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IMPLICATIONS OF U-PB AGES OF DETRITAL ZIRCONS IN MESOZOIC STRATA OF THE FOUR CORNERS REGION FOR PROVENANCE RELATIONS IN SPACE AND TIME

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ABSTRACT—U-Pb ages for individual detrital zircons in sandstone record the ages of igneous source rocks in which zircon and accompanying quartz crystals formed because zircon U-Pb ages are not reset by either sedimentary or diagenetic processes. Ages of detrital zircons reflect ultimate sand sources in basement rocks but allowance must be made in provenance interpretations for potential recycling of resistant zircon grains from more proximate sources in sedimentary assemblages. Our database for Mesozoic strata in the Four Corners region includes 2213 concordant or nearly concordant U-Pb ages of detrital zircons from 24 samples (Triassic to Cretaceous). Chinle channel sands were derived largely from the Ouachita orogen where uplifted on the northern shoulder of the pre-Gulf of Mexico rift system, from which Ouachita-derived sand was carried westward by paleoriver systems ~1500 km long with headwaters in the Ouachita foreland. Southern tributaries of central Chinle paleorivers contributed detritus from Precambrian basement and the Cordilleran magmatic arc lying south of the Colorado Plateau. Eolian dune sands of Glen Canyon and San Rafael ergs were derived largely from pre-Atlantic rift highlands along the Appalachian belt, transported to deltas or floodplains in the northern Rocky Mountains region by a transcontinental paleoriver system ~2000 km long carrying Appalachian-derived sediment, and delivered southward to the Colorado Plateau ergs by the paleowinds recorded by dune crossbedding. Salt Wash (Morrison) and Burro Canyon (including Jackpile) fluvial sands were largely reworked from older Jurassic eolianites forming sedimentary cover over the Mogollon paleohighlands, but Westwater Canyon (Morrison), Cretaceous (Toreva-Gallup-Menefee) fluvial and fluviodeltaic sands contain prominent components of detrital zircon derived from Proterozoic Mogollon basement and its sedimentary cover, and from the Mesozoic Cordilleran magmatic arc lying still farther south.

INTRODUCTION

Determining U-Pb ages for detrital zircons (DZ) has become standard methodology for constraining the provenance of sand and sandstone (Fedo et al., 2003; Ross and Villeneuve, 2003; Link et al., 2005; Dickinson and Gehrels, 2009b). During the years 2004-2008, we studied DZ ages in Mesozoic strata of the Colorado Plateau and adjoining regions by means of a research seminar supported by the National Science Foundation at the University of Arizona involving 15 students and seven professional confreres from other institutions. This paper presents an overview of results for 2213 DZ grains in 24 samples (average of 92 DZ grains per sample) from the Four Corners region, extending from Black Mesa and Monument Valley on the west to the Rio Grande rift on the east, and from the Dolores River on the north to Interstate Highway I-40 through Gallup on the south. U-Pb ages were determined for individual DZ grains by laser ablation-multicollector-inductively coupled plasma-mass spectrometry (LA-ICP-MS; Gehrels et al., 2008). Full U-Pb analytical data, concordia diagrams, age-bin histograms, and age-distribution curves (probability-density plots) for each sample were reported by Dickinson and Gehrels (2008a, 2008b, 2009a), who also discussed stratigraphic relations and petrographic aspects of the samples more fully than we attempt here and provided detailed descriptions (including GPS coordinates) of all sample localities. Dickinson and Gehrels (2009c) further presented a summary of provenance relations from a regional perspective.

INTERPRETIVE BACKGROUND

DZ grains are especially useful for provenance studies because (a) resistant zircon is persistent in the sedimentary environment; (b) sedimentary zircon and quartz are both derived principally from felsic igneous rocks, hence zircon serves as a proxy for more abundant quartz; (c) DZ ages faithfully reflect the ages of igneous source rocks because the U-Pb isotopic system is not reset by temperatures prevalent in diagenesis; (d) the ultimate sources of DZ grains can be inferred from independent knowledge of the geographic distribution of potential source rocks of different ages; and (e) the double decay scheme of the U-Pb isotopic system (^{238}U to ^{206}Pb and ^{235}U to ^{207}Pb) allows disturbance of the U-Pb isotopic system (typically by lead loss through leaching of DZ grains) to be detected without ambivalence because the double U-Pb ages are then discordant and plot off the standard concordia curve.

Discordant grains are rejected for provenance analysis because discordia chords cannot be interpreted for DZ grains having varied histories. In practice, minor discordance is allowed according to set criteria (see Dickinson and Gehrels, 2008a, 2008b, 2009a), but <10% and commonly <5% of grain ages were rejected for discordance. Best age estimates for DZ grains are provided by $^{206}Pb/^{238}U$ for grains <1 Ga, declining in accuracy with increasing age, and by $^{206}Pb/^{207}Pb$ for grains >1 Ga, declining in accuracy with decreasing age. Uncertainty in U-Pb grain age is thus inherently greatest near 1.0-1.3 Ma (Grenvillean). Measurement of $^{206}Pb/^{204}Pb$ ratios allows corrections to U-Pb ages to allow for the presence of non-radiogenic lead (dominantly but not exclusively ^{204}Pb).

The spectrum of U-Pb ages in a population of DZ grains is best displayed visually as an age-distribution curve, which is a probability-density plot (Ludwig, 2003) generated by incorporating each U-Pb age and its analytical uncertainty as a normal distribution, and stacking the individual normal distributions into a compound curve. For ease of visual comparison, the probability plots are normalized to enclose equal areas beneath age-distribution curves. For comparison of DZ age spectra, equivocal visual impressions can be supplemented by Kolmogorov-Smirnoff (K-S) statistics (Press et al., 1986). K-S analysis calculates a probability P that two age spectra are comparable, and where P>0.05 (the reciprocal of 0.95), there is <95% confidence that two age spectra do not represent grains selected at random from the same parent population (P=1.0 indicates statistical identity). Where P>0.05, we conclude that there is no robust contrast in provenance even where visual differences can be seen between the age spectra of different DZ populations.

There are three important caveats for provenance interpretations from DZ age spectra: (a) DZ grains integrate detrital contributions from multiple source rocks, and DZ age spectra are not sensitive to minor variations in provenance; (b) proportions of DZ grains of various ages do not necessarily equate to proportions of total detritus from different source rocks because differential zircon fertility (Moecher and Samson, 2006; Dickinson, 2008) of different igneous assemblages comes into play for provenance interpretations; and (c) DZ ages reflect the ages of the ultimate igneous sources of DZ grains, but cannot detect the nature of proximate sedimentary strata from which durable zircon grains have been recycled (Link et al., 2005; Dickinson et al., 2009b). Nevertheless, DZ analysis provides important information about provenance that cannot be obtained from either paleocurrent studies, which indicate directions of sediment transport at depositional sites but provide no direct information about distant provenances, or petrofacies analysis which indicates the general nature of sediment provenance but cannot distinguish between similar source rocks of disparate ages.

For provenance interpretations, emphasis is placed on clusters of multiple grain ages that provide robust indications of provenance contributions. Individual grain ages can be spurious, and isolated grain ages may be selective records of minor age clusters but not representative of those age clusters as a whole. The sampling challenge for DZ work is daunting. First one selects a finite number of sample localities, always small to keep analytical costs down. Then one must select a particular part of an outcrop to sample, or else devise some scheme for channel sampling which we have not attempted. Finally, one must select at random (our practice, although other approaches are possible) ~100 DZ grains (our standard, but more or fewer are possible) for laser ablation from an epoxy mount of 1000-2000 DZ grains, separated laboriously from the sample. These considerations virtually guarantee minor variations in DZ age spectra that may lack any significance for provenance interpretations. All our DZ grains are very fine to medium sand in size, and our methodology did not test zircon grains of silt size. Within the DZ size range treated, we observed no consistent correlations between grain age and color, habit, or other morphology (such as abrasion) of zircon grains.

SAMPLE CONTEXT

Figure 1 shows the geographic distribution of our DZ samples (Table 1) on a geologic sketch map of the Four Corners region, Figure 2 indicates schematically their stratigraphic distribution on a chronostratigraphic section (NW-SE) across the Four Corners region, and Figure 3 depicts the regional relationships of key depositional systems from which most of the DZ samples derive.

Most DZ grains in Mesozoic strata of the Four Corners region were derived ultimately from basement sources in eastern and southern North America, with only subordinate contributions from bedrock in the Cordilleran region, although intraregional recycling of DZ grains became important as depositional systems evolved. Figure 3 (Four Corners region highlighted by bold squares), depicts sequentially the major provenance relations for the DZ samples as follows:

(1) Upper Triassic (Chinle) sandstones (Fig. 3A) were collected mainly along the courses of major regional rivers, the Shinarump trunk paleoriver of the lower Chinle depositional system and the Cottonwood paleovalley of the upper Chinle depositional system. Each of those two major Chinle paleodrainages had their headwaters in the Ouachita foreland of west Texas, although selected DZ samples derive from southern Chinle tributaries sourced in ancestral Mogollon paleohighlands and the Cordilleran magmatic arc.

(2) Jurassic ergs (Fig. 3BC) were fed by sand that was transported across the craton to the northern Rocky Mountains region by transcontinental paleorivers with headwaters in the central to southern Appalachian region, and then blown southward (in present coordinates) by deflation of floodplains or deltas to deliver eolian sand of Appalachian derivation to the plateau ergs.

(3) Upper Jurassic (Morrison) fluvial systems (Fig. 3D) included two foreland megafans (Leier et al., 2005), Salt Wash and Westwater Canyon, having distinctly different provenances, with the Salt Wash megafan issuing from the syntaxis between Sevier and Mogollon tectonic trends and the Westwater Canyon megafan built off the flank of the rift shoulder (Mogollon paleohighlands) of the Border rift system.

(4) Cretaceous fluvial and fluviodeltaic sands (Fig. 3EF) were transported northward into the Four Corners region from the Mogollon paleohighlands, and eventually also from the Cordilleran magmatic arc farther south, as progressive onlap of coastal and marine strata of the Dakota Formation gradually buried the Mogollon paleohighlands, but we did not sample Cretaceous marine strata from the interior of the San Juan basin to avoid mixed provenance signals introduced by longshore marine transport.

KEY DZ POPULATIONS

DZ grains derived from Cordilleran arc assemblages of Mesozoic age, and their Permian antecedents (Iriondo and Arvizu, 2009), are <285 Ma. Paleogeographic relations (Fig. 3) and the nature of accompanying older DZ grains imply that the arc-derived grains derive exclusively from segments of the Cordilleran arc lying south and southwest of the Colorado Plateau in Mexico, southernmost Arizona, and southern California (Fig. 3) where the arc was built across Paleoproterozoic (1800-1600 Ma) Yavapai-Mazatzal basement of southwest Laurentia (Shaw and Karlstrom, 1999; Whitmeyer and Karlstrom, 2007; Barth et al., 2009). The DZ signal of Yavapai-Mazatzal provenance incorpo-

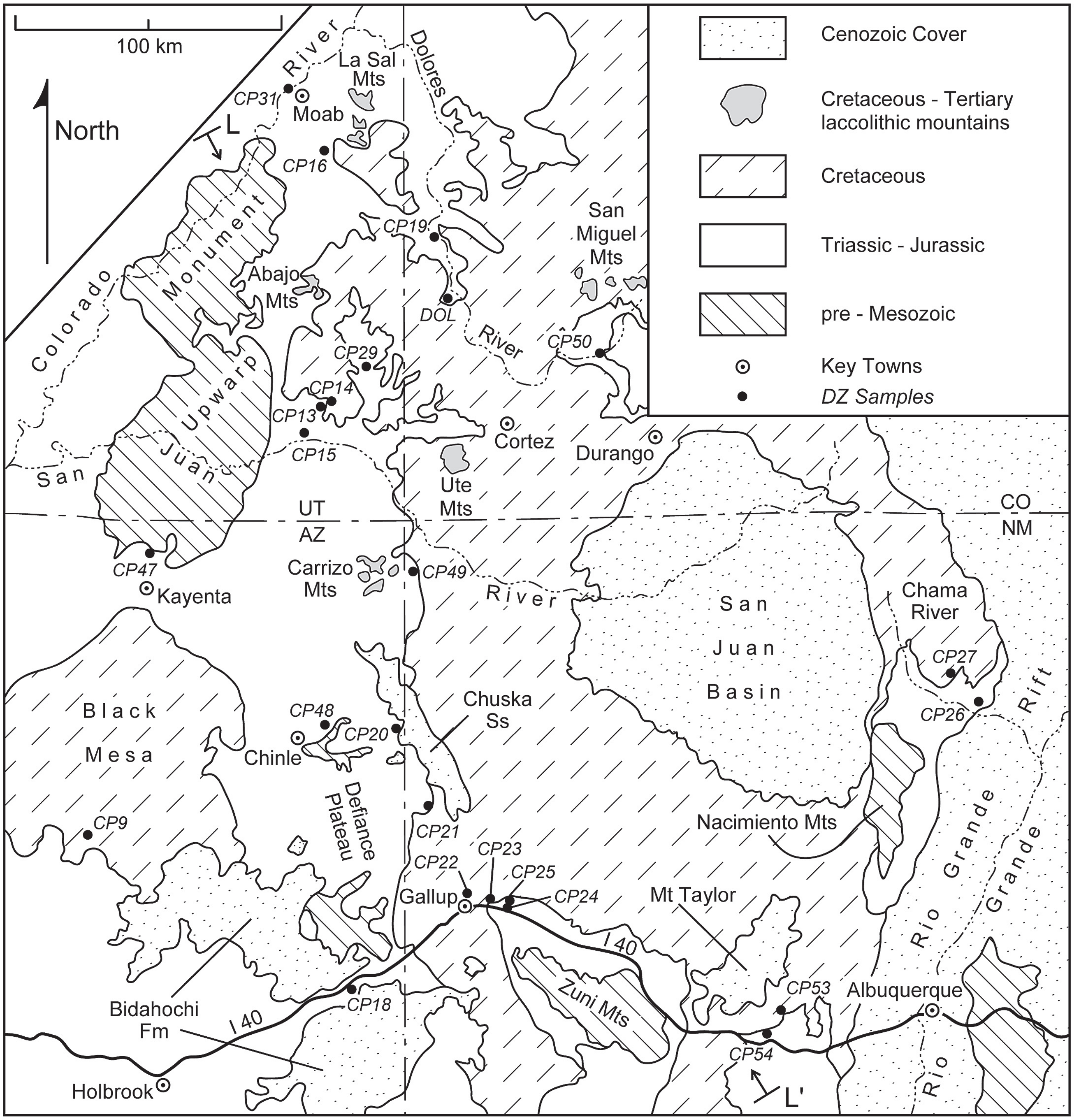

FIGURE 1. Detrital-zircon (DZ) localities in the Four Corners region. See Table 1 for stratigraphy. Bars with arrows (L-L') denote ends (N30W-S30E) of schematic stratigraphic section (Fig. 2).

rates contributions from anorogenic Mesoproterozoic (1450-1400 Ma) plutons intrusive into Yavapai-Mazatzal basement (Anderson, 1989). There is no hint, however, from the DZ age spectra of Mesozoic strata in the Four Corners region that any DZ contributions were recycled from pre-Mezozoic suspect terranes associated with Cordilleran arc assemblages farther north in California and Nevada (Dickinson and Gehrels, 2000).

The composite DZ signal recording derivation of detritus from the Appalachian-Ouachita region of eastern and southern North America is an association of age peaks for (a) Grenvillean (1250-

TABLE 1. Stratigraphy and geography of DZ samples from Mesozoic strata of the Four Corners region.

Symbol	Stratigraphic Unit	Geographic Location
CP9	Toreva Formation (upper sandstone member)	at Shungopovi AZ on Black Mesa
CP13	Westwater Canyon Member (Morrison Formation)	Recapture Creek near White Mesa UT
CP14	Burro Canyon Formation (Lower Cretaceous)	McCracken Mesa near White Mesa UT
CP15	Bluff Sandstone of San Rafael Group	on US Highway 191 near Bluff UT
CP16	Slick Rock Member of Entrada Sandstone	in Muleshoe Canyon near Moab UT
CP18	Shinarump Member (Chinle Formation)	on Highway I-40 near Sanders AZ
CP19	Salt Wash Member (Morrison Formation)	beside Dolores River near Slick Rock CO
CP20	Sonsela Sandstone Member (Chinle Formation)	on Navajo Route 12 near Black Pinnacle AZ
CP21	Westwater Canyon Member (Morrison Formation)	off Twin Buttes Road near Todilto Park NM
CP22	Menefee Formation of Mesaverde Group	on US Highway 491 north of Gallup NM
CP23	Gallup Sandstone Member of Mancos Shale	hogback off Highway I-40 east of Gallup NM
CP24	Slick Rock Member of Entrada Sandstone	on Church Rock Road east of Gallup NM
CP25	Recapture Member (Morrison Formation)	off Church Rock Road east of Gallup NM
CP26	Poleo Formation of Chinle Group	on US Highway 84 near Abiquiu Dam NM
CP27	Burro Canyon Formation (Lower Cretaceous)	on US Highway 84 near Ghost Ranch NM
CP29	Salt Wash Member (Morrison Formation)	Montezuma Canyon near Monticello UT
CP31	"Black Ledge Sandstone" (basal Glen Canyon Group)	cliff near mouth of Moab Canyon UT
CP47	Shinarump Member (Chinle Formation)	south edge of Monument Valley AZ
CP48	Shinarump Member (Chinle Formation)	on Navajo Route 164 near Canyon de Chelly AZ
CP49	Salt Wash Member (Morrison Formation)	south side of Beclabito Dome NM
CP50	Dolores Formation (lower member = Moss Back)	on Dolores River between Dolores and Rico CO
CP53	Jackpile Sandstone (=Burro Canyon Formation)	edge of Clay Mesa near Paguate NM
CP54	Bluff Sandstone ("sandstone at Mesita")	on NM Highway 124 at Laguna NM
DOL	Kayenta Formation of Glen Canyon Group	in Big Creek tributary to Dolores River CO

950 Ma) grains derived either directly from Grenville basement rocks or recycled from deformed miogeoclinal, foreland, or remnant-ocean successions derived from Grenville sources, (b) Neoproterozoic to Early Cambrian (750-510 Ma) grains derived either from accreted peri-Gondwanan terranes or pre-Iapetan rift plutons, and (c) Paleozoic (500-285 Ma) grains derived from either native or accreted Paleozoic magmatic arcs. Bedrock sources for DZ grains in the age range of 1250-285 Ma are absent or severely limited in western North America (Whitmeyer and Karlstrom, 2007; Dickinson and Gehrels, 2009a).

Age peaks for Mesoproterozoic Grenvillean (1250-950 Ma) and anorogenic granite (1450-1400 Ma) sources are doubtless enhanced by the high zircon fertility of granitic rocks of those ages in North America (Dickinson, 2008). If plutons in magmatic arcs of varied ages (Archean, Paleoproterozoic, Neoproterozoic, Paleozoic, Mesozoic) are assigned a zircon fertility factor (ZFF) of 1.0 based on their mean Zr content, then collision-related Grenville plutons have mean ZFF=3.5 and anorogenic granite plutons, as well as rift-related pre-Iapetan plutons, have mean ZFF=2.5. For provenances containing source rocks with high ZFF, the heights of relevant age peaks on DZ age-distribution curves are higher relative to other age peaks than proportions of total detritus would dictate. In effect, ZFF amplifies the DZ signals for both Grenvillean and anorogenic or rift-related plutons. Grenvillean age peaks are also inordinately broader, with less sharply defined crests, than other age peaks because age uncertainties for individual DZ grains are greatest in the Grenvillean age range (see above).

UPPER TRIASSIC–LOWER JURASSIC FLUVIAL STRATA

Figure 4 shows the heterogeneous age spectra of DZ grains derived largely from distant Appalachian and Ouachita provenances in Upper Triassic (Chinle, "Black Ledge") and Lower Jurassic (Kayenta) fluvial sandstones of the Four Corners region. A Ouachita provenance (Gleason et al., 2007) influenced Chinle-Dockum sedimentation from uplift of the Ouachita system on the northern shoulder of Texas rift highlands that were antecedent to Jurassic opening of the Gulf of Mexico (Dickinson et al., 2009a). All the samples of Figure 4 display prominent Grenvillean (1300-900 Ma) and Neoproterozoic-Paleozoic (750-300 Ma) subpopulations, whether of Appalachian or Ouachita parentage. Minor arc-derived grains (<285 Ma) from the Cordilleran flank of the continent are ubiquitous but subordinate. The DZ age spectra of Shinarump (basal Chinle) sandstones display more prominent 1500-1350 Ma age peaks, reflecting derivation from anorogenic granite plutons intrusive into the Yavapai-Mazatzal belt, than do the DZ age spectra of the other samples. This relationship probably reflects contributions from southern tributaries of the Shinarump trunk paleoriver (Fig. 3A). Other samples from farther north along the Cottonwood paleovalley (Fig. 3A), and within

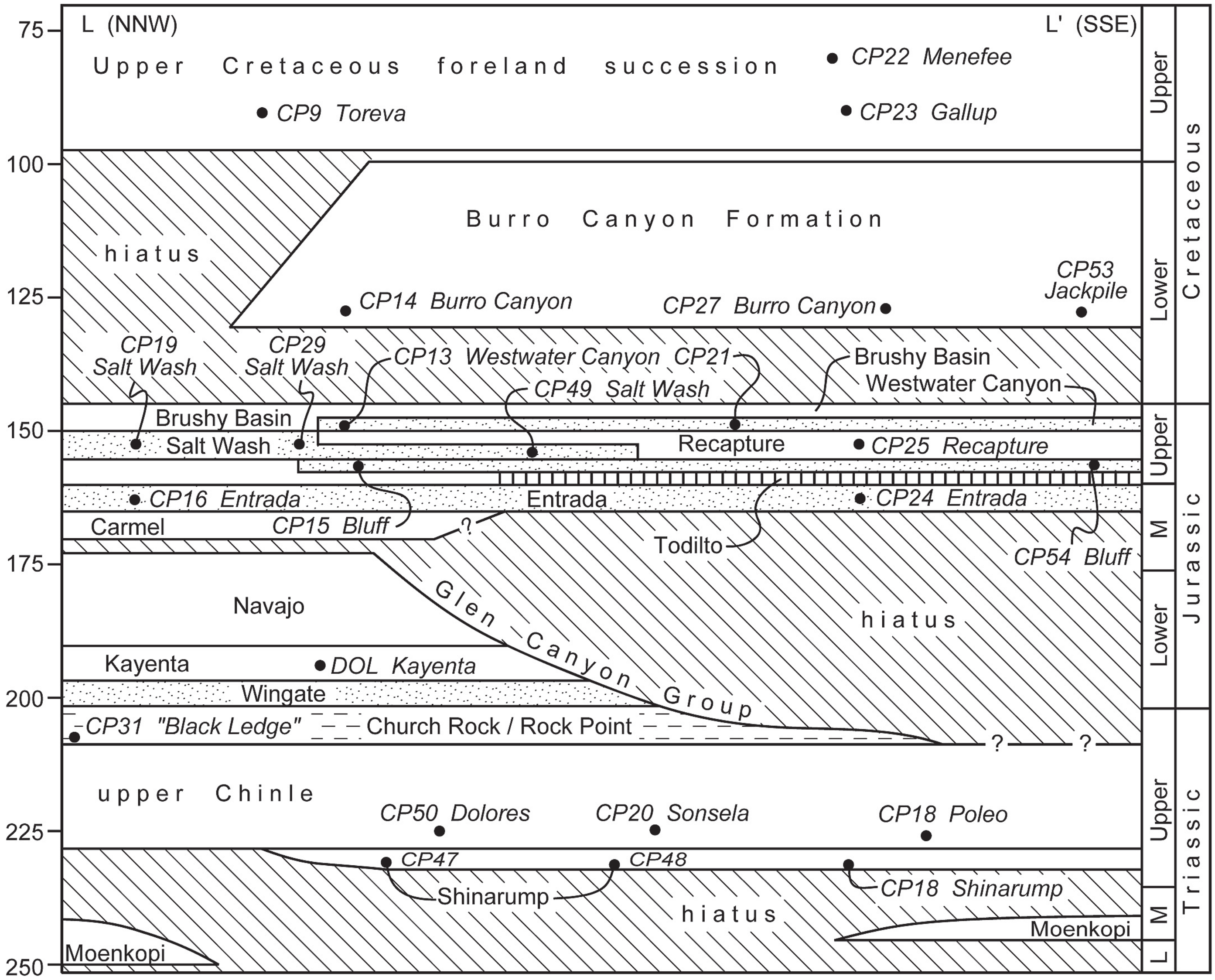

FIGURE 2. Stratigraphic positions (schematic) of DZ samples (Table 1) from Mesozoic strata of the Four Corners region. Localities projected at right angles to line of section L-L' (Fig. 1) oriented N30W-S30E. Chronostratigraphy after Walker and Geissman (2009). Stipples denote dominantly sandstone units.

younger "Black Ledge"-Kayenta fluvial systems, evidently did not receive detritus from the south in comparable measure. The Shinarump samples also contain smaller subpopulations of Neoproterozoic grains than the other samples. In general, however, the curves of Figure 4 fail to document any robust distinctions in provenance.

Of special note is the observation that the "Black Ledge" sandstone at the base of the Church Rock Member (or Formation) of the Chinle Formation (or Group), which is the lateral analogue in Utah of the Rock Point Member (of the Wingate Sandstone or Chinle Formation) in Arizona, contains a cluster of 205-200 Ma DZ grains (Dickinson and Gehrels, 2009d) that define the maximum possible depositional age for the unit. This age span (Rhaetian) is younger than the Chinle age span (Carnian-Norian), and is compatible with our view (Dickinson and Gehrels, 2009a) that the Church Rock/Rock Point interval is better regarded as basal Glen Canyon Group than as part of the underlying Chinle Formation or Group (Fig. 2).

JURASSIC EOLIANITES

Our eolianite samples from Jurassic erg complexes of the Four Corners region include two from the Entrada Sandstone underlying Todilto lacustrine strata or their lateral equivalents, and two from the Bluff Sandstone overlying Todilto lacustrine strata or their lateral equivalents (Fig. 1-2; Table 1). Bluff eolianites have locally been assigned to the Cow Springs Sandstone, but we regard that stratal designation as inappropriate because the type Cow Springs Sandstone is a bleached upper part of the Entrada Sandstone (Dickinson and Gehrels, 2009a). Entrada and Bluff eolianites display heterogeneous DZ age spectra analogous to age spectra for underlying and overlying fluvial units (Figs. 5-6),

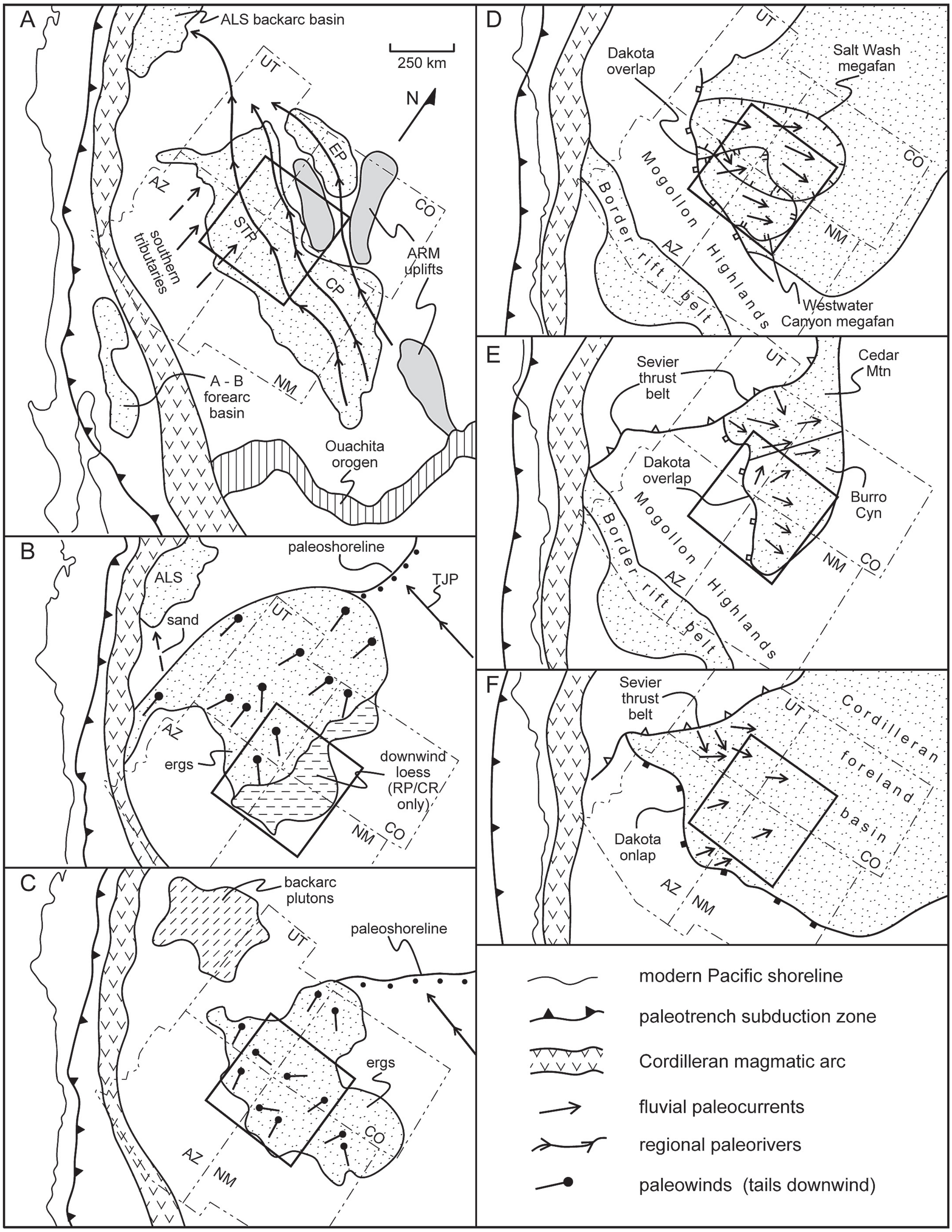

FIGURE 3. Regional context of key Mesozoic depositional systems in the Four Corners region (bold square denotes study area and stipples indicate outcrop-subcrop of key strata) adapted after Dickinson and Gehrels (2009c): A, Upper Triassic Chinle-Dockum fluvial system (CP, Cottonwood paleovalley; EP, Eagle paleoriver; STR, Shinarump trunk paleoriver); B, Lower Jurassic Glen Canyon ergs (Wingate-Navajo); C, Middle (to Upper) Jurassic San Rafael ergs (Entrada-Bluff); D, Upper Jurassic Morrison foreland megafans and associated strata; E, Lower Cretaceous Cedar Mountain-Burro Canyon fluvial system; F, Upper Cretaceous marginal-marine to marine foreland basin. Selected states: AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah. Other abbreviations: A-B, Antimonio-Barranca; ALS, Auld Lang Syne; ARM, Ancestral Rocky Mountains.

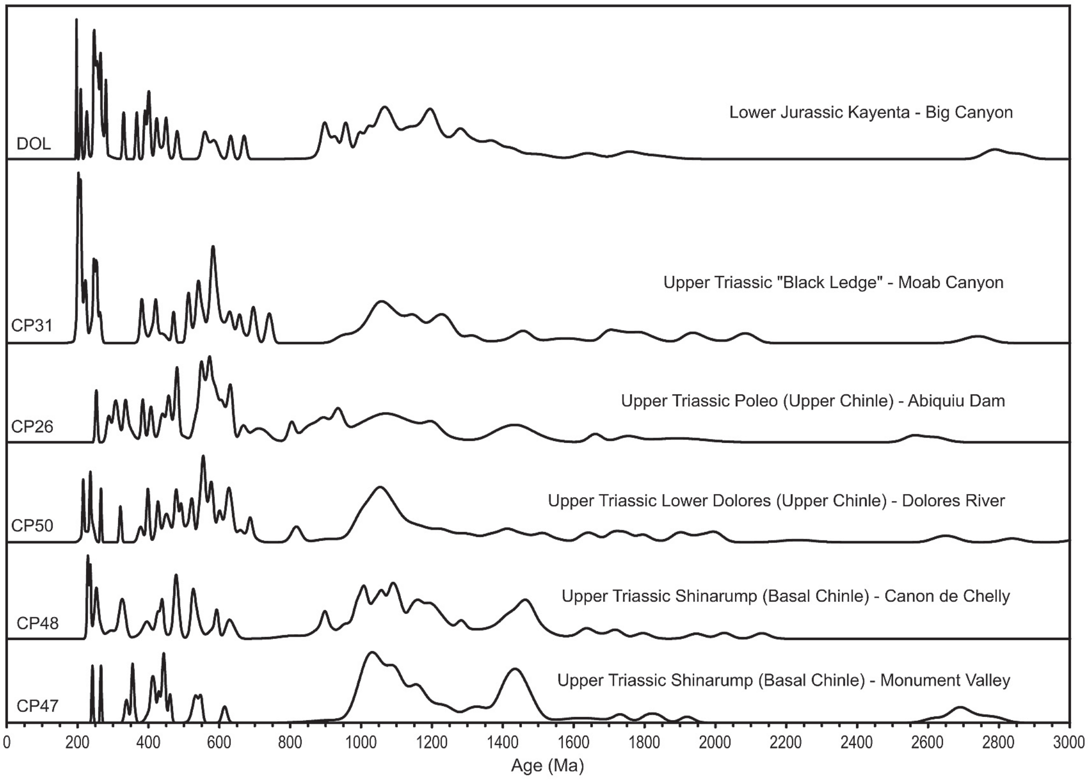

FIGURE 4. Heterogeneous DZ age spectra (age-distribution curves) for selected Upper Triassic and Lower Jurassic fluvial strata. Sample numbers (Table 1) on left.

and similarly indicative of ultimate DZ sources in distant provenances of southeast Laurentia. The Bluff Sandstone has been assigned alternately to either the uppermost San Rafael Group or the basal Morrison Formation (Dickinson and Gehrels, 2009a), but DZ populations provide no means to resolve that stratigraphic controversy (Fig. 6).

The large subpopulations of Grenvillean Mesoproterozoic (1250-900 Ma) and Proterozoic-Paleozoic (650-300 Ma) DZ grains in Jurassic eolianites (Figs. 5-6) are inferred to have reached western Laurentia by transport down a persistent transcontinental paleoriver system, with headwaters in rift highlands of the nascent Atlantic Ocean, toward a Cordilleran paleoshoreline lying north and northeast of the Colorado Plateau (Fig. 3BC). Paleowinds deflated floodplains and deltas near the paleoshoreline to carry eolian sand into the Entrada erg (southerly to southwesterly paleowind vectors of Figure 3C), with subsequent redistribution of eolian sand into the younger Bluff erg (easterly to northeasterly paleowind vectors of Figure 3C). A similar transcontinental fluvial-eolian system for sediment transport was operative for older Permian eolianites of the Colorado Plateau derived largely from the Appalachian orogen (Dickinson and Gehrels, 2003).

Arc-derived grains of Cordilleran origin were admixed with eolian sand of more distant provenance, either by fluvial delivery to the transcontinental paleoriver system through southern tributaries heading in northeastern Mexico (for the Entrada Sandstone) or by airborne transport of ash from the west or southwest (for the Bluff Sandstone). Fluvial redistribution of eolian sand into “Black Ledge” and Kayenta sandstones, coupled with analogous admixture of arc-derived grains, is inferred to account for the close similarity of DZ age spectra for Entrada-Bluff eolianites and the older fluvial sandstones (Figs. 4-5).

UPPER JURASSIC–LOWER CRETACEOUS FLUVIAL STRATA

DZ age spectra in samples from the Upper Jurassic Morrison Formation reflect two different provenances (Fig. 7). Heterogenous DZ populations in the Salt Wash Member and the laterally equivalent Recapture Member resemble the DZ populations of underlying Jurassic eolianites (Fig. 6), whereas more restricted DZ populations in the Westwater Canyon Member lack significant subpopulations of Grenvillean, Neoproterozoic, or Paleozoic grains. Westwater Canyon age spectra instead display prominent peaks for Yavapai-Mazatzal (1750-1550 Ma) and anorogenic granite (1500-1400 Ma) sources, and for arc-derived (<285 Ma) grains. Coupled with paleocurrent trends (Fig. 3D), these relationships suggest that most of the sand in the Salt Wash megafan was recycled from Jurassic eolianites uplifted near the tectonic syntaxis between the Sevier thrust belt or its antecedents on the west and the Mogollon paleohighlands forming the rift shoulder of the Border rift belt on the south (Fig. 3D), whereas the younger Westwater Canyon megafan was apparently derived from farther east in basement rocks and volcanic cover of the Mogollon paleohighlands.

K-S analysis for the four Salt Wash and Recapture samples yields $P \geq 0.20$ for all sample pairs (n=6), with mean $P=0.60\pm0.25$. K-S comparison of all grains in those four Morrison samples and in the four eolianite (Entrada-Bluff) samples yields $P=0.75$,

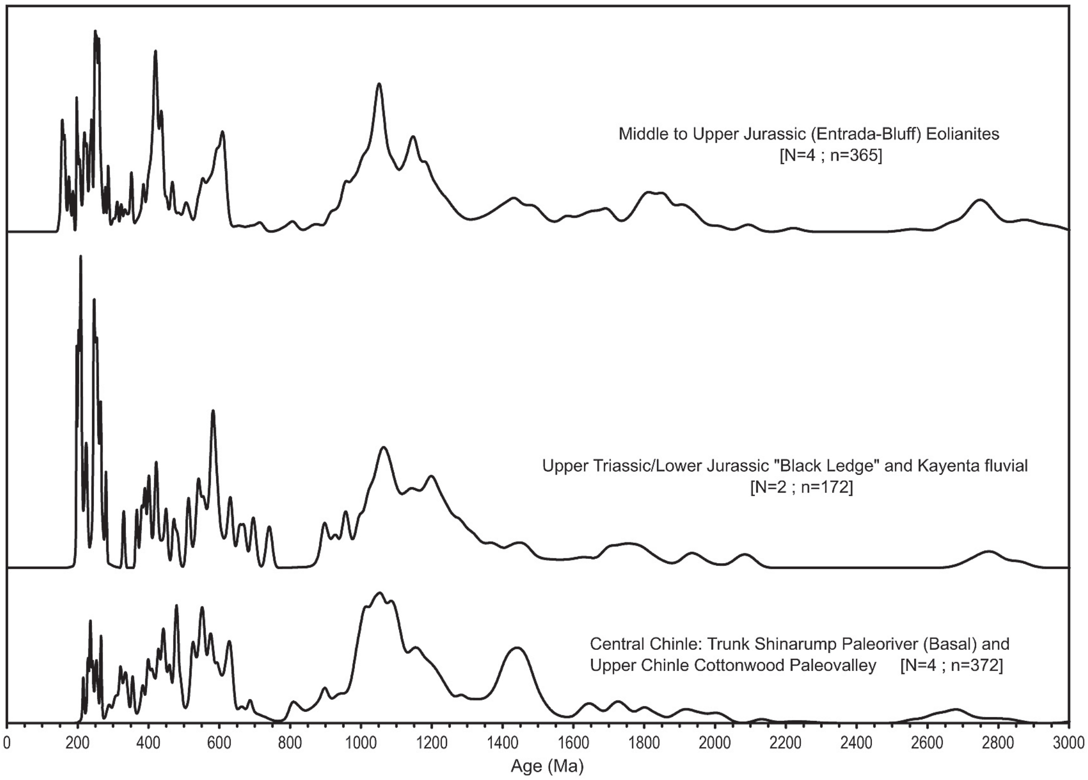

FIGURE 5. Aggregate DZ age spectra (age-distribution curves) for Jurassic eolianites (top) and selected Upper Triassic to Lower Jurassic fluvial strata (Fig. 4). Sample numbers (Table 1) on left. N=number of samples; n=number of DZ grains.

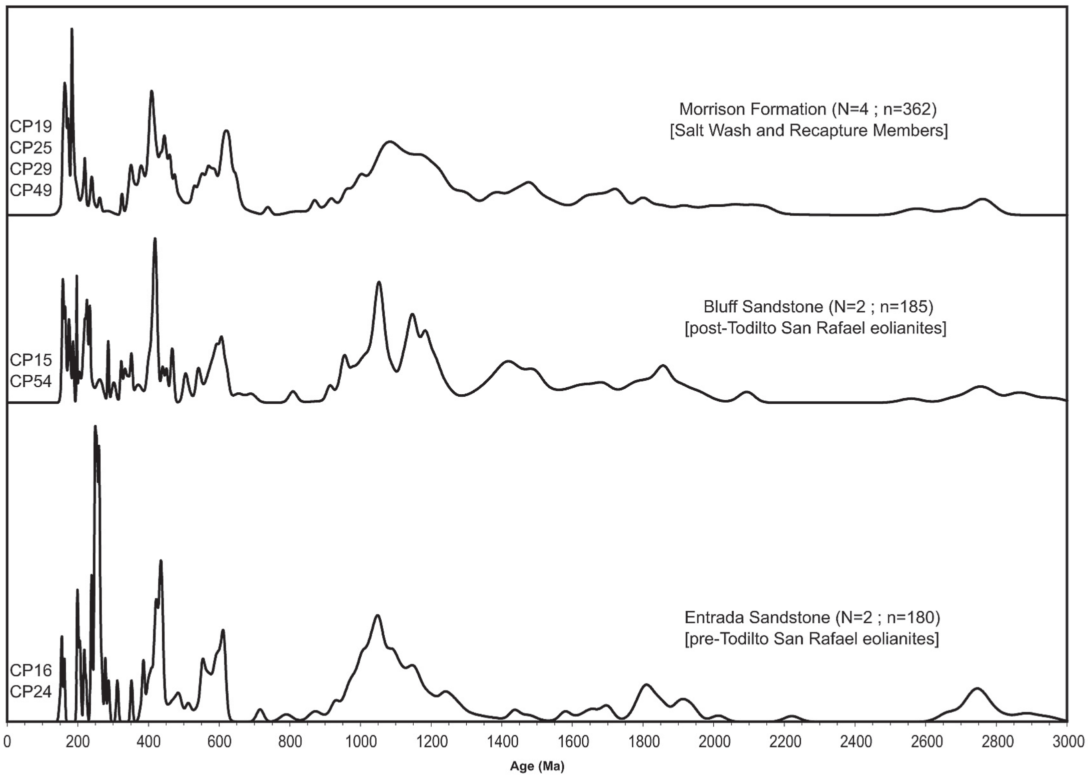

FIGURE 6. Aggregate DZ age spectra (age-distribution curves) for Jurassic eolianites (Entrada-Bluff) and sandstones of the Upper Jurassic Morrison Formation largely recycled from eolianite sources. Sample numbers (Table 1) on left. N=number of samples; n=number of DZ grains.

with P=0.53 for >285 Ma subpopulations. These statistical relationships confirm that Salt Wash and Recapture sand has a DZ signature appropriate for recycling of DZ grains from exposed Jurassic eolianites, with or without minor additional admixture of arc-derived (<285 Ma) grains. By contrast, Westwater Canyon sand (P≤0.03 from K-S comparison of either Westwater Canyon sample with any of the other Morrison samples) has a DZ signature appropriate for derivation from Mogollon basement coupled with admixture of arc-derived (<285 Ma) grains. Petrographic differences between Salt Wash and Westwater Canyon sandstones are also notable (Dickinson and Gehrels, 2008b). Our Salt Wash DZ samples contain 80%-90% quartz and <10% feldspar, whereas our Westwater Canyon DZ samples contain 20% feldspar and only 65%-70% quartz (QFL percentages).

DZ age spectra for samples of Lower Cretaceous fluvial sandstone in the Burro Canyon Formation display the heterogeneous character expected for recycling from Jurassic eolianites exposed as sedimentary cover along the Mogollon paleohighlands (Fig. 7). Quartzose Lower Cretaceous sandstone in the Cintura Formation of the Bisbee basin in the Border rift system lying south of the Mogollon paleohighlands was recycled as well from Jurassic eolianite cover over Mogollon basement (Dickinson et al., 2009b). Comparative K-S analysis for Cintura and Burro Canyon DZ populations yields P=0.43 for all DZ grains and P=0.94 for DZ grains >285 Ma, thus confirming a close similarity between detritus shed to the north and to the south off the Mogollon paleohighlands rift shoulder. The segment of the Mogollon paleohighlands stripped to basement at the Late Jurassic time of Westwater Canyon sedimentation clearly could not have been the segment still yielding detritus from sedimentary cover during Early Cretaceous Burro Canyon sedimentation. It seems most likely that the Westwater Canyon provenance lay farther west than the Burro Canyon provenance (Fig. 3DE), suggesting that the western Mogollon paleohighlands were eroded more deeply in Mesozoic time than the eastern Mogollon paleohighlands.

The Jackpile sandstone unit (CP53) near Laguna (Table 1) and its environs has long been treated as the uppermost local member of the Morrison Formation (Owen et al., 1984), but Aubrey (1992) concluded that the Jackpile unit is instead a local expression of the overlying Burro Canyon Formation. DZ analysis strongly supports the latter correlation (Fig. 7). K-S analysis indicates that P=0.985, almost statistical identity, for comparison of Jackpile DZ with Burro Canyon DZ from the Chama River (CP27), whereas comparison of either Jackpile or Burro Canyon DZ with Westwater Canyon DZ yields P≤0.01 in all cases (n=6 pairs). For our three Jackpile and Burro Canyon samples (CP14-CP27-CP53), K-S analysis yields P≥0.52 for sample pairs (n=3), with mean P=0.70±0.20.

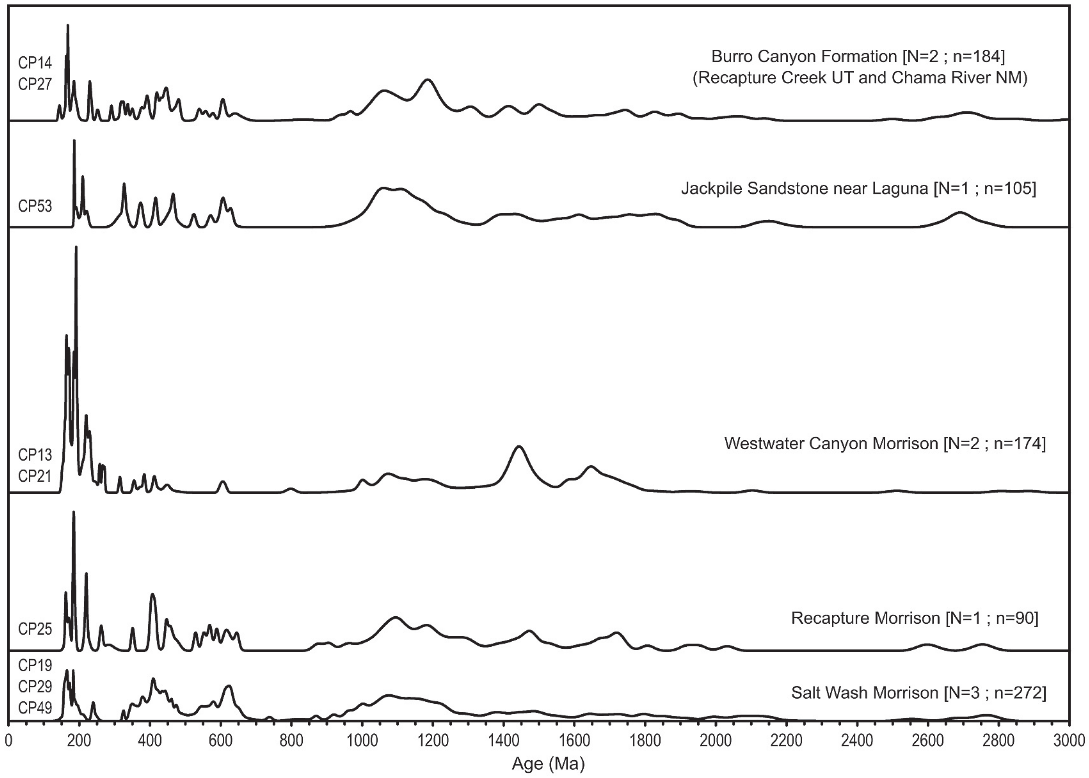

FIGURE 7. Varied DZ age spectra (age-distribution curves) for fluvial sandstones of the Upper Jurassic Morrison Formation and the Lower Cretaceous Burro Canyon Formation (Jackpile correlated with Burro Canyon). Sample numbers (Table 1) on left. N=number of samples; n=number of DZ grains.

UPPER CRETACEOUS FLUVIODELTAIC STRATA

Facies relationships indicate that Late Cretaceous fluviodeltaic systems along the flank of the interior Cretaceous seaway prograded into the Black Mesa and San Juan basins from the southwest (Fig. 3F). The DZ age spectra for samples of Upper Cretaceous (Turonian and Campanian) fluviodeltaic sandstone display prominent age peaks for Yavapai-Mazatzal Paleoproterozoic basement (1800-1600 Ma) and Mesoproterozoic anorogenic granite plutons (1450-1400 Ma) indicative of derivation from the Mogollon paleohighlands, but lack any Grenvillean Mesoproterozoic, Neoproterozoic, or Paleozoic age peaks reflective of Appalachian or Ouachita provenance. Analogous Yavapai-Mazatzal and anorogenic granite age peaks are present in older Morrison (Westwater Canyon) and southern Chinle samples also derived in large part from the Mogollon paleohighlands (Fig. 8). Twin age peaks for Yavapai-Mazatzal and anorogenic granite sources more prominent than Grenvillean or younger pre-Mesozoic age peaks are the apparent DZ signature of Mogollon provenance. In effect, age-distribution curves for DZ grains in sands derived from Mogollon basement constitute a recurring "bumpy barcode" (Link et al., 2005) indicative of sand origin.

Varied arc-derived DZ subpopulations (<285 Ma), derived from the Cordilleran magmatic arc that lay to the southwest beyond the Mogollon paleohighlands (Fig. 3F), are prominent in the Campanian Menefee sample but not in the Turonian Toreva and Gallup samples. The difference reflects blockage of sediment delivery across the Mogollon paleohighlands from the magmatic arc to the southwest until sedimentation had filled the Bisbee basin of the Border rift belt and erosion had subdued the rift shoulder represented by the Mogollon paleohighlands (Fig. 3F).

ARC-DERIVED (CORDILLERAN) DZ GRAINS

Only 331 DZ grains (15% of the total) are <285 Ma, the maximum age for derivation from the Cordilleran magmatic arc. With an average of only 14 arc-derived grains per sample, and only 11 per sample exclusive of the Upper Cretaceous Menefee sample (CP22), there is no opportunity to assess statistically their age distributions sample by sample. Age-distribution curves for arc-derived DZ grains in different age subsets of samples are instead shown by Figure 9. Three general relationships are evident. First, the ages of the youngest arc-derived grains tend to decrease as expected with stratal age, and the youngest in most age subsets approximate the depositional ages. Second, subpopulations of arc-derived grains span a broad range of ages in each age group of samples, indicating that the arc-derived grains are mainly detrital grains, derived from eroded arc assemblages, rather than being crystals of airborne ash. Third, there are essentially no arc-derived grains in the age interval of 140-115 Ma, a period during which past analyses of the arc assemblages of California and Baja California suggest a distinct null in arc activity (Dickinson and Gehrels, 2009c). Fourth, age peaks for arc-derived grains in the different age subsets of samples do not match closely in most instances, indicating derivation of the arc-derived grains from the

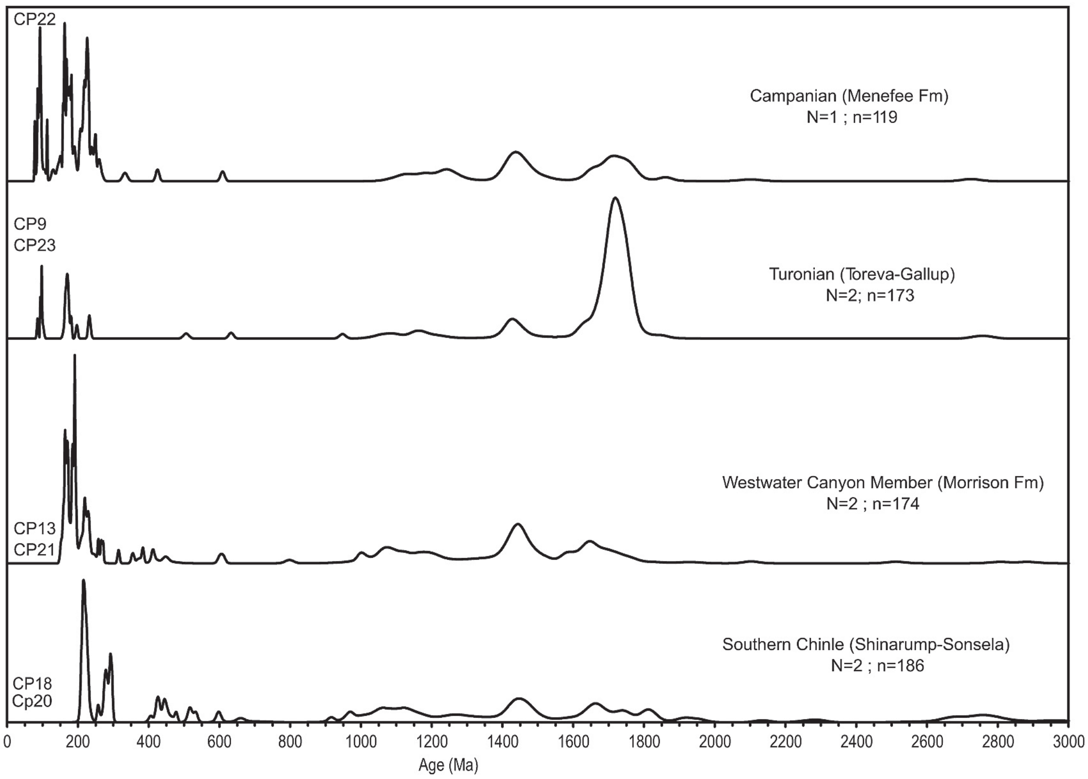

FIGURE 8. Comparative DZ age spectra (age-distribution curves) for sandstones of Mogollon provenance in the Four Corners region. Sample numbers (Table 1) on left. N=number of samples; n=number of DZ grains.

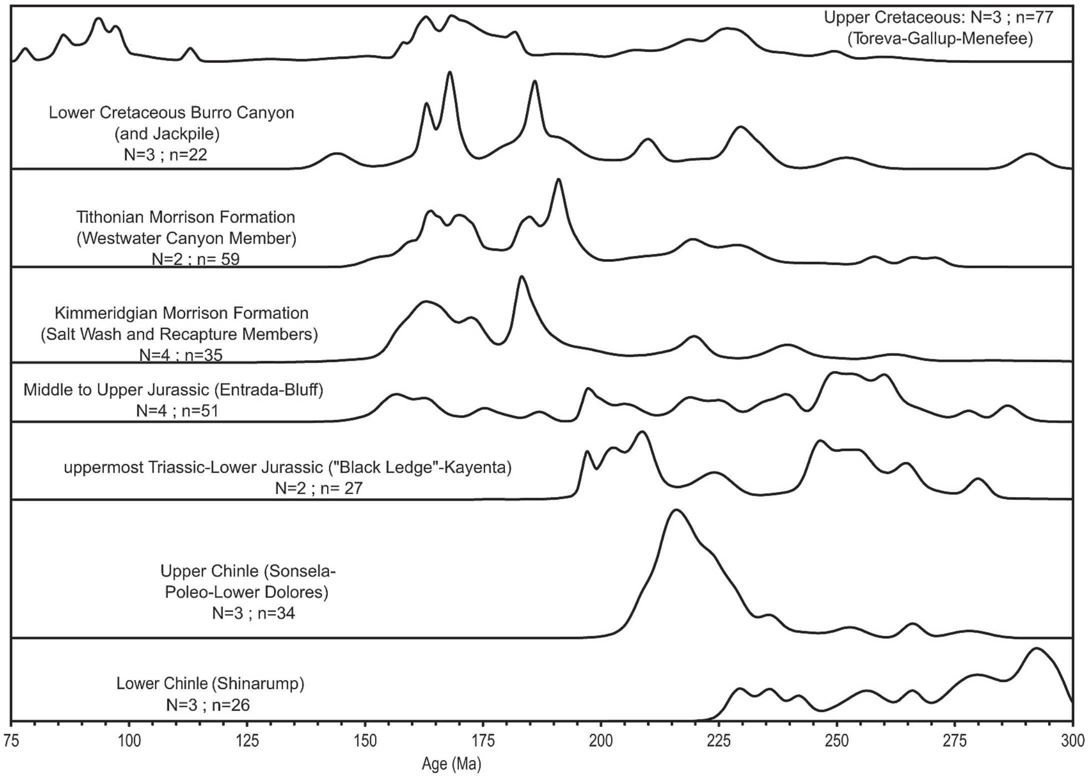

FIGURE 9. Age-distribution curves for arc-derived (Cordilleran) DZ grains (<285 Ma) in age subsets of sandstone samples from the Four Corners region. N=number of samples; n=number of DZ grains. Stratal ages (after Walker and Geissman, 2009): lower Chinle, 232-228 Ma; upper Chinle, 228-208 Ma; "Black Ledge"–Kayenta, 208-190 Ma; Entrada-Bluff, 166-156 Ma; Morrison, 156-146 Ma; Burro Canyon, 130-125 Ma; Upper Cretaceous, 92-89 Ma (Toreva-Gallup) and 81-75 Ma (Menefee).

erosion of heterogeneous arc assemblages that contributed varied age groups of zircon to depositional systems draining toward the Colorado Plateau.

SUMMARY CONCLUSIONS

U-Pb ages for individual DZ grains in Mesozoic strata of the Four Corners region shed fresh light on provenance relations over both space and time, but valid interpretations of provenance relations require keeping the possibility of recycling resistant DZ grains from older sedimentary strata constantly in mind. The ultimate bedrock sources for a high proportion of the DZ grains are located in the Appalachian and Ouachita regions of eastern and southern North America, with only 15% of the DZ grains derived from Cordilleran igneous assemblages of western North America. Without DZ analysis, the distal origin of such a large fraction of sedimentary detritus in Mesozoic strata of the Colorado Plateau would not be evident.

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