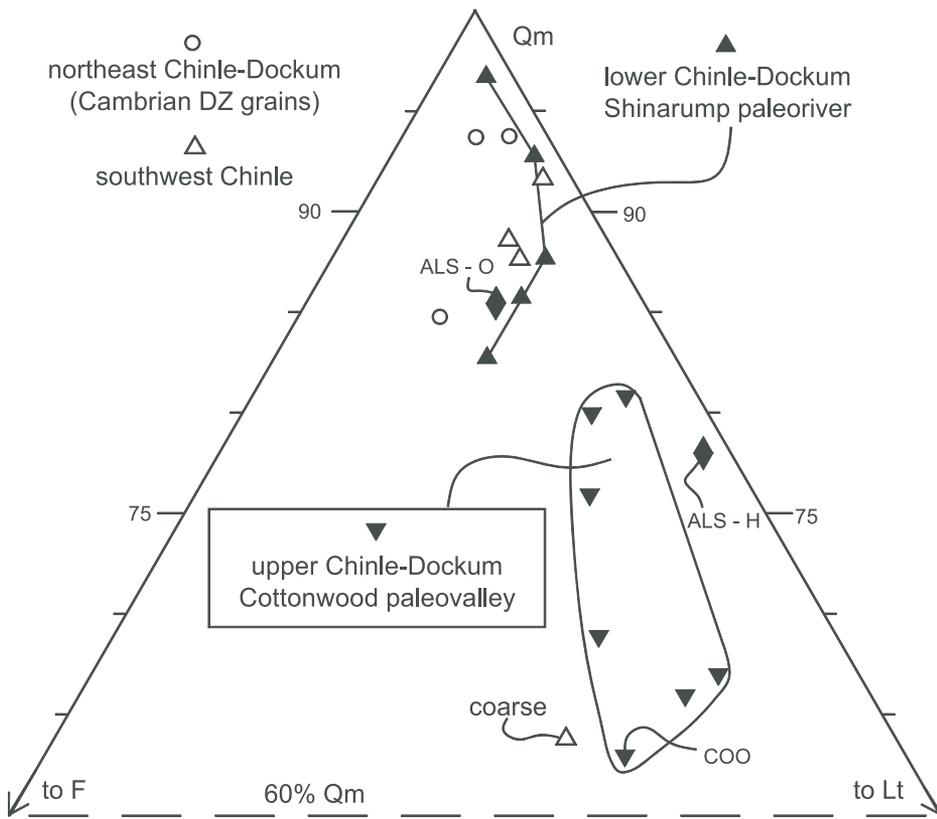
The transition upward stratigraphically from highly quartzose sand to more lithic sand is interpreted as a form of inverted clast stratigraphy. Alternately, slower erosion of more deeply weathered source rocks early during Chinle-Dockum sedimentation, followed by more rapid erosion of less deeply weathered source rocks later, might be invoked to account for the higher quartz content of the lower strata. The consis-

tently low feldspar contents of both lower and upper Chinle-Dockum assemblages argues, however, that differential weathering of source rocks was not the primary factor that controlled the contrast in petrofacies.

**APPALACHIAN-OUACHITA RELATIONS**

Figure 6 compares age-distribution curves for detrital zircon grains older than 290 Ma (Early Permian and older) in (1) Jurassic eolianites of the Colorado Plateau (upper panel) containing sand derived principally from the Appalachian orogen (Dickinson and Gehrels, 2009a, 2010), and in (2) fluvial and marine sandstones of Chinle-Dockum and Auld Lang Syne strata (lower panel) containing sand derived principally from the Ouachita orogen. Overall similarity is evident, and probably stems from the finite number of pre-Mesozoic age provinces in North America from which detrital zircon grains can be derived. Salient differences in the curves include the following. (1) A more prominent Archean (2750 Ma) age peak for the eolianites is a function of the delivery of Archean grains from the Laurentian shield at the core of the continent to the transcontinental paleorivers that transported Appalachian detritus to sites north of the Colorado Plateau, from which paleowinds blew the riverine sand into Jurassic ergs (sand seas) to the south. (2) A more prominent 1440 Ma age peak in the Chinle-Dockum and Auld Lang Syne sands is a function of more widespread Mesozoic exposures of anorogenic Mesoproterozoic granitic plutons across southwest Laurentia in positions more favorable for contribution to Ouachita-derived sands than to Appalachian-derived sands. (3) Somewhat different Neoproterozoic age peaks, 615 Ma for Appalachian-derived sands but 630 Ma and 550 Ma for Ouachita-derived sands, may reflect different ages of accreted Gondwanan terranes along different segments of the Appalachian-Ouachita-Mesoamerican orogenic system. (4) There is a more discrete Paleozoic age peak (420 Ma) for the Appalachian-derived sands than for the Ouachita-derived sands.

There is no evidence in the detrital zircon data for net longitudinal age variation along the Grenville orogen, nor do compilations of U-Pb bedrock ages along the trend of the orogen suggest any systematic regional age differences (Dickinson and Gehrels, 2009a). Distinctions among Grenvillian grains of different ages is inherently difficult, however, because the uncertainties of U-Pb ages are intrinsically largest in the Grenvillian age range. Grenvillian age peaks therefore tend to be broader, with crests less sharply defined, than older and younger age peaks (Fig. 6).



**Figure 5. Petrofacies of sandstone samples from the Chinle-Dockum and Auld Lang Syne (ALS) Groups (ALS-O, Osobb Formation; ALS-H, Hollywood Formation). Qm—monocrystalline quartz; F—monocrystalline feldspar; Lt—total polycrystalline lithic fragments. Note that the base of the ternary diagram is at 60% Qm (not zero Qm). COO is Cooper Canyon Formation (the stratigraphically youngest of the Chinle-Dockum samples).**

## NON-OUACHITA PROVENANCES

Sandstone samples from the northeastern and southwestern fringes of the Chinle-Dockum depositional system contain detrital zircon populations indicative of derivation from non-Ouachita sources (Fig. 1). Figure 7 illustrates the strong differences in the detrital zircon age spectra of the two disparate data sets (Fig. 7, top and bottom panels) as compared to the data set (Fig. 7, middle panel) from central Chinle-Dockum paleodrainages (Shinarump trunk paleoriver and Cottonwood paleovalley) with headwaters in the Ouachita foreland adjacent to the Texas uplift.

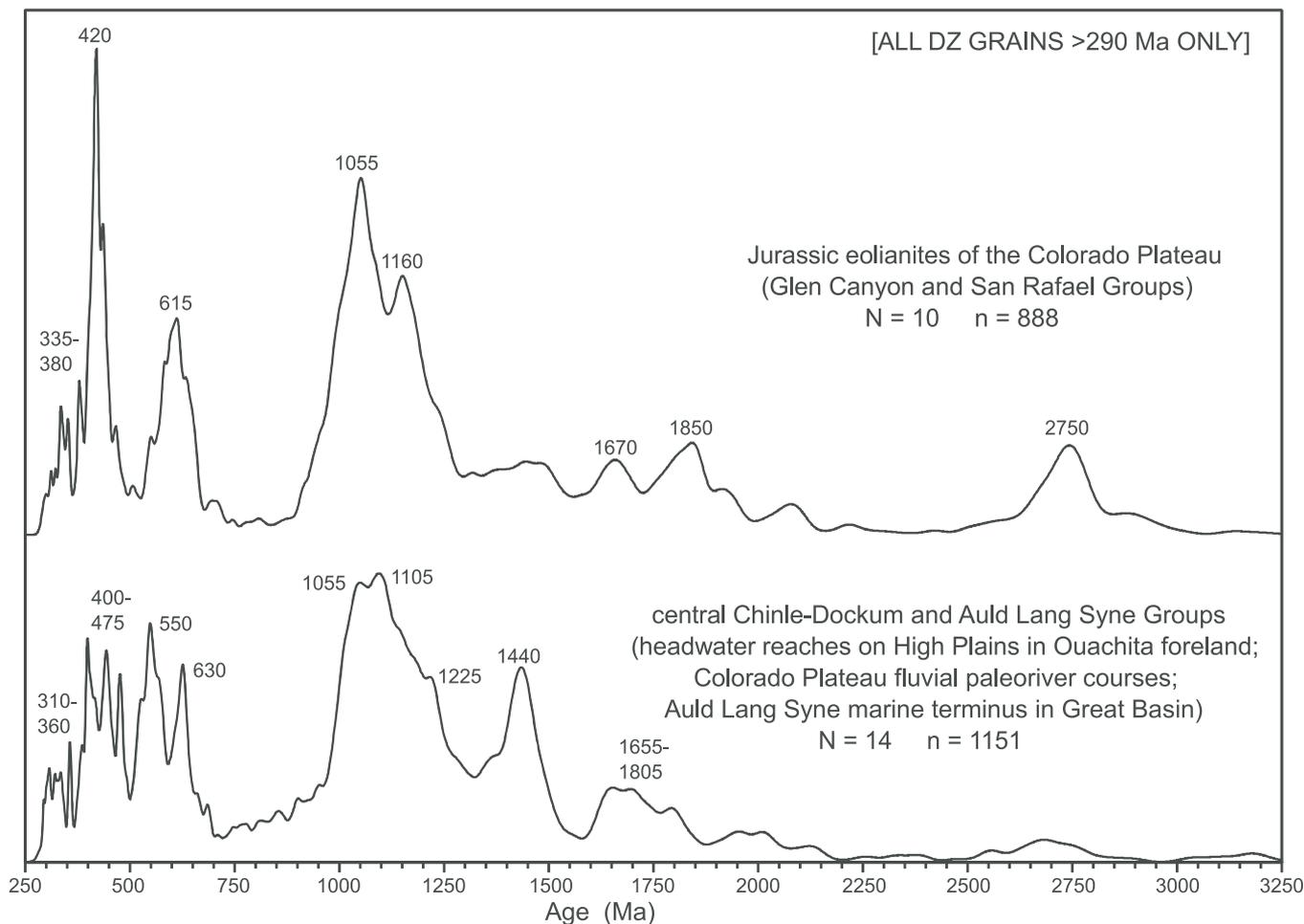
### Amarillo-Wichita Provenance

The age-distribution curve composited from a sample of the Gartra Formation deposited

along the lower course of the Eagle paleoriver (Fig. 1), and two samples from basal sandstones of the Chinle-Dockum depositional system on the High Plains of Texas (Dockum) and New Mexico (Chinle), are dominated by a sharp Cambrian age peak (516 Ma); grains of all other ages are distinctly subordinate (Fig. 7, top panel). The inferred Cambrian source rocks are granites and perhaps rhyolites formed as the floor of the southern Oklahoma aulacogen (Hogan and Gilbert, 1998), and uplifted in Pennsylvanian time in the Amarillo-Wichita uplift (Fig. 1) of the Ancestral Rocky Mountains. The predominant Cambrian detrital zircon grains in the samples were probably reworked from Permian sedimentary cover that overtopped the uplift (Johnson, 1989), rather than being derived directly from Cambrian igneous rocks in the uplift core. Ultimate derivation from the Cambrian igneous assemblage of the

Amarillo-Wichita uplift is inferred because there is no other extensive igneous assemblage of exclusively Cambrian age in North America (Dickinson and Gehrels, 2009a). Moreover, the uplift was perfectly positioned to yield a flood of Cambrian detrital grains to the northeastern fringe of Chinle-Dockum exposures (but not, as observed, to other Chinle-Dockum strata). The presence of abundant Cambrian detrital grains in the Gartra Formation provides evidence that the headwaters of the Eagle paleoriver extended into the Amarillo-Wichita uplift (750+ km distant). The paleoriver course may have exploited residual paleotopography to flow along the central Colorado trough between Ancestral Rocky Mountains uplifts (Fig. 1).

Samples dominated by Cambrian detrital zircons from the Amarillo-Wichita uplift were collected from basal horizons of the Chinle-Dockum assemblage only. We infer that



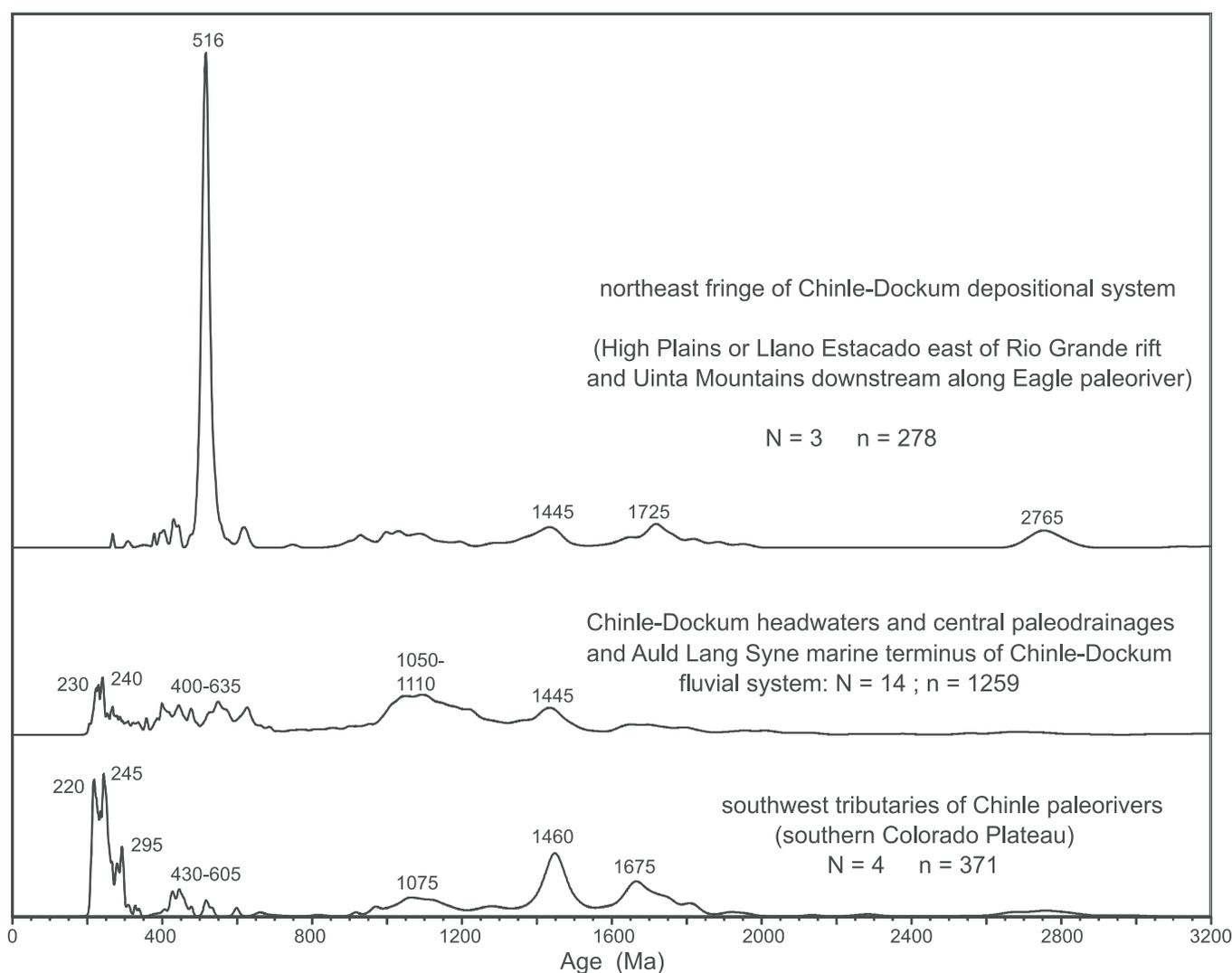
**Figure 6. Comparative detrital zircon (DZ) subpopulations (age-probability plots of U-Pb ages older than 290 Ma) in Jurassic eolianites (dominantly Appalachian provenance) of the Colorado Plateau (top curve) and in Upper Triassic sandstones (dominantly Ouachita provenance) in the Chinle-Dockum and Auld Lang Syne Groups (bottom curve). N denotes the number of samples and n is the number of detrital zircon ages composited for each curve. Numbers denote salient age peaks to the nearest 5 m.y.**

sediment dispersal from the Amarillo-Wichita uplift was significant, relative to sediment dispersal from the Texas uplift, only during the initial phases of Chinle-Dockum sedimentation. Later, any contributions from the Amarillo-Wichita uplift were overwhelmed and masked by the flood of detritus derived from recycling of sand from the Ouachita system. No Cambrian age peak at 516 Ma is evident in the Ouachita-derived sands (Fig. 6, bottom panel) between older Neoproterozoic and younger Paleozoic age peaks. Only 29 grains (2% of the total) in the Ouachita-derived sands have best age estimates of 535–500 Ma, forming a minor terrace on the young shoulder of the prominent 550 Ma Neoproterozoic age peak (Fig. 6, bottom panel).

Surface exposures of Cambrian granite and rhyolite in the Wichita Mountains near the eastern end of the Amarillo-Wichita uplift have yielded zircon U-Pb ages of 533–530 Ma (Hanson et al., 2009; Gilbert, 2009), whereas the composite Cambrian age peak for derivative detrital zircons is 516 Ma (Fig. 8). All the grain ages that contribute to the 516 Ma age peak are concordant, with ovals of uncertainty for  $^{206}\text{Pb}/^{238}\text{U}$  and  $^{206}\text{Pb}/^{207}\text{Pb}$  ages that overlap concordia. Although the grain ages that contribute to the 516 Ma age peak for detrital zircon populations include grains that overlap the ages for surface exposures (Fig. 8), the dichotomy between ages for surface outcrops and the mean age of the detrital zircon grains seems robust.

The age discrepancy cannot be ascribed readily to interlaboratory variance because the requisite difference of 3% in age is unexpected for U-Pb methodology. We provisionally ascribe the age differential to one of two factors (we prefer the first): (1) the ages for surface outcrops, which are limited in areal extent, do not provide an adequate census of granite-rhyolite ages along the full expanse of the Amarillo-Wichita uplift, which is now largely buried in the subsurface; or (2) the detrital zircon population includes contributions from young components of the granite-rhyolite assemblage that were largely removed by post-Pennsylvanian but pre-Triassic erosion.

With respect to the second hypothesis (erosional removal of detrital zircon sources), any



**Figure 7.** Comparative detrital zircon populations (age-probability plots of U-Pb ages) in Upper Triassic Chinle-Dockum sandstones (basal units) of dominantly Amarillo-Wichita provenance on the northeast (top curve), along trunk paleorivers (including the marine terminus of the fluvial system) of dominantly Ouachita provenance (middle curve), and of southern provenance on the southwest (bottom curve). N denotes the number of samples and n is the number of detrital zircon ages composited for each curve. Numbers denote salient age peaks to the nearest 5 m.y. (or 1 m.y. for the prominent Cambrian age peak).

correlation of detrital zircons with potential source rocks is plagued by the fact that the source rocks that yielded sedimentary detritus in the past are no longer present. With respect to the first hypothesis (age diachroneity of the Amarillo-Wichita igneous province), it seems quite possible that the igneous floor of the aulacogen became younger to the northwest, where most of the Amarillo-Wichita uplift is now buried and inaccessible for outcrop collection, as the rift structure of the aulacogen was progressively wedged into the ancestral margin of Laurentia.

### Ancestral Mogollon Provenance

Four Chinle samples (CP11, CP18, CP38 of lower Chinle age; CP20 of upper Chinle age; see Supplemental File 1 [footnote 1]) from the

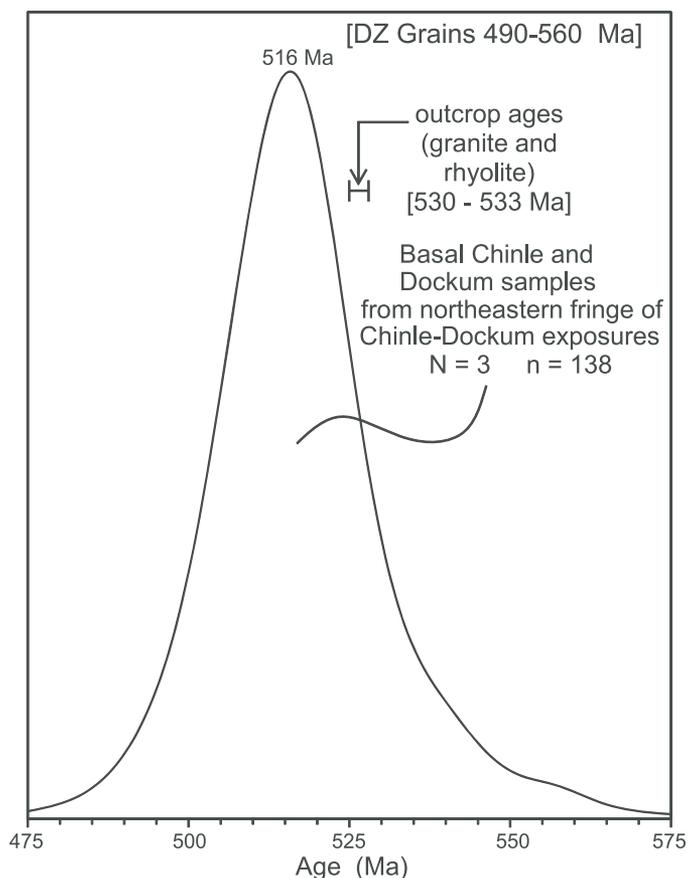
southern Colorado Plateau in Arizona came from outcrops that display paleocurrent indicators documenting fluvial paleoflow from the south (Dickinson and Gehrels, 2008). This azimuth points toward the late Mesozoic Mogollon paleohighlands that formed the rift shoulder of the Late Jurassic–Early Cretaceous Bisbee basin (Dickinson and Lawton, 2001b). The composite age-distribution curve (Fig. 7, bottom panel) for Chinle sands derived from the south has conspicuous Yavapai-Mazatzal (1675 Ma) and anorogenic granite (1455 Ma) age peaks more prominent than the Grenvillian age peak (1075 Ma). This pattern of relative Proterozoic age peaks is the inverse of that for Ouachita-derived Chinle-Dockum sands (Fig. 6, bottom panel), and minor Grenvillian grains in the detrital zircon population were probably reworked from Paleozoic cover of the Yavapai-Mazatzal

belt in southwest Laurentia (Gross et al., 2000; Stewart et al., 2001).  $P \leq 0.02$  (statistical distinction) for K-S comparison of pre-Pennsylvanian (older than 318 Ma) grains in any of the four southern Chinle samples with any of the central Chinle-Dockum and Auld Lang Syne samples of Table 3. A significant proportion of arc-derived grains (220–245 Ma age peak) implies derivation from the segment of the Cordilleran arc assemblage that was south of Yavapai-Mazatzal basement exposures (Fig. 1).

The greater height of the age peak for anorogenic granite sources, as compared to the age peak for Yavapai-Mazatzal sources, probably reflects the greater zircon fertility (Moecher and Samson, 2006) of anorogenic granite as opposed to orogenic granite. When orogenic granites are assigned a zircon fertility factor (ZFF) of 1.0, anorogenic granites have an average ZFF of 2.5 (Dickinson, 2008). Lowering the observed age peak for anorogenic Mesoproterozoic granite by a factor of 2.5 would make it comparable to the age peak for Yavapai-Mazatzal orogenic basement (Fig. 7, bottom panel). That adjusted relationship is more compatible with the relative exposure areas of the two Precambrian assemblages than the raw detrital zircon data seem to imply.

We conclude that the Chinle sands transported into the southwestern flank of the Chinle-Dockum depositional system were derived from Precambrian Yavapai-Mazatzal basement capped and locally intruded by a Mesozoic arc assemblage along a paleotopographic high ancestral to the Mogollon paleohighlands. That inference is supported by Figure 9, comparing composite age-distribution curves for the detrital zircon populations in Upper Triassic Chinle sands derived from the south (upper panel) and in Triassic strata of the Antimonio and Barranca Groups (lower panel). The latter were deposited in northwestern Sonora within a forearc basin beyond both Yavapai-Mazatzal exposures in southern Arizona and the Cordilleran magmatic arc crossing Sonora (Fig. 1). We infer that Permian detrital zircon grains in both southern Chinle strata (292 Ma age peak) and Antimonio-Barranca strata (284 Ma age peak) were derived jointly from Permian plutons that locally intrude Proterozoic basement in northern Sonora (Fig. 1).

Although  $P = 0$  from K-S analysis of the two detrital zircon populations of Figure 9, the comparability of all the age peaks of the two age-distribution curves implies that the differences between them stem from different proportions of detritus from the same array of source rocks, rather than from a significant difference in provenance. Local drainages in paleo-Mogollon highlands between two depositional sites



**Figure 8.** Comparison of age-distribution curve (age-probability plot of U-Pb ages) for detrital zircon (DZ) grains in Upper Triassic Chinle-Dockum sandstones derived from the Amarillo-Wichita uplift with older U-Pb ages for exposed Amarillo-Wichita bedrock (Wichita Mountains).  $N$  denotes the number of samples and  $n$  is the number of detrital zircon ages composited for the detrital zircon age curve (age peak at 516 Ma). All detrital zircon ages incorporated into the curve are concordant at  $1\sigma$ .

apparently mixed contributions from different components of Precambrian basement and its sedimentary and volcanic cover in proportions different enough to account for the K-S contrast. The two detrital zircon populations of Figure 9 are composites of four samples each, and P = 0 for 5 of the 6 Antimonio-Barranca sample pairs, and for 3 of the 6 southern Chinle sample pairs. These results are interpreted to reflect vagaries of exposure of common source rocks in local segments of the joint provenance.

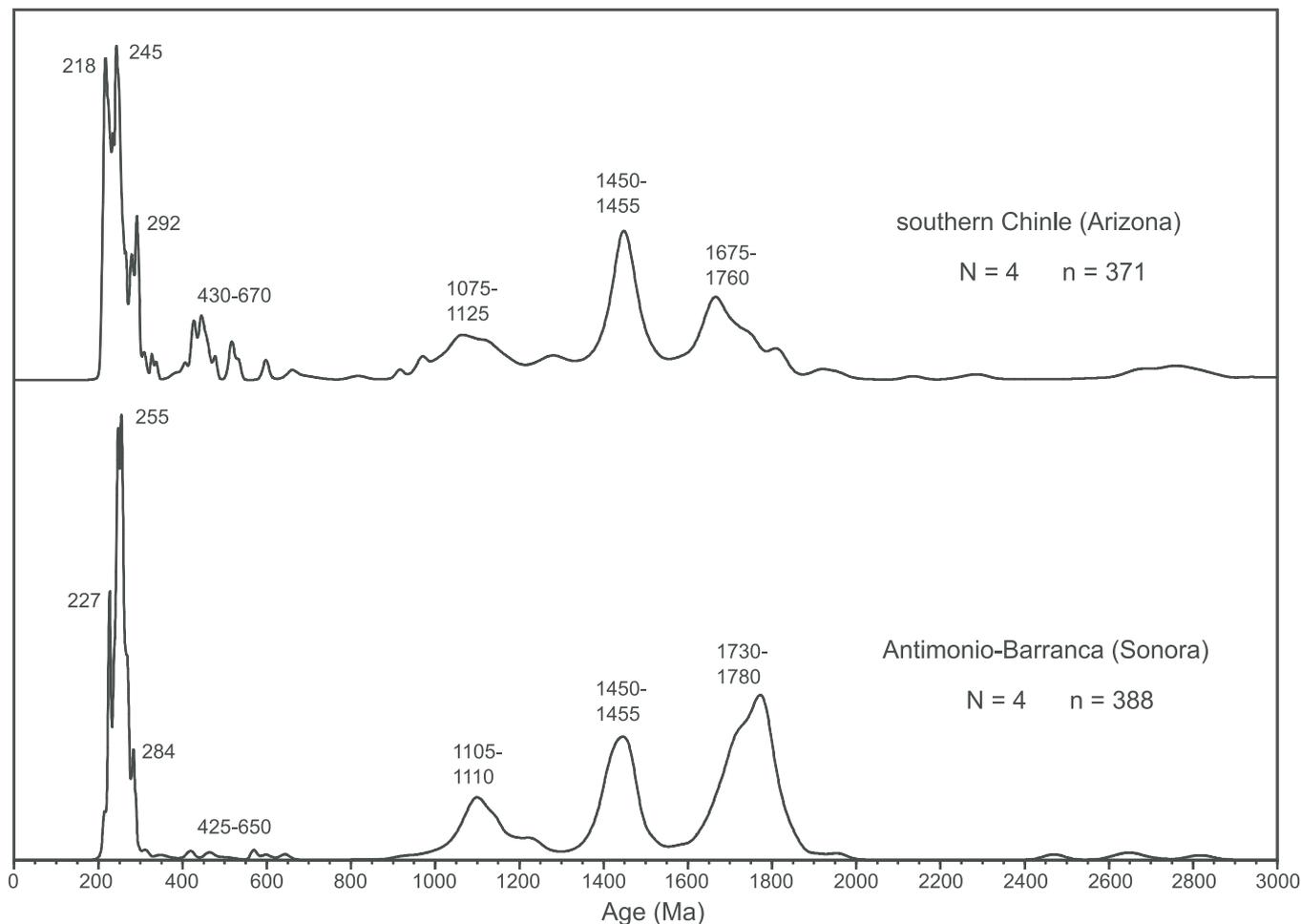
### POTOSÍ FAN PALEOTECTONICS

Sediment was delivered to the Potosí subsea fan by the El Alamar paleoriver (Barboza-Gudiño, 2009) issuing westward longitudinally from the Texas uplift (Fig. 1). Previous analysis has suggested that the Potosí fan was built to the west-southwest (Barboza-Gudiño et al.,

2010) across a Late Triassic (Fig. 2) passive continental margin during an interval between episodes of arc magmatism along the Permian–Triassic East Mexico arc and the younger Cordilleran magmatic arc of Jurassic and younger age in northeastern Mexico (Centeno-García, 2005). A belt of discontinuous arc magmatism recorded by isolated Permian plutons (Iriondo and Arvizu, 2009; Arvizu et al., 2009) scattered across northern Mexico (asterisks in Fig. 1) suggests that arc activity migrated northwest during Permian time across northern Mexico, as an extension of the East Mexico arc. Arc magmatism reached California by Early Triassic time (245–235 Ma), when plutons associated with the earliest phases of the Cordilleran arc in the Mojave Desert region were emplaced (Barth and Wooden, 2006). The Permian arc magmatism across northern Mexico may have been triggered by oblique subduction along the

Permian–Triassic California-Coahuila transform (Dickinson and Lawton, 2001a).

Paleogeography does not require cessation of arc magmatism during deposition of the Potosí fan. The tectonic setting of the modern Columbia River is an apt reminder that major drainage systems can cross active magmatic arcs. The Columbia River rises in mountainous backarc highlands of the U.S.–Canadian Cordillera, flows across the Cascades arc through the Columbia River gorge, overfills the Cascadia trench, and pours a subsea fan across the surface of the oceanic Juan de Fuca plate. By exploiting a fracture zone transecting the Juan de Fuca Ridge, the Columbia dispersal system even spreads turbidites across the Pacific plate to a distance of at least 2000 km from the continental margin (Menard, 1964). Highlands along the Texas uplift behind the arc trend of northeastern Mexico may similarly have given



**Figure 9.** Comparative detrital zircon populations (age probability plots of U-Pb ages) of similar provenance in southern Chinle samples from Arizona (top curve) and in Triassic samples from the Antimonio and Barranca Groups of Sonora (bottom curve). Antimonio and Barranca data are from González-León et al. (2009). N denotes the number of samples and n is the number of detrital zircon ages composited for each curve. Numbers denote salient age peaks to the nearest 5 m.y.

rise to a major paleoriver (El Alamar) that could have transported sediment across the arc trend of northeastern Mexico to promote deposition of the Potosí subsea fan on adjacent oceanic crust beyond a filled trench. The configuration of upstream reaches of the El Alamar paleoriver is unknown because only its terminus in northeastern Mexico is preserved in outcrop. The record of any upstream tributaries may have been removed by Triassic–Jurassic erosion, or may be present today in the subsurface beneath post-Triassic sediment prisms deposited along the rifted margins of the Gulf of Mexico. Upstream tributaries may, however, have tapped paleotopography that once existed across the full span of the Texas uplift from the Ouachita orogen along its northern flank to the Yucatán–Campeche block along its southern flank. Longitudinal extensions of the El Alamar paleodrainage eastward toward Florida in the region south of subsurface uplifts in eastern Texas and adjacent states are also possible (Fig. 1).

To evaluate the provenance of the Potosí subsea fan, Figure 10 compares detrital zircon populations from the El Alamar paleoriver–Potosí fan depositional system (Barboza-Gudiño et al., 2009, 2010) and Chinle–Dockum sandstones of the High Plains in the Ouachita foreland; the former was built longitudinally to the southwest from the Texas uplift, whereas the latter were transported toward the northwest transverse to the Texas uplift. Grain ages from one Chinle sample (CP6) containing no arc-derived grains younger than 310 Ma, and one El Alamar sample composed almost exclusively of grains younger than 290 Ma (90% of total grains) derived from the nearby East Mexico arc assemblage, were excluded from the composite grain populations plotted.

The High Plains Chinle–Dockum and El Alamar–Potosí age-distribution curves (Fig. 10, bottom panel) are similar but not identical. Arc-derived grains of both detrital zircon populations (Fig. 10, upper left panel) define the same age span, but El Alamar–Potosí arc-derived grains are biased toward grains older than 245 Ma apparently derived largely from the nearby Permian–Triassic East Mexico magmatic arc (Fig. 1), whereas Chinle–Dockum arc-derived grains are biased toward grains younger than 245 Ma probably derived mainly from the evolving Cordilleran magmatic arc of wider geographic extent. The El Alamar–Potosí arc-derived subpopulation may reflect some diminution of arc activity in northeastern Mexico during Late Triassic time (235–202 Ma), but provides no evidence for cessation of arc activity over that time interval. A sharp Chinle–Dockum age peak at 405 Ma (Early Devonian) is not present on the El Alamar–Potosí age-

distribution curve (Fig. 10, bottom and upper right panels), and may represent especially voluminous detritus from the nearby Ouachita orogen (Fig. 1) to Chinle–Dockum sands of the High Plains. Grenvillian (1300–900 Ma) age peaks are slightly displaced for the two age-distribution curves (Fig. 10, bottom and upper right panels), from 1040 Ma and 1230 Ma for Chinle–Dockum to 970 Ma and 1195 Ma for El Alamar–Potosí. The contrast in Grenvillian age peaks may reflect sources for El Alamar–Potosí sediment in Grenville terranes of Mexico that did not contribute detritus to Chinle–Dockum strata of the High Plains, but the net age spans of Grenvillian grains in the two assemblages are effectively indistinguishable. Paleogeography might predict that post-Grenvillian Neoproterozoic terranes possibly present within the Yucatán–Campeche block (Fig. 1) may have been more significant for El Alamar–Potosí provenance than for High Plains Chinle–Dockum provenance, but there is no suggestion from the age-distribution curves of Figure 10 that such was the case. On balance, the age spectra of detrital zircon populations in El Alamar–Potosí and High Plains Chinle–Dockum assemblages are compatible with derivation of the sediment in both cases largely from the nearby Texas uplift (Fig. 1), with indeterminate local variations in sediment dispersal patterns.

### ARC-DERIVED GRAINS

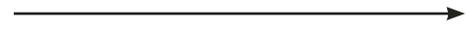
Of the detrital zircons in southern Chinle sandstone samples from the southern Colorado Plateau (Fig. 7, bottom panel; Fig. 9, top panel), 27% are inferred to derive from younger than 300 Ma arc assemblages south of the Colorado Plateau (Fig. 1). More than half the arc-derived grains in these samples are appropriate in age for sources within the nearby Cordilleran magmatic arc (compound age peak at 245–220 Ma), but an older fraction of arc-derived grains (nearly half the total) are inferred to derive from the isolated Permian igneous centers of northern Sonora (Fig. 1). In previous interpretations (Dickinson and Gehrels, 2008, 2009a, 2010), the presence of Permian detrital zircons in southernmost Chinle samples, and in younger fluvial units intercalated with Jurassic eolianites on the Colorado Plateau, was attributed exclusively to sediment transport from the East Mexico magmatic arc. Knowledge of more proximal sources for the Permian zircon grains reduces the requisite distance of transport from 1500 km to as little as 500 km for some occurrences.

The proportion of arc-derived grains is only 8% in the composite detrital zircon population of sandstones deposited along central Chinle–Dockum paleoriver courses and the eastern

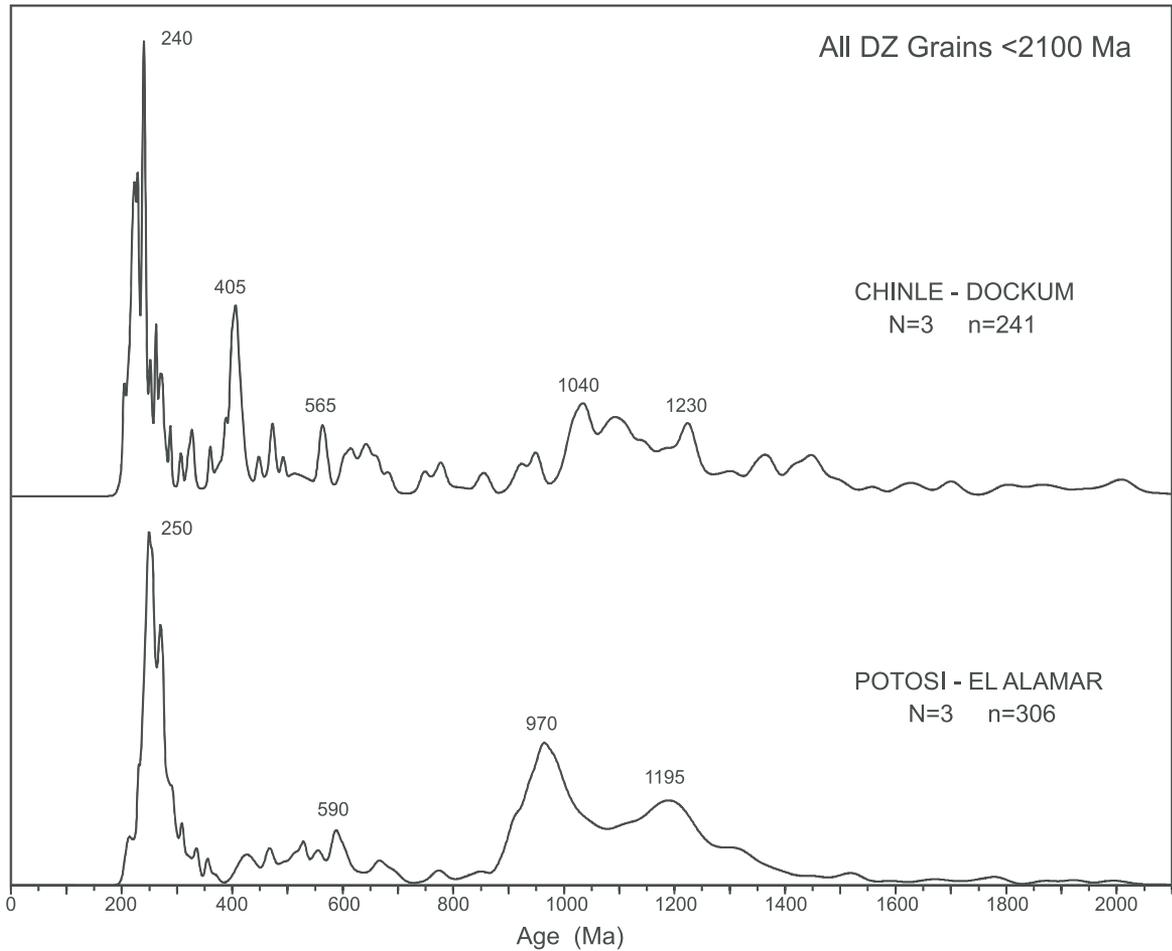
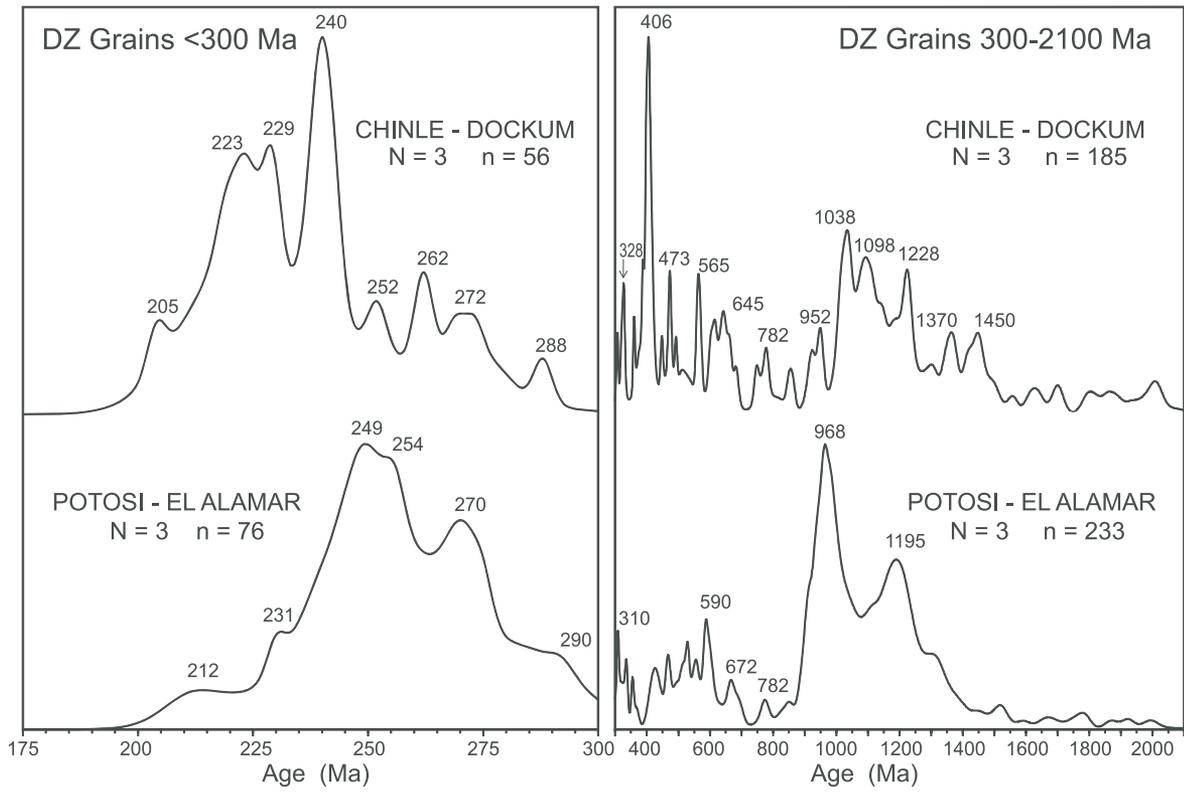
fringe of the Auld Lang Syne marine basin, but the pattern of grain ages (Fig. 11) yields information about the evolution of arc assemblages in northeastern Mexico. Most if not all of the arc-derived detrital zircons were presumably delivered to Chinle–Dockum paleorivers from tributaries heading west of the trend of the Tehuantepec paleotransform (Fig. 1). The age-distribution curves of Figure 11 do not support a hiatus in arc magmatism in northeastern Mexico during deposition of the Potosí fan in Late Triassic time (235–205 Ma from Fig. 2). Although no U–Pb ages for the Nazas segment of the Cordilleran arc in northeastern Mexico predate 195 Ma (Jones et al., 1995; Barboza-Gudiño et al., 1998, 1999, 2008, 2009), the detrital zircon ages of Figure 10 are consistent with whole-rock Rb–Sr ages of 225–220 Ma (Barboza-Gudiño et al., 1998) for the arc assemblage. Some fraction of downstream detrital zircon grains from Chinle sandstones on the Colorado Plateau and Auld Lang Syne sandstones in the Great Basin (Fig. 11, bottom) could have been added to the linked dispersal system from sources south of those locales and well west of northeastern Mexico. There is no indication, however, that subpopulations of arc-derived grains differ significantly in age from upstream to downstream sites along the sediment transport path (Fig. 11), and the sediment in samples of upstream Dockum Group from the High Plains of Texas and New Mexico (Fig. 11, top) was almost surely derived from no farther west than northeastern Mexico (Fig. 1).

### High Plains Chinle–Dockum

Figure 12 indicates the stratigraphic variation of detrital zircon populations in Chinle–Dockum samples from the High Plains and in their presumed Ouachita provenance. The progressive enhancement in the content of arc-derived (younger than 300 Ma) detrital zircon grains



**Figure 10. Comparative detrital zircon (DZ) subpopulations in strata of the Potosí subsea fan and El Alamar paleoriver of northeastern Mexico (three westernmost solid squares of Fig. 1) and in Chinle–Dockum strata of the High Plains in the Ouachita foreland (three easternmost inverted triangles of Fig. 1). All the curves are age-probability plots where N denotes the number of samples and n is the number of detrital zircon ages composited for each curve. Numbers denote salient age peaks to the nearest 5 m.y. (bottom curves) or 1 m.y. (top curves). Potosí and El Alamar data are from Barboza-Gudiño et al. (2010).**



over time (bottom curve to top curve, Fig. 12) may reflect the progressive integration of head-water paleodrainages over time. The stratigraphically lowest Chinle-Dockum sample (Fig. 12C) essentially reproduces the detrital zircon signal of presumed Ouachita source rocks (Fig. 12D). Successively younger samples, stacked in stratigraphic order (Figs. 12B, 12A), contain a progressively larger proportion of arc-derived grains, perhaps recording the extension of tributary drainages headward into the arc assemblage of northeastern Mexico (Fig. 1). The stratigraphically highest sample (Fig. 12A) also displays a prominent Silurian-Devonian age peak (430–380 Ma with crest at 410–405 Ma) not apparent on the age-distribution curves of the older samples. The appearance of the anomalous age peak in the youngest High Plains strata may reflect erosional stripping of the Ouachita orogen over time down to its metamorphic core, which is now preserved only in the subsurface

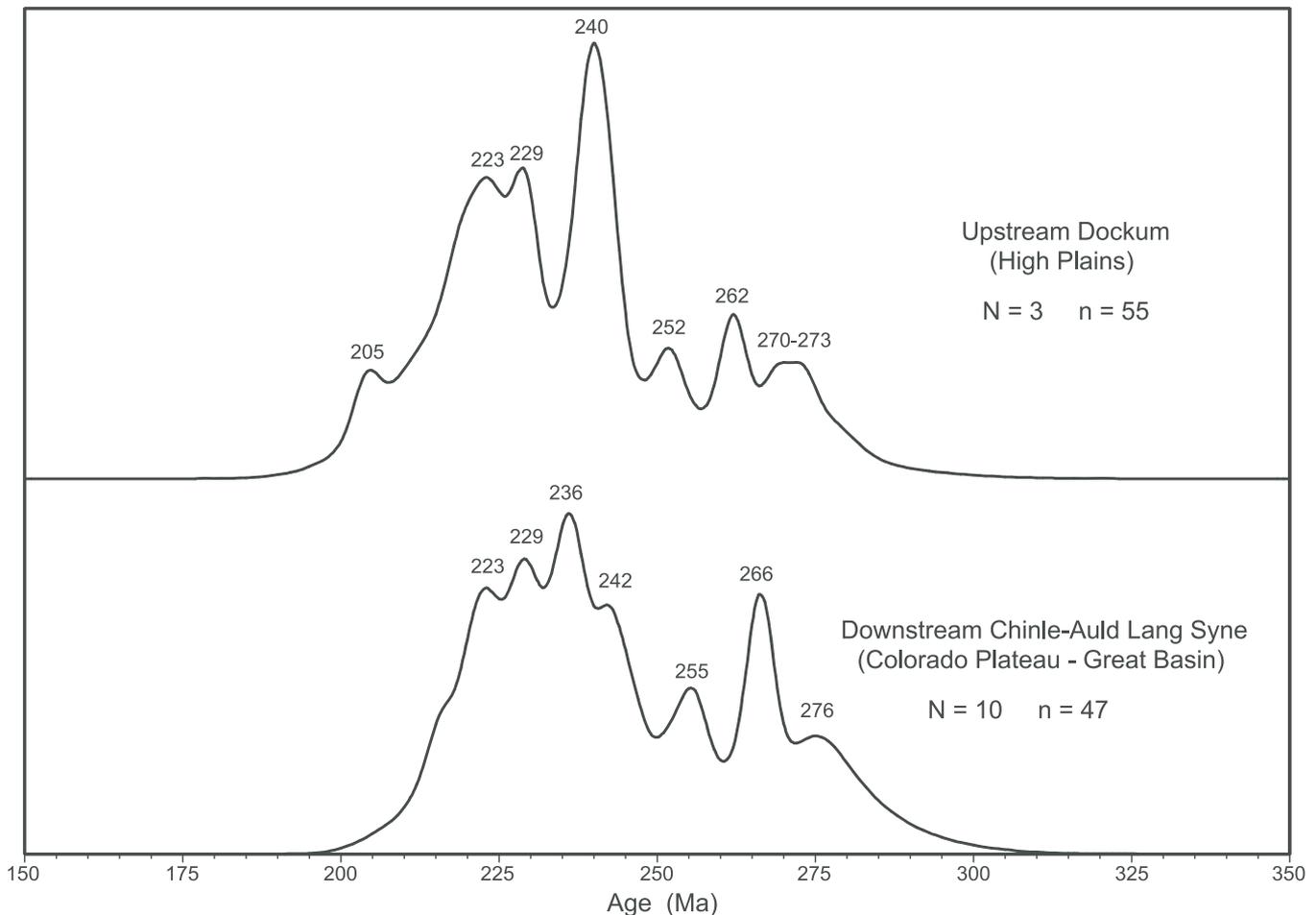
of central Texas (Fig. 1). Detrital muscovite of metamorphic origin and Devonian age (370–340 Ma) is also known from the Dockum Group of the High Plains (Long and Lehman, 2009).

### REGIONAL SEDIMENT VOLUMES

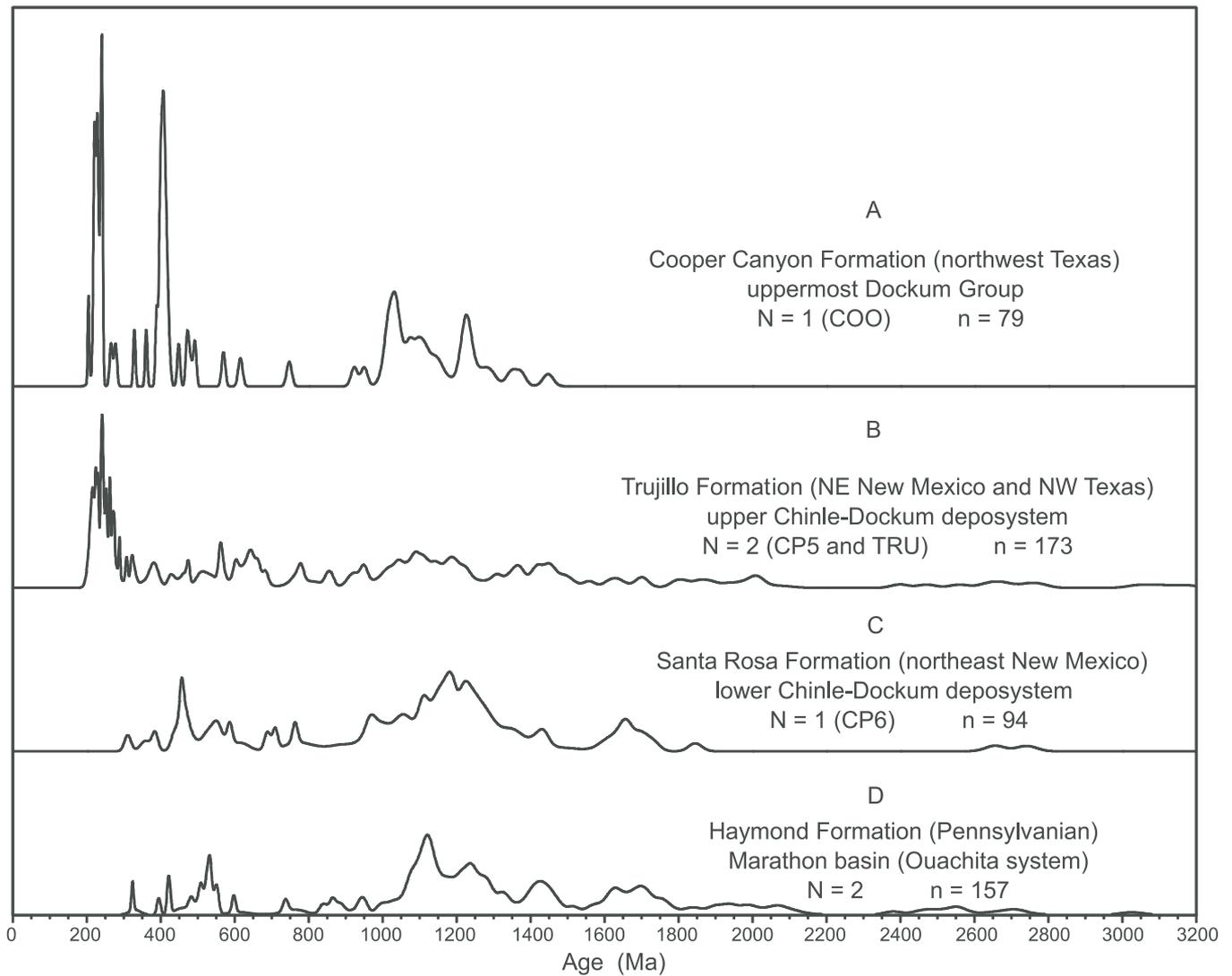
Table 4 estimates the sediment volumes derived from the Texas uplift during Late Triassic time based on the paleogeographic relations shown by Figure 1. The estimates are orders of magnitude only, all are minimum estimates, and all should be treated with caution for several reasons. For example, both thickness variations and areal extent are poorly known for the subsurface Eagle Mills rift assemblage. The thickness of Chinle-Dockum strata is well known, but the proportion of net volume derived from the Texas uplift as opposed to other provenances is uncertain, as is the initial areal extent of the Chinle-Dockum depositional system before post-

Triassic erosion. Auld Lang Syne strata have been severely telescoped by multiple Luning-Fencemaker thrust sheets, which make reconstruction of the Auld Lang Syne basin a challenge, and the proportion of the basin fill derived from the magmatic arc to the west remains uncertain. The original volume estimated for the severely deformed Potosí subsea fan is little more than an educated guess. Of the estimated minimum volume of sediment ( $700 \times 10 \text{ km}^3$ ), ~75% is contained in deformed marine strata of the Auld Lang Syne basin and Potosí subsea fan where structural complexities make any estimates of net sediment volume questionable.

The estimated sediment volume derived from the Texas uplift can be used in principle to infer the depth of erosion along the rift uplift during Late Triassic time, but the extent of the uplifted belt along the incipient continental rift is uncertain. The position of the rift axis of the Texas uplift can be specified as the location of



**Figure 11.** Comparison of U-Pb ages (age-probability plots) for composite subpopulations of arc-derived detrital zircon grains in upstream (top curve) and downstream (bottom curve) segments of the linked fluvial and marine depositional system of the central Chinle-Dockum and Auld Lang Syne Groups with headwaters in the Ouachita foreland. N denotes the number of samples and n is the number of detrital zircon ages composited for each curve. Numbers denote salient age peaks to the nearest 1 m.y.



**Figure 12. Comparative detrital zircon populations (age-probability plots of U-Pb ages) in sandstones of the Paleozoic Ouachita system (bottom curve) and at successively higher horizons of the Chinle-Dockum depositional system (deposystem) of Late Triassic age on the High Plains in the Ouachita foreland. Note the prominent age peak at 405–410 Ma for Cooper Canyon Formation (top curve; sample COO) not present on the other curves. N denotes the number of samples and n is the number of detrital zircon ages used to plot each curve.**

TABLE 4. ESTIMATED VOLUMES OF SEDIMENT ERODED FROM THE TEXAS RIFT UPLIFT IN LATE TRIASSIC TIME (TOTAL 700 km<sup>3</sup>)

Sedimentary assemblage	Basis of estimate	Volume (km <sup>3</sup> )
Eagle Mills	1250 m mean thickness x 84,000 km <sup>2</sup>	105,000
Chinle-Dockum	180 m mean thickness x 390,000 km <sup>2</sup>	70,000
Auld Lang Syne	4500 m mean thickness x 60,000 km <sup>2</sup>	270,000
Potosí subsea fan	1500 m mean thickness x 170,000 km <sup>2</sup>	255,000

*Note:* Extent of Chinle-Dockum depositional system trimmed to exclude Chinle strata in Arizona derived from the ancestral Mogollon highlands directly to the south and Gartra strata derived from the Amarillo-Wichita uplift, but expanded to include inferred downstream continuation within the Great Basin. Extent of Auld Lang Syne backarc marine basin trimmed to exclude western flank derived from the Cordilleran magmatic arc, but expanded by 50% to allow for thrust telescoping.

the prerift juncture between the Llano uplift of central Texas and the reconstructed position of the Yucatán-Campeche block (Fig. 1). The length of the uplift is taken here as the distance of 600 km from the Tehuantepec paleotransform on the west to the microcontinental blocks of the Sabine and other uplifts on the east (Fig. 1). The lateral span of the belt uplifted along the rift system is uncertain, however, because both the northern and southern flanks of the Late Triassic uplift are now buried beneath sediment deposited after separation of the Yucatán-Campeche block from southern Texas and thermal subsidence of the conjugate rifted margins. From the presence of detrital zircons in the Chinle-Dockum depositional system derived from the Ouachita system, the minimum half-width of the uplift can be taken as the distance from the axis of the rift to the Ouachita thrust front, from which the full width of the rift uplift can be estimated as 300 km.

A Texas prerift uplift with an areal extent of  $175 \times 10^3 \text{ km}^2$  ( $300 \times 600 \text{ km}$ ) implies average erosion of 4 km to yield the estimated sediment volume of  $700 \times 10^3 \text{ km}^3$ . That depth of erosion does not seem excessive for a highland belt that must have risen isostatically as erosion proceeded, but the estimate given here could be improved through better knowledge of sediment volumes and the configuration of the rift uplift.

## SUMMARY AND CONCLUSIONS

Analysis of detrital zircon populations transported across southwest Laurentia by the Late Triassic Chinle-Dockum fluvial depositional system indicates that most of the detritus was derived from a prerift uplift in central Texas that was precursory to Jurassic opening of the Gulf of Mexico. Sediment of other provenance is confined to the northeastern and southwestern fringes of the Chinle-Dockum sedimentary assemblage. The detrital zircon signature of central Chinle-Dockum paleorivers propagated into the Auld Lang Syne Group deposited in a Cordilleran backarc basin at the marine terminus of the Chinle-Dockum paleodrainage 2000 km from its headwaters along the northern flank of the Texas uplift. A similar detrital zircon population in the Potosí subsea fan of central Mexico indicates that sediment was shed longitudinally oceanward from the Texas uplift, as well as transversely across the continent. Preliminary appraisal of sediment volumes indicates that the inferred thermal uplift centered in Texas was an adequate provenance for all these sedimentary successions bearing common detrital zircon signatures, as well as for Eagle Mills rift successions preserved only in the subsurface.

## ACKNOWLEDGMENTS

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