U-Pb ages of detrital zircons in Jurassic eolian and associated sandstones of the Colorado Plateau: Evidence for transcontinental dispersal and intraregional recycling of sediment

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ABSTRACT

U-Pb ages for 1655 individual detrital zircon grains in 18 samples of eolian and associated marine and fluvial sandstones of the Glen Canyon and San Rafael Groups from the Colorado Plateau and contiguous areas show light on patterns of Jurassic sediment dispersal within Laurentia. Most detrital zircon grains in Jurassic eolianites were derived ultimately from basement provinces younger than 285 Ma in eastern and central Laurentia, rather than from rock assemblages of the nearby Cordilleran margin. The most prominent peaks of constituent age populations at 420 Ma, 615 Ma, 1055 Ma, and 1160 Ma reflect derivation from Paleozoic, Neoproterozoic, and Grenvillian sources within the Appalachian orogen or its sedimentary cover. Sediment was transported to a position upwind to the north of the Colorado Plateau by a transcontinental paleoriver system with headwaters in the central to southern Appalachian region, but subordinate non-Appalachian detritus was contributed by both northern and southern tributaries during sediment transit across the continent. Subordinate detrital zircons younger than 285 Ma in selected Middle to Upper Jurassic eolianites were derived from the Permian-Triassic East Mexico and the Mesozoic Cordilleran magmatic arcs. Lower Jurassic fluvial sandstones typically contain a mixture of detrital zircons redistributed from eolian sand and derived from the East Mexico arc, which lay up-current to the southeast. Zircons in marine Curtis sandstone were largely reworked from underlying Entrada eolianite, with minor contributions from the Jurassic backarc igneous assemblage of the Great Basin. Once mature quartzose detritus was dispersed widely across southwest Laurentia by a transcontinental paleoriver system and paleowinds, which deposited extensive Jurassic ergs, durable zircon grains were recycled by multiple intraregional depositional systems. Lower Jurassic fluvial sand is locally composed, however, of detritus derived from the nearby Cordilleran magmatic arc assemblage and its Precambrian basement.

KEYWORDS: Colorado Plateau, detrital zircon, eolianite, Glen Canyon Group, provenance, San Rafael Group.

INTRODUCTION

Dickinson and Gehrels (2003) showed that typical Jurassic eolianites (eolian sandstones) of Colorado Plateau ergs (sand seas) contain age populations of detrital zircons derived from essentially all Precambrian and Paleozoic granitoid basement provinces of central and eastern Laurentia (Fig. 1), though a few Mesozoic zircon grains were derived from the nearby Cordilleran orogen. Sand was transported across the continent by a Jurassic paleoriver, which had its headwaters in the Appalachian province, to fluvial or deltaic plains lying north of the Colorado Plateau. From temporary sediment storage there, sand was then blown southward to growing Colorado Plateau ergs by paleowinds well known from eolian cross-bedding.

Our preliminary study was restricted to just three samples of Jurassic eolianite from a single stratigraphic section near the center of the Colorado Plateau, and it was inadequate to gauge the possible variability of detrital zircons in eolianites of various ages exposed across the length and breadth of the Colorado Plateau. For this study, we expanded analytical coverage to include seven more samples of Lower to Upper Jurassic eolianites distributed over >175 × 10^6 km^2 of the Colorado Plateau, correlative intra-arc eolianite of various ages exposed across the length and breadth of the Colorado Plateau, and it was inadequate to gauge the possible variability of detrital zircons in eolianites of various ages exposed across the length and breadth of the Colorado Plateau. For this study, we expanded analytical coverage to include seven more samples of Lower to Upper Jurassic eolianites distributed over >175 × 10^6 km^2 of the Colorado Plateau, correlative intra-arc eolianite from southern Arizona, and seven samples of fluvial and marine sandstones closely associated with erg deposits of the Glen Canyon and San Rafael Groups. We present here 1655 reliable U-Pb ages (concordant or nearly so) for individual zircon grains from 18 samples.

An evaluation of the enlarged database confirms transcontinental dispersal of sand to Jurassic ergs of the Colorado Plateau. Admixtures of grains derived from basement or magmatic arcs in southwestern North America are present, along with recycled eolian sand, in associated fluvial units, and these combinations occur as well in selected eolian units, including some either intercalated with arc volcanics or deposited by westerly winds. Recycling of eolian sand by intraregional depositional systems can be attributed to the durability of zircon grains in sedimentary environments. Nevertheless, documentation that voluminous sand of the central and eastern Laurentian provenance dominated Jurassic eolian deposits on the Colorado Plateau through a period of >40 m.y. indicates the persistence of an integrated system for transcontinental sediment dispersal.

Descriptions of sample localities (see Supplementary Text 1) and U-Pb age data for all samples discussed in this paper are included in accompanying data repositories. The tabulated analytical data (Supplementary Text 2) are supplemented by a concordia diagram for each sample and superimposed graphs of age-binned histograms and probability-density plots (age-distribution curves) for grains in each sample discussed in this paper are included in accompanying data repositories.
sample falling within the ranges of 0–4000 Ma, 0–800 Ma, and 800–2400 Ma (Supplementary Text 3). Preliminary U-Pb age data for three of the eolianite samples (Jwnw—Wingate; Jn—Navajo; Jen—Entrada) from North Wash in Utah (Dickinson and Gehrels, 2003) are superseded by data of improved precision and accuracy obtained during the present study (Gehrels et al., 2008). Preliminary data for other samples were presented by Amar and Brenneman (2005), Brenneman and Amar (2005), Hard and Schmidt (2005), Schmidt et al. (2005), Amar et al. (2006), Brenneman et al. (2006), and Dickinson et al. (2007). Comparative data for the Navajo Sandstone in Zion National Park were reported by Rahl et al. (2003).

ANALYTICAL METHODS

Samples of sandstone were collected in plastic buckets of five-gallon capacity as 22–24 kg of rock chips <10 cm in largest dimension from selected areas or horizons of the outcrops at sampling localities. Zircon crystals were extracted from samples by traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. Sample processing was designed to retain all zircon grains in the final heavy mineral fraction. A large split of these grains (generally 1000–2000) was incorporated into a 1 in. epoxy mount together with fragments of standard Sri Lanka zircon and SRM 610 trace-element glass. The mounts were sanded down to a depth of ~20 µm, polished, imaged, and cleaned prior to isotopic analysis.

For analysis by laser ablation, target zircons are preferably >35 µm (>0.035 mm) in diameter, or at least as coarse as very fine sand. Given the high specific gravity of zircon (4.65), as compared to quartz (2.65), hydraulically equivalent zircon is expected to be approximately one sand grade finer than accompanying quartz grains (Komar, 2007). Accordingly, we preferentially sought samples composed of medium quartzose sand because detrital zircon grains might be too small to occur in abundance with coarse quartz sand, but we were also able to date zircon grains from the two-thirds of our samples composed of fine quartzose sand.

Age Determination

U-Pb geochronology of ~100 individual zircon grains per sample was conducted by laser-ablation–multicollector inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the Arizona LaserChron Center (Gehrels et al., 2006). The analyses involve ablation of zircon with a New Wave DUV193 Excimer Laser (operating at a wavelength of 193 nm) using a spot diameter of 35 µm. The ablated material was carried in helium into the plasma source of a GVI Isoprobe, which was equipped with a flight tube of sufficient width that U, Th, and Pb isotopes could be measured simultaneously. All measurements were made in static mode, using Faraday detectors with 10e11 ohm resistors for 238U, 232Th, 206Pb, and 206Pb, a Faraday detector with a 10e12 ohm resistor for 208Pb, and an ion-counting channel for 204Pb. Ion yields were ~1.0 mv per ppm. Each analysis consisted of one 12-second integration on peaks with the laser off (for backgrounds), twelve 1-second integrations with the laser firing, and a 30-second delay to purge the previous sample and prepare for the next analysis. The ablation pit was ~12 µm in depth.

For each analysis, the errors in determining 206Pb/238U and 206Pb/208Pb resulted in a measurement error of ~1%–2% (at 2σ level) in the 206Pb/238U age. The errors in measurement of 206Pb/207Pb and 206Pb/208Pb also resulted in ~1%–2% (at 2σ level) uncertainty in age for grains older than 1000 Ma, but errors were substantially larger for younger grains due to the low intensity of the 207Pb signal. For most analyses, the crossover in precision of 206Pb/238U and 206Pb/207Pb ages occurs at ca. 1000 Ma.

Common Pb correction was accomplished by using the measured 204Pb and assuming an initial Pb composition from Stacey and Kramers (1975) with uncertainties of 1.0 for 204Pb/208Pb and 0.3 for 206Pb/208Pb. Our measurement of 204Pb was unaffected by the presence of 204Hg because backgrounds were measured on peaks (thereby subtracting any background 204Hg and 204Pb), and because very little Hg was present in the argon gas (background 204Hg = ~300 counts per second).

Interelement fractionation of Pb/U is generally ~20%, whereas fractionation of Pb isotopes is generally ~2%. In-run analysis of fragments of a large Sri Lanka zircon crystal (generally every fifth measurement) with known age of 564 ± 4 Ma (2σ error) was used to correct for this fractionation. The uncertainty resulting from the calibration correction was generally 1%–2% (2σ) for both 206Pb/238U and 206Pb/207Pb ages. Concentrations of U and Th were calibrated relative to the Sri Lanka zircon standard and SRM 610 trace-element glass, which contains ~460 ppm of each element.

Data Presentation

Full analytical data are reported in Supplementary Text 2 (ST2; see footnote 1). Age uncertainties (at 1σ) for individual grains in the data table include only measurement errors. Interpreted ages are based on 204Pb/238U for grains younger than 1000 Ma and 206Pb/207Pb for grains older than 1000 Ma. The division point for each sample is at a slightly different age near 1000 Ma to avoid splitting up age clusters of grains. In any case, age uncertainties are inherently greatest near 1000 Ma (Gehrels, 2000).

Analyses that were >30% discordant (by comparison of 206Pb/238U and 206Pb/207Pb ages) or >5% reverse discordant were not considered further (average of 92 grain ages retained per sample). The resulting interpreted ages are shown for individual samples on superimposed relative age-probability plots (from Ludwig, 2003) and age-bin histograms. For the latter, best estimates of ages are assigned arbitrarily to age bins of 20 m.y. each, starting at 0 Ma. The age-probability plots incorporate each age and its uncertainty (for measurement error only) as a normal distribution and sum all ages from a sample into a single curve. The resulting age-probability plots derived from the probability density function were made from an in-house Excel program (available from www.geo.arizona.edu/alc) that normalizes each curve according to the number of constituent analyses, such that each curve contains the same area, and then stacks the probability curves.

There is a temptation to regard the age-bin histograms as raw data and the age-probability plots as derivative curves, but the reverse is the case. Age uncertainties for some individual grains are larger than the widths of the age bins for the histograms, which are accordingly selective plots of the analytical data. By contrast, the age-probability plots take all age uncertainties into account (Vermeesch, 2004) and are accordingly here termed age-distribution curves because they display graphically all the analytical data. The value of the age-bin histograms is to provide a graphic impression of the numbers of grains associated with age peaks on the age-distribution curves and thereby allow age peaks, no matter how sharp, associated with only one or two grain ages to be discounted relative to age peaks, even if broad, associated with multiple grain ages. Age-bin histograms are omitted from age-distribution curves composited from multiple related samples.

Statistical Comparisons

Although age populations of detrital zircons in different samples can be compared by inspection of their respective age-distribution curves and age-bin histograms, it is difficult to gauge visually the degree of similarity or dissimilarity of any two age populations. We have found it useful to apply Kolmogoroff-Smirnoff (K-S) statistics (Press et al., 1986, p. 472–474) to intersample
If the permissive extent of Jurassic ergs is taken into account, exposures of eolianite contiguous with outcrops on the Colorado Plateau may represent just a relict fraction of eolian sand that summed to a total volume approaching $250 \times 10^3$ km$^3$ across southwest Laurentia as a whole. As the Jurassic ergs mantled sub-stratum continuously throughout their extent, a super-regional system for sediment dispersal was required to deliver the voluminous sand to the erg accumulations from outside the erg boundaries. Because the eolian sand is $\approx 85\%$ quartz (see following), and quartz forms only a third or less of typical granite rocks by volume, perhaps 250 to $650 \times 10^3$ km$^3$ of granite bedrock was eroded to produce the eolian sand in Colorado Plateau and related Jurassic eolianites.

Glen Canyon Group

Over the central Colorado Plateau, a distinctive formational triad (eolian Wingate Sandstone, fluvial Kayenta Formation, eolian Navajo Sandstone) is typical of the Glen Canyon Group (Fig. 3). To the north, the fluvial Kayenta Formation (Miall, 1988) pinches out in the subsurface of the Uinta Basin (Fig. 2A), and the unbroken eolian succession farther north, along the south flank of the Uinta Mountains, is equivalent to the Nugget Sandstone of Wyoming (Johnson and Johnson, 1991). To the southwest (Fig. 2A), eolian Wingate Sandstone intertongues with fluvial deposits of the Moenave Formation (Blakey, 1989, 1994; Peterson, 1994), and the Navajo Sandstone is termed the Aztec Sandstone in exposures southwest of the Colorado Plateau (Stewart, 1980). The Springdale Sandstone Member (Fig. 3) was long regarded as the uppermost member of the Moenave Formation (Harshbarger et al., 1957; Blakey, 1989), but it is now widely regarded as a lowermost member of the Kayenta Formation (Riggs and Blakey, 1993; Lucas et al., 2005; Lucas and Tanner, 2006; Kirkland and Milner, 2006; Tanner and Lucas, 2007).

Basal Contact

The eolian Wingate Sandstone is underlain by a red-bed interval, dominantly silstone, that was named the Rock Point Member of the Wingate Formation in Arizona (Harshbarger et al., 1957) and the Church Rock Member of the Chinle Formation in Utah (Stewart, 1957), with an arbitrary change in stratigraphic nomenclature near the Arizona-Utah border (Stewart et al., 1972; Blakey and Gubitosa, 1983; Dubiel, 1989). The same stratigraphic interval in southwestern Colorado forms the upper member of the Dolores Formation (Dubiel, 1989; Lucas et al., 1997; Lucas and Heckert, 2005), and lithologically similar strata farther north have been termed red siltstone, ocher siltstone, and upper members of the Chinle Formation (Stewart et al., 1972; Dubiel, 1992). To resolve the nomenclatural dichotomy, the Rock Point–Church Rock interval has been termed the Rock Point Formation (Lucas and Hunt, 1992; Lucas and Heckert, 2005), but that usage is not universal. The Rock Point Formation is widely exposed eastward beyond the limit of Glen Canyon erg deposition (Fig. 2A), and it locally interfingers upwind toward the northwest with the overlying Wingate Sandstone (Harshbarger et al., 1957).

The contact between the Chinle Group (or Formation) and the Glen Canyon Group is commonly placed at the base of the Wingate Sandstone where desiccation mud cracks in the top of the underlying Rock Point Member.
Figure 2. Distribution and facies of (A) uppermost Triassic to Lower Jurassic Glen Canyon Group and (B) Middle Jurassic to lowermost Upper Jurassic San Rafael Group within and near the Colorado Plateau (shaded outline) in relation to sample localities (crosses): prefix CP not affixed to numerical sample numbers. D—sample DOL; N—North Wash samples (Jwnw, Jnnw, Jennw). Subsurface limit of post-Todilto (Bluff) erg near Four Corners (conjunction of Arizona–Utah–Colorado–New Mexico) is adapted after Lupe (1983). Paleowinds are after Peterson (1988b), and fluvial paleocurrents are after Luttrell (1993, 1996). Positions of magmatic arc are after Dickinson (2004), retroarc Luning-Fencemaker thrust belt is after Wyld (2002), backarc magmatism is after Dickinson (2006), and Utah-Idaho trough is after Peterson (1972). Cities: A—Albuquerque; F—Flagstaff; G—Grand Junction; L—Las Vegas; P—Phoenix; S—Salt Lake City. (Continued on following page.)
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Figure 2 (continued).
Figure 3. Regional stratigraphic relations (thicknesses approximate) of sampled erg eolianites and associated strata of Jurassic Glen Canyon and San Rafael Groups (Colorado Plateau). Solid dots represent stratigraphic positions of samples collected for detrital zircon analysis. Chronostratigraphic correlations (dashed lines) are inferred from limited fossil control. Stratigraphic abbreviations: BL—"Black Ledge" sandstone; CF—Curtis Formation; MT—Moab Tongue; RP/CR—Rock Point–Church Rock interval (Rock Point Formation); RS—Romana Sandstone; SSM—Springdale Sandstone Member (of Moenave Formation or of Kayenta Formation); TC—Temple Cap Sandstone; TF—Todilto Formation. Map key at upper right shows locations of columns A–F. States: AZ—Arizona; CO—Colorado; NM—New Mexico; NV—Nevada; UT—Utah.
other fluvial strata of the group. The Glen Canyon Group, and we sampled it for Rock Point–Church Rock interval in central belt. Accordingly, we regard the “Black Ledge” formation before transit of Laurentia into the desert represents the final phase of Chinle sedimentation (Tanner, 2000, 2003), and Owl Rock deposition arid environments during Chinle sedimentation.

103 km² of the Wingate erg lying to the northeast of Chinle pedogenesis reflects increasingly carbonate beds reflecting deposition on water.

Owl Rock Member (or Formation) of the Chinle in wadi-like arid environments. Both rest on the Owl Rock Member (or Formation) of the Chinle Formation (or Group), which includes palustrine carbonate beds reflecting deposition on waterlogged floodplains (Tanner, 2000). The record of Chinle pedogenesis reflects increasingly arid environments during Chinle sedimentation (Tanner, 2000, 2003), and Owl Rock deposition represents the final phase of Chinle sedimentation before transit of Laurentia into the desert belt. Accordingly, we regard the “Black Ledge” sandstone (8–14 m thick) at the base of the Rock Point–Church Rock interval in central Utah (Figs. 2A and 3) as a basal sandstone of the Glen Canyon Group, and we sampled it for detrital zircons for comparison with those from other fluvial strata of the group.

Kayenta Interval

During Early Jurassic time, the Kayenta fluvial system spread northward over >100 × 10³ km² of the Wingate erg lying to the northeast of the Moenave fluvial tract. Readvance of Glen Canyon dune fields subsequently prograded the Navajo–Aztec erg back southward over the Kayenta facies tract (Figs. 2A and 3). Despite its wide extent, the Kayenta Formation averages only 60 m (range 40–90 m) in thickness (aspect ratio >5000:1). Consistent paleocurrent indicators document fluvial transport of Kayenta sand westward to northwestward in a regionally integrated pattern (Luttrell, 1993, 1996). The direction of fluvial sand transport (Fig. 2A) implies lateral expansion, rather than progradation, of fluvial deposition over the Wingate erg, as fluvial sedimentation spread northward from the Moenave facies tract during Kayenta deposition.

An unconformity (“J-sub-K”) has been postulated locally at the base of the Kayenta Formation (Riggs and Blakey, 1993), but the Wingate-Kayenta contact is widely reported as gradational or even intertonguing over wide areas (Doelling, 2003; Morris et al., 2003). Preservation of the Wingate Sandstone as a sheet-like body, 60–150 m thick over 100 × 10³ km² (aspect ratio ~3500:1), implies that any sub-Kayenta erosion of the erg complex was limited. Aggradation of the Moenave fluvial succession adjacent to the Wingate erg may have elevated the land surface enough to allow streamflow to overtop the erg and spread fluvial Kayenta deposition across its undulating surface. Saturation of dune sand by lateral percolation of groundwater from the Moenave fluvial environment may have prevented deflation of dune sand and thereby aided preservation of the Wingate erg accumulation beneath the aggrading Kayenta fluvial system.

Thickness Relations

The regional parallelism of the upper and lower contacts of the eolian Wingate Sandstone and the overlying fluvial Kayenta Formation is striking but unexpected, for there is no evident sedimentological reason why the surface of an erg accumulation should have the regional slope of a fluvial system. The explanation for the consistent Wingate-Kayenta thicknesses may lie in the relationship of the Wingate erg to the substratum formed by Chinle floodplains in a direction subparallel to paleoflow in the Kayenta fluvial system. If Chinle rivers had an average slope of 6 × 10⁻⁴ (Heller et al., 2003), relief on the subjacent Chinle floodplain across the span of Wingate deposition would have been ~250 m, or two to three times the mean thickness of the Wingate erg. This relation implies that the Wingate erg formed only a veneer of dune sand covering a fluvially constructed ramp, and that overtopping of the Wingate erg by the Kayenta fluvial system allowed streamflow to resume in the same direction and at the same gradient as before erg construction.

By contrast, the Navajo Sandstone thickens systematically westward from <100 m in western Colorado to >300 m in southwestern Utah (Fig. 3), where the flank of the Navajo erg was buried beneath marine to marginal-marine Middle Jurassic strata. This onlap of the thickest part of the erg by strandline sedimentation implies that the westward increase in net erg thickness does not reflect westward increase in the elevation of the erg surface. Dynamic backarc subsidence (Mitrovica et al., 1989) behind the Cordilleran magmatic arc was apparently required to control the Navajo erg depocenter and to carry the thick flank of the erg below sea level (Allen et al., 2000).

Glen Canyon–San Rafael Transition

The Navajo Sandstone (Glen Canyon Group) is overlain over most of the Colorado Plateau by the Carmel Formation (San Rafael Group), which is composed of finer-grained strata that record eastward transgression of marine, marginal-marine, and associated coastal-plain deposits over the erg complex (Fig. 3). In southwestern Utah, however, tongues of the Carmel Formation intertongue eastward with eolianite of the Page Sandstone, which locally overlies the Navajo Sandstone (Figs. 2B and 3). The Navajo–Page contact has been termed the J-2 unconformity (Pipiringos and O’Sullivan, 1978), beneath which subjacent sandstone is polygonally fractured. Polygonal disruption of Navajo dune sand below the contact was initially interpreted as jointing in consolidated rock (Peterson and Pipiringos, 1979), but Kocurek and Hunter (1986) showed that the polygonal fracturing is the record of desiccation cracking on an exposed evaporite-encrusted surface that formed within an evolving erg during an episode of deflation to the water table. The J-2 surface is a diastem marking a hiatus of uncertain duration, but it is not a regional unconformity (Anderson and Lucas, 1994).

We accordingly view the Page erg as a rejuvenation of the Navajo erg, but we did not sample the thin local erg of the Temple Cap Sandstone (Peterson and Pipiringos, 1979), which occupies an analogous stratigraphic position farther west but nowhere occurs in the same stratigraphic succession as the Page Sandstone (Figs. 2B and 3). Polygonally fractured horizons marking superfluvial surfaces of temporary deflation analogous to the basal J-2 surface are present at multiple horizons within the Page Sandstone (Havholm et al., 1993; Havholm and Kocurek, 1994) and reflect repetitive flooding of the Page erg during intermittent but progressive Carmel transgression, which eventually overtopped the erg (Fig. 3). The most prominent superfluvial surfaces correlate with tongues of Carmel Formation that intertongue with different members of the Page Sandstone (Blakey et al., 1996).

San Rafael Group

The San Rafael Group can be divided into lower and upper stratal assemblages; the contact between them occurs at the base of the marine Curtis Formation in Utah (the J-3 unconformity of Pipiringos and O’Sullivan, 1978) and the
broadly correlative Todilto Formation deposited in a nonmarine salina farther to the southeast (Fig. 3), or at the top of the Entrada Sandstone across an intervening belt where neither of those two distinctive units is present (Fig. 2B). Thick eolianites occur in both assemblages and form the widespread Entrada erg and the younger (post-Todilto) and more restricted Bluff erg (Fig. 2B). Marine sandstone of the Curtis Formation was also sampled to compare its zircon age spectrum to that of underlying eolian sandstone.

**Lower Assemblage**

The Carmel Formation at the base of the San Rafael Group grades and thins eastward from largely marine strata (subtidal) on the west to thinner marginal-marine (intertidal) and nonmarine (supratidal) red beds on the east (Blakey, 1994). To the southeast, thin distal tongues of Carmel lithology (Fig. 3) are commonly regarded as basal members of the overlying Entrada Sandstone. The Entrada Sandstone is an internally heterogeneous assemblage of cross-bedded dune sand, flat-bedded eolian sand sheets, interdune sabkha deposits, and erg-margin red beds (Kocurek, 1981; Carr-Crabaugh and Kocurek, 1998). Polygonally fractured super-bounding surfaces commonly separate dune successions from sabkha intervals and attest to temporary episodes of deflation at times of rising water tables during evolution of the Entrada erg. Across Utah, Entrada eolianites (“slickrock facies”) grade westward (Fig. 2B) to an “earthy facies” of finer-grained strata, including water-laid deposits of coastal sabkhas and tidal flats developed along a dune-fringed palaeoshoreline (Mariño and Morris, 1996).

The lower San Rafael Group (Carmel-Entrada) thickens from <100 m on the eastern Colorado Plateau to almost 500 m along its western fringe near the Utah-Idaho trough (Fig. 2B), within which ~1500 m of correlative Middle Jurassic marine strata overlie the Nugget Sandstone (Glen Canyon Group). Several tectonic interpretations have been offered for development of the Utah-Idaho trough, but none is yet fully satisfactory. These include: (1) a retroarc foredeep (Bjerum and Dorsey, 1995), but the basin keel lies 500 km from the nearest known coeval retroarc thrust system (Fig. 2B); (2) a backbulge basin (DeCelles and Currie, 1996), but the stratal thickness in the basin seems excessive for such an origin; and (3) a backarc rift basin (Dickinson, 2006), but postulated bounding faults are buried in the subsurface and difficult to evaluate. In any case, westward thickening of the tapering wedge of lower San Rafael strata across Utah can be attributed to the flexural effect of the thick sediment load within the Utah-Idaho trough.

Eastward from the central Colorado Plateau, beyond the flexural influence of the sediment load in the Utah-Idaho trough, the Entrada Sandstone forms a thin sediment blanket, <25 m thick, on the High Plains (Lucas, 2004) over a lobate area of at least 150 × 10³ km², extending as far as the Oklahoma panhandle (Fig. 2B). From paleowind directions (Fig. 2B), the blanket Entrada erg lying east of the central Colorado Plateau was not a downwind fore-erg accumulation, but a crosswind flank of the main Entrada erg. Thin Entrada Sandstone oversteps an eastern wedge edge of Navajo Sandstone to rest directly on underlying Kayenta Formation across a narrow facies tract in western Colorado. The blanket phase of the Entrada erg also spreads still farther east over massive red silstone of the Rock Point–Church Rock interval and correlative lacustrine strata of the Redonda Formation on the High Plains (Hester and Lucas, 2001). There is no evidence, however, for fluvial incision or marine planation below the Entrada eolian interval, nor any discernible paleosol below it.

**Curtis-Todilto Event**

Recent ammonite collections document the Oxfordian (basal Late Jurassic) age of the Curtis Formation (Wilcox and Currie, 2006), which is composed of glauconitic marine sandstone 40–60 m thick (Fig. 3) that transgressed over Entrada Sandstone in central Utah from the Utah-Idaho trough to the west and tapered to a feather edge on the southeast (Figs. 2B). Curtis marine strata grade upward and eastward into finer-grained tidal-flat and sabkha deposits of the overlying Summerville Formation, and the eolian Moab Tongue locally present at the top of the Entrada Sandstone (Figs. 2B and 3) is a nonmarine equivalent of the Curtis Formation (Crabaugh and Kocurek, 1993; Peterson, 1994; Doelling, 2003). Flooding of the Entrada erg was punctuated by local scours associated with ravinement along a desert coast and buried relict dune topography (Eschner and Kocurek, 1988; Peterson, 1994), but there was no prolonged hiatus or paleosol development beneath the Curtis Formation.

Further inland to the southeast, the broadly coeval (Anderson and Lucas, 1994) but lacustrine Todilto Formation, which may be slightly older than the Curtis Formation (Peterson, 1994), was deposited in an evaporative salina occupying >100 × 10³ km² (Fig. 2B). The Todilto salina may have been flooded initially by marine waters related to the Curtis transgression, but it was then maintained by influxes of freshwater from the south and by seepage of seawater through coastal sand barriers like the eolian Moab Tongue lying northwest of the salina toward the marine Curtis facies tract (Anderson and Lucas, 1994, 1996; Kirkland et al., 1995). The Todilto Formation includes a thin lower limestone member, generally <5 m thick, that is present throughout Todilto exposures, and an upper gypsum member confined to the interior of the salina, where a brine pool persisted after evaporation had reduced its extent. The lateral continuity of the thin Todilto Formation above the Entrada Sandstone shows that the upper surface of the Entrada erg drowned by the lacustrine salina was approximately level within an elevation range of <50 m.

**Upper Assemblage**

The upper San Rafael Group forms a sheet-like body of sediment only 50–100 m thick over most of its distribution, although thicknesses >100 m are reached along the western edge of the Colorado Plateau toward the Utah-Idaho trough (Fig. 3). Different stratigraphic nomenclature is used for the upper assemblage by different workers and in different states, and controversy also surrounds the placement of the stratigraphic base of the overlying Morrison Formation. Resolution of nomenclature issues is beyond the scope of this paper, but a brief discussion of their nature is necessary because we sampled eolianite within the upper assemblage to test for possible differences in age populations of detrital zircons in Entrada and post-Entrada ergs for which prevailing winds blew from the northeast or north and from the west or southwest, respectively (Fig. 2B).

In central Utah, red beds of tidal-flat and sabkha origin (Petersen and Pack, 1982; Caputo and Pryor, 1991; Peterson, 1994) form the Summerville Formation (Fig. 3), which conformably overlies the marine Curtis Formation and the laterally equivalent Moab Tongue of eolian origin. To the southwest, the Summerville Formation grades laterally to a sandier and more onshore facies (Peterson, 1988a, 1994; Blakey, 1989) termed the Romana Sandstone (Fig. 3). To the southeast, strata that are homotaxial and lithologically similar to Summerville Formation extend to areas where neither the Curtis Formation nor the Moab Tongue is present. A change in nomenclature adopted by some workers stems from the lateral continuity of the limestone member of the Todilto Formation in New Mexico with the Pony Express Limestone Member at the base of the Wanakah Formation in Colorado, beyond the extent of Todilto gypsum. This correlation has led to treatment of the Todilto interval as a member of the Wanakah Formation, and to the assignment of red beds of tidal-flat or sabkha origin overlying the Todilto interval to the Wanakah Formation rather than the Summerville Formation (Condon and Peterson, 1986; Condon and Huffman, 1988; O’Sullivan, 2003).
For Figure 3, we follow others (Anderson and Lucas, 1992, 1997) who prefer the name Summerville Formation and retain the formational status of the Todilto interval.

In southeastern Utah, the eolian Bluff Sandstone, which is younger than the Moab Tongue (Fig. 3) at the top of the Entrada Sandstone farther north (O’Sullivan, 1980), overlies finer-grained strata assigned alternately (see previous) to the Summerville or the Wanakah Formation. The Bluff Sandstone, identical to the Junction Creek Sandstone of Colorado (Lucas and Heckert, 2005), was originally described as the basal member of the overlying and dominantly fluvial Morrison Formation (Gregory, 1938). The Bluff Sandstone was later shifted to the San Rafael Group on the basis of its lithology and recognition that a vestige of the basal Salt Wash Member of the Morrison Formation is present within the overlying and dominantly finer-grained Recapture Member (Craig et al., 1955; Craig and Shawe, 1975; Lupe, 1983).

A thin interval of nonfluvial and even-bedded tidal-flat and sabkha deposits resembling Summerville or Wanakah Formation in lithology is present within the overlying and dominantly fineredged Recapture Member (Craig et al., 1955; Craig and Shawe, 1975; Lupe, 1983). A thin interval of nonfluvial and even-bedded tidal-flat and sabkha deposits resembling Summerville or Wanakah Formation in lithology is present within the type Recapture Member (Gregory, 1938) between the Bluff Sandstone and the Salt Wash Member of the Morrison Formation (Anderson and Lucas, 1997).

In recent years, some have reassigned the upper part of the Bluff Sandstone to the Morrison Formation and have postulated an unconformity (the J-5 unconformity of Pipiringos and O’Sullivan, 1978) between horizontally bedded sandstone forming the lower part of type Bluff Sandstone and cross-bedded sandstone forming the upper part of type Bluff Sandstone. This interpretation has led to designation of the lower part of the type Bluff Sandstone as the Horse Mesa Member of the Wanakah Formation, after a unit exposed to the south and traceable still farther southeast into the lower part of the “sandstone at Mesita” exposed near the Rio Grande rift (Condon and Peterson, 1986; Condon and Huffman, 1988; Condon, 1989a). The upper part of the “sandstone at Mesita” is cross-bedded, as is upper Bluff Sandstone at the type locality (Condon, 1989b).

Sedimentologically, the upward transition from horizontally bedded to cross-bedded sandstone in the type Bluff Sandstone and the “sandstone at Mesita” is the record of dune progradation over eolian sand sheets without a significant break in eolian sedimentation. Accordingly, we regard the entire Bluff Sandstone as part of the San Rafael Group and follow interpretations of others (Anderson and Lucas, 1996; Lucas and Heckert, 2003; Lucas, 2004) in regarding the Horse Mesa and Mesita sand bodies as local phases of the Bluff erg. Local stratil discordance between the lower, horizontally bedded and the upper, cross-bedded facies of the “sandstone at Mesita” (Condon, 1989b) can be attributed to syndepositional flowage of evaporites in the underlying Todilto Formation (Anderson and Lucas, 1992). Our Bluff samples come from the cross-bedded upper facies in both the type locality and near Mesita, where the sandstone body we sampled was mapped as Bluff Sandstone (Moench and Schlee, 1967) before the stratigraphic disputes arose.

**SANDSTONE PETROFACIES**

Table 1 and Figure 4 indicate numerically and graphically the detrital modes of all samples. The 11 eolianite samples (Table 1A) are fine- to medium-grained sandstones composed of subrounded to rounded aggregates of well-sorted grains that plot as a compact elongate cluster in QmFLt space (Fig. 4), and they are quartz-rich siltstone in the classification of McBride (1963). The two samples of marine sandstone are well-sorted, fine-grained sandstones composed of subrounded to subangular grains that plot close to the eolianite samples in QmFLt space (Fig. 4), with no statistically significant difference in QFL composition when inherent counting error is taken into account (Van der Plas and Tobi, 1965), but they contain mica flakes (Table 1C) that are absent from the eolianites. The five fluvial samples (Table 1B) are also fine- to medium-grained sandstones, but they are only moderately to poorly sorted aggregates of subangular to subrounded grains, and they are less quartzose than the eolian and marine sandstone samples (Fig. 4), though still subarkose, with one exception. Some but not all fluvial samples contain detrital mica flakes in variable abundances, which are probably dictated by local sedimentology rather than provenance.

Table 2 compares mean detrital modes for generic groups of samples. Eolianite samples are tabulated both stratigraphically (columns 1–2) and areally (columns 3–4). The tabulations show no statistical distinction among QmFLt values for the eolian sandstones no matter how they are grouped, nor any distinction in QmFLt values between eolian and marine sandstones. All samples of fluvial sandstone are less quartzose and more feldspathic, with the “Black Ledge” sample (column 7) being more lithic as well.

**P/F ratios** are different for Glen Canyon and San Rafael eolianites and for eolianites from the eastern and western Colorado Plateau (Table 2). The contrasts in ratio are similar because all Glen Canyon samples derive from

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**TABLE 1. DETRITAL MODES OF DETRITAL ZIRCON SAMPLES FROM SANDSTONES OF THE GLEN CANYON AND SAN RAFAEL GROUPS**

<table>
<thead>
<tr>
<th>Grains</th>
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<th>Jnnw</th>
<th>Jenw</th>
<th>CP2</th>
<th>CP3</th>
<th>CP12</th>
<th>CP15</th>
<th>CP16</th>
<th>CP24</th>
<th>CP30</th>
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<th>QFL</th>
<th>Dol</th>
<th>CP1</th>
<th>CP10</th>
<th>CP31</th>
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<td>83</td>
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*Notes: See Supplementary Text 1 (ST1; see text footnote 1) for sample localities. Modes are based on point counts of 400 QFL framework grains per sample (plus extra framework points for mica). Monocrystalline grains: Qm—quartz; P—plagioclase; K—K-feldspar; F—total feldspar (P + K). Polycrystalline grains: Op—polycrystalline quartz (dominantly chert), Lvm—volcanic and metavolcanic lithic fragments; Lsm—sedimentary and metasedimentary lithic fragments; L—total labile lithic fragments (Lvm + Lsm), L1—total lithic fragments (L + Op). Q—total quartzose grains (Qm + Op), M—mica flakes (% of total framework with QFL grains summed to 100%, exclusive of mica)."
the west, whereas most San Rafael samples derive from the east (Figs. 2 and 3). P/F ratios for the marine and most fluvial samples (columns 6–7) resemble the higher eolianite values (San Rafael and eastern plateau), but the P/F ratio for the Springdale sample (column 8) is as low as the lowest eolianite values (Glen Canyon and western plateau). The variations in P/F ratio correlate with variations in the age populations of detrital zircons, as developed next.

**DETRITAL ZIRCON MORPHOLOGY**

Zircon populations in all samples (eolian, fluvial, marine) are dominantly rounded to subrounded grains (although some are subangular), vary from sub spherical to elongate in shape, and display varied colors. There is no systematic correlation between shape, color, or angularity and U-Pb age. We conclude that sediment dispersal systems incorporated grains from age provinces that all included multiple sediment dispersal systems incorporated grains from source rocks containing zircons of varying character, and that the transport histories of individual zircon grains were also variable. Transport in stream bed load or as eolian saltation blankets tends to abrade grains readily, whereas transport as suspended load in streams or sand storms allows transport over arbitrarily long distances with little grain abrasion.

**EOLIANITE DETRITAL ZIRCONS**

Visual inspection of the superimposed age-bin histograms and age-distribution curves of Figure 5 shows that heterogeneous age populations of detrital zircons in all eolianite samples from the Colorado Plateau are broadly similar. The salient difference is in the variable content of grains younger than 285 Ma derived from Cordilleran igneous suites (Fig. 1). Arc-derived grains are paradoxically more abundant in eolianites from the eastern plateau (Figs. 5G–5J) than from the western plateau (Figs. 5A–5F), even though the latter is geographically closer to the Cordilleran orogen.

Composite age-distribution curves for eastern and western plateau samples are compared in Figure 6. All major age peaks for grains older than 285 Ma are closely comparable on the two plots, and the P value from K-S analysis for composite populations of grains older than 285 Ma in the two sample sets (n = 574 western; n = 316 eastern) is 0.98, where 1.0 would represent identity. The contrasting abundances of grains younger than 285 Ma in eolianite samples from the eastern and western parts of the plateau (Fig. 6) stem from variable additions of arc-derived grains to otherwise uniform eolian sand. Six western plateau samples contain only three grains younger than 285 Ma in age (0.5%), whereas four eastern plateau samples contain 7%–25% (mean 13% or 49 total grains).

We first address the origins of the dominant grains older than 285 Ma in the eolianite samples and then turn to the grains younger than 285 Ma of Cordilleran derivation (~5% overall).

**Non-Cordilleran Grains**

We evaluated the apparent similarity of heterogeneous age populations of grains older than 285 Ma in 10 Colorado Plateau eolianite samples (Fig. 5) by applying the K-S test to all 45 pairs of samples. The K-S test is a stringent approach to sample comparison because it is sensitive to proportions of grains of different ages as well as to the spread of ages. P values <0.05, indicating statistical differences, can thus derive from comparison of sets of samples containing age populations derived from the same sources but in differing proportions. P values for 75% of the sample pairs are >0.05, indicating that we cannot be 95% confident that those pairs of grain populations were not selected at random from the same parent population. All the samples have calculated P values >0.05 when compared to half or more of the other samples. We conclude that grains older than 285 Ma form a heterogeneous but coherent age spectrum in the plateau eolianite.

**TABLE 2. COMPARATIVE MEAN DETRITAL MORPHOLOGIES (KEY PARAMETERS) OF DETRITAL ZIRCON SAMPLES (TABLE 1)**

<table>
<thead>
<tr>
<th>Group</th>
<th>Mountain</th>
<th>Sandstone</th>
<th>Curtis Formation</th>
<th>Kayenta Formation</th>
<th>&quot;Black Ledge&quot; Sandstone</th>
<th>Springdale Sandstone</th>
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<tr>
<td>Glen Canyon</td>
<td></td>
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<td></td>
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<tr>
<td>Group</td>
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<tr>
<td>Group</td>
<td>(n = 6)</td>
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<td></td>
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<tr>
<td>Colorado Plateau</td>
<td>(n = 6)</td>
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<tr>
<td>Eastern</td>
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<tr>
<td>Colorado Plateau</td>
<td>(n = 5)</td>
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<td>&quot;Black Ledge&quot; Sandstone</td>
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<td>Springdale Sandstone</td>
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<td>8 ± 2</td>
</tr>
<tr>
<td>P/F</td>
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<td>46 ± 13</td>
<td>25 ± 9</td>
<td>52 ± 4</td>
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<td>43 ± 2</td>
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</table>

**Note:** See Table 1 for Qm, F, Lt, M; P/F = 100 x (plagioclase feldspar)/total feldspar. Standard deviations (±) are for n samples where n > 2. Col. 1 includes Page Sandstone (CP12), Col. 2 includes Mt. Wrightson Formation (CP2), Cols. 3–4 were divided at 110°W longitude.
Figure 5. Age-bin histograms and age-distribution curves (superimposed) for Colorado Plateau eolianites keyed to collecting localities (central map). Abscissas are U-Pb grain ages (0–4000 Ma), and ordinates are numbers of grains (variable scales). See Supplementary Text 3 [see text footnote 1] for the same and additional plots including concordia diagrams at larger scale. States: AZ—Arizona—CO—Colorado; NM—New Mexico; NV—Nevada; UT—Utah.
samples, and that variable P values reflect vagaries of sampling, including stratigraphic and areal selection of sample sites, choice of horizons collected on outcrop, and selection of grains in the laboratory for laser ablation.

Figure 7 is a composite plot of 890 grains older than 285 Ma in age in the eolianite samples (Fig. 5). Distinct and prominent age peaks include (ages rounded to nearest 5 Ma): (1) 420 Ma (Late Ordovician), with other minor Paleozoic peaks in the range of 290–390 Ma; (2) 615 Ma (Neoproterozoic); and (3) 1055 Ma (Grenvillian Mesoproterozoic), with a subordinate Grenvillian peak at 1160 Ma. Paleoproterozoic and Archean grains define five less prominent but well-defined age peaks (Fig. 7).

The distribution of granitoid basement provinces in North America (Fig. 1) provides a guide to the ultimate sources of the grains defining each age peak. Table 3 groups the net eolianite age populations into clusters around the age peaks and indicates the inferred dominant sources for each age cluster. Approximately two-thirds of the grains apparently derive from the Appalachian orogen and its Grenville flank in southeast Laurentia, or its extensions into the Mesoamerican region. No other basement provinces in North America could provide the Paleozoic, Neoproterozoic, and Grenvillian grain populations in the observed abundances relative to grains of other ages.

Appalachian Provenance

Granitoid source rocks of Paleozoic, Neoproterozoic, and Grenvillian age are present in elongate parallel domains along the Appalachian orogenic belt and its extensions (Fig. 8). Basement rocks of the late Mesoproterozoic Grenville orogen were incorporated into the cratonic flank of the Appalachian orogen. Neoproterozoic granitic rocks are present both as rift plutons intruded into Grenville basement during the multiphase pre-Iapetan breakup of Rodinia within the interval 735–560 Ma (Tollo et al., 2004), and within peri-Gondwanan arc terranes accreted to Laurentia during evolution of the Appalachian orogen. Neoproterozoic and Cambrian grains are also present as detrital zircons in capping lower Paleozoic sedimentary strata of the accreted peri-Gondwanan assemblages (Murphy et al., 2004). Paleozoic plutons of diverse ages are present along the length of the Appalachian orogen, both intruded into native Laurentian basement of Grenville age and within Paleozoic assemblages accreted to the flank of Laurentia during evolution of the orogen (Hibbard et al., 2007). The tendency for populations of detrital zircons to integrate age signals from diverse bedrock sources within the same provenance is shown by the compound age peak for
grains of Paleozoic age in the eolianites (Fig. 7) without discrimination among pulses of Paleozoic magmatism along the Appalachian belt.

Reported U-Pb ages of granitoid rocks along seven transects of the Appalachian belt (Fig. 8) are compiled in Figure 9, which shows that the four most prominent age peaks for detrital zircons in Colorado Plateau Jurassic eolianites match the distribution of known ages for granitic rocks along the Appalachian-Ouachita-Mesoamerican flank of Laurentia. Derivation of the Neoproterozoic grains dominantly from accreted peri-Gondwanan arc assemblages, rather than from pre-Iapetan rift assemblages, is inferred from the greater areal extent of the former. The paucity of detrital zircon grains of Neoproterozoic age in Paleozoic strata of the Appalachian foreland basin (McLennan et al., 2001; Eriksson et al., 2004; Becker et al., 2005, 2006; Thomas and Becker, 2007) suggests that peri-Gondwanan terranes accreted along the distal flank of Laurentia were not uplifted to become significant sources of sediment until rift highlands developed along the trend of the incipient Atlantic Ocean in Mesozoic time.

Coincidental mixing of Paleozoic, Neoproterozoic, and Grenvillian zircon grains from disparate rock masses, including Gondwanan continents once adjacent to Laurentia, as an alternative to postulated Appalachian origin, is disfavored for several reasons: (1) there are consistent proportions of key age populations of detrital zircons in plateau eolianites, all of which display separate peaks for Paleozoic and Neoproterozoic age populations, and Grenvillian age peaks larger than either (Fig. 5); (2) a 520–510 Ma gap between ages of Neoproterozoic and Paleozoic granitoids in the Appalachian-Ouachita-Mesoamerican orogen is closely matched by a 515–505 Ma gap between age peaks for detrital zircons in the eolianites; (3) derivation of zircons from cratons lying within Pangea, beyond the Hercynian Appalachian-Ouachita suture between Laurentia and Gondwana, is unlikely because it would have required transport of detritus across remnant Paleozoic uplands along the relict Appalachian orogen and rift highlands that formed during initial phases of Mesozoic Atlantic rifting; (4) derivation of Neoproterozoic grains from Pan-African orogenic belts of Africa or South America is unlikely because the nearest Pan-African sources on those continents lay 1500 km and 3500 km, respectively, from the Hercynide Appalachian-Ouachita suture bounding Laurentia; and (5) the proximate edge of the Guiana craton, which lay directly south of Laurentia before breakup of Pangea (Dickinson and Lawton, 2001a), is dominated by the 2200–1950 Ma Maroni-Itacaiunas belt (Tassinari et al., 2000; Chew et al., 2007), and the conjugate Birimian belt of West Africa is of similar age (Boher et al., 1992), yet 2200–1950 Ma detrital zircons form only 2% of the grain population in plateau eolianites.

**Grenvillian Zircons**

Zircon grains of Grenvillian age form 60% of the age suite of eolianite detrital zircons inferred to derive from the Appalachian orogen (Table 3), yet the Grenville province forms a relatively narrow belt along the proximal flank of the orogen (Fig. 8). Domination of grains of Grenvillian age may reflect the high zircon fertility of Grenville plutons (Moecher and Samson, 2006), rather than especially voluminous Grenville sources. Recycling of Grenvillian grains from Paleozoic strata of the Appalachian foreland basin (Fig. 10), in which detrital zircon grains of Grenvillian provenance are abundant (McLennan et al., 2001; Eriksson et al., 2004; Becker et al., 2005, 2006; Thomas and Becker, 2007), is a clear possibility, as is recycling from Neoproterozoic rift and miogeoclinal assemblages of Grenvillian provenance along the Appalachian belt (Cawood and Nemchin, 2001; Cawood et al., 2007; Thomas and Becker, 2007). From our

![Figure 8. Transects (heavy barred lines keyed by letter to Fig. 9) of the Paleozoic Appalachian-Ouachita-Mesoamerican orogen showing late Mesoproterozoic Laurentian and Oaxaquian Grenville belts (Fig. 1), distribution of early Mesoproterozoic anorogenic plutons (Anderson, 1983; Anderson and Morrison, 2005) in Grenville foreland after Anderson and Cullers (1999) and Barnes et al. (2002), and accreted Neoproterozoic terranes of the Appalachian belt (AvT—Avalon; CaT—Carolina; SuT—Suwannee) adapted after Hatcher et al. (1989, 2007), Reed (1993), and Barr and Kerr (1997). Paleogeologic pre-Jurassic edge of sedimentary cover over Laurentian craton is from Figure 10. Yucatan-Campeche block and Baja California Peninsula (BC) were restored after Dickinson and Lawton (2001a).](image-url)
distant vantage point on the Colorado Plateau, we cannot distinguish between bedrock and recycled sources of Grenvillian detritus lying within the Appalachian orogen, but Jurassic paleogeographic implications are the same in either case.

Recycling of Grenvillian zircon grains from the Paleozoic platform cover of the continental interior is unlikely, both because the platform cover is still largely intact over most of the expanse between the Rocky Mountains and the Appalachian belt (Fig. 10) and because the platform cover is in large part carbonate rock that contains few, if any, zircon grains. Neoproterozoic and lower Paleozoic strata of the Western Cordillera are known to contain abundant detrital zircon grains of Grenvillian derivation (Rainbird et al., 1992, 1997; Gross et al., 2000; Stewart et al., 2001; Timmons et al., 2005; Mueller et al., 2007), but these strata were buried beneath upper Paleozoic and lower Mesozoic cover until late Mesozoic Cordilleran orogenesis and were not exposed to erosion in Lower to Middle Jurassic time. Neoproterozoic strata in the midcontinent containing Grenvillian detritus (Santos et al., 2002) are still buried beneath Paleozoic cover and similarly could not have contributed recycled Grenvillian zircon grains to Jurassic dispersal systems. Voluminous sediment of partly Appalachian derivation transported into the midcontinent by a major Pennsylvanian paleoriver that flowed parallel to the Appalachian chain (Archer and Greb, 1995) has also been largely preserved from erosion even to the present time.

Recycling of Grenvillian zircon grains into plateau eolianites from pre-Mesozoic strata is further disfavored by combined U-Pb and (U-Th)/He dating of zircon grains of Grenvillian...
age in the Navajo Sandstone of Zion National Park (Rahl et al., 2003), located midway between our Navajo (Jnnw) and correlative Aztec (CP30) samples. The Grenvillian granitoid rocks, or perhaps deeply buried metasedimentary rocks, that yielded detrital zircon grains to the Zion sample were not unroofed until early Mesozoic time (youngest He age only 35–45 m.y. older than depositional age). This “double-dating” result precludes posterosion sediment storage of basement-derived Grenvillian grains for any appreciable length of time at shallow depths before delivery to the Jurassic ergs.

**Paleoriver Course**

The prevalence of paleowinds blowing southward in present coordinates across the Colorado Plateau (Figs. 2A–2B) shows that the proximate source of the Jurassic ergs lay north of the plateau in a direction from which none of the zircon age populations of ultimate Appalachian provenance could have been derived (Fig. 1). We infer, after Dickinson and Gehrels (2003) and Rahl et al. (2003), that a transcontinental Jurassic paleoriver system transported Appalachian detritus toward Jurassic paleoshorelines north of the Colorado Plateau (Fig. 10) and deposited sand on riverine or deltaic floodplains that were then systematically deflated to feed the eolian depositional system of the Colorado Plateau.

Because no Jurassic strata are exposed across the midcontinent region between the Rocky Mountains and Triassic-Jurassic rift basins of the Appalachian belt, the detrital zircon record in Mesozoic strata of the Colorado Plateau is the only remaining evidence for the transcontinental Jurassic paleoriver system. In the modern world, however, rivers transiting cratons for 1500–2500 km from marginal or interior highlands toward distant continental margins are common.
age, which contributed a significant fraction of Grenville plutons younger than 1000 Ma in the Ouachita suture belt west of the Appalachians.

The most attractive course for the trunk paleriver of the fluvial system was from headwaters in the central to southern Appalachians, with tributaries of unknown number and location joining the paleriver from both the north and the south as it crossed the continent (Fig. 10). The postulated course of the trunk stream thereby followed a direct path along a belt of low-inferred paleotopography between residual uplands of the Pennsylvania Ancestral Rocky Mountains to the southwest and the broadly elevated tract of the Canadian Shield forming the cratonic nucleus of Laurentia on the northeast (Fig. 10).

A more northerly trunk stream rising in the northern Appalachians is disfavored because (1) avoidance of significant detritus from Archean basement of the Superior province lying immediately to the west (Fig. 10) would then seem difficult, yet Archean grains form <10% of the detrital zircons in plateau eolianites (Table 3); (2) the accreted peri-Gondwanan assemblages capable of yielding Neoproterozoic grains lie progressively farther east toward the north, beyond wider Grenville and Paleozoic belts (Fig. 8), in a position more difficult for potential headwaters to tap; and (3) Alleghanian (<340 Ma) plutons are unknown north of New England (Fig. 9).

A more southerly trunk stream is disfavored because (1) Grenville basement flanking the Ouachita suture belt west of the Appalachians was largely buried beneath Paleozoic platform cover during Jurassic time (Figs. 8 and 10); (2) Grenville plutons younger than 1000 Ma in age, which contributed a significant fraction of Grenvillian grains to plateau eolianites (Table 3), are unknown along the Grenville belt where exposed sparsely west of the Appalachians, except far away in southern Mexico (Talavera-Mendoza et al., 2005); and (3) flysch successions of the Ouachita orogen (Gleason et al., 2007), from which some eolianite detritus may have been derived, contain detrital zircon populations that (a) lack the Neoproterozoic age peak near 615 Ma prominent for plateau eolianites, (b) have a prominent Cambrian age peak at 533 Ma, probably reflecting sediment contributions from the Amarillo-Wichita province (Fig. 1), which are not present in plateau eolianites, and (c) display Grenvillian age peaks of 1125 Ma and 1245 Ma, which are somewhat different from the 1055 Ma and 1160 Ma Grenvillian age peaks for plateau eolianites.

In general, however, the U-Pb age spans of Grenvillian plutons are similar along the entire length of the Grenville orogen flanking Laurentia (Fig. 9), and do not provide a robust guide to regional provenance. Another factor that compounds the difficulty of sensing regional differences in sources within the Grenville orogen is the inherent imprecision of U-Pb ages across the Grenvillian age spectrum. For example, the mean age uncertainty for ~265 individual detrital zircon grains in plateau eolianites with best estimates of grain age in the range of 1200–1000 Ma is ±65 Ma.

Provenance Erosion

In evaluating central and southern Appalachian sources, whether juvenile or recycled, for sand in plateau eolianites, two principles of provenance analysis are relevant:

(1) Potential source rocks still uneroded in the provenance region cannot have contributed to any body of sediment in the past. This principle comes into play because the fill of the Appalachian foreland basin and its miogeoclinal substratum is still largely preserved, to thicknesses in the range of 2500–7500 km above basement (Muehlberger, 1992), beneath the Allegheny-Cumberland Plateau along the western flank of the orogen. Accordant ridges of the plateau expose nearly undeformed Pennsylvanian and Permian strata that cap the miogeoclinal–foreland succession and were not dissected until incised by modern stream valleys during the currently active post-Jurassic cycle of erosion. Recycling of Grenvillian detritus from Appalachian foreland successions in Jurassic time could only have involved deformed strata forming the Valley and Ridge province, 25–65 km wide along the proximal flank of the foreland basin adjacent to the Blue Ridge thrust front (Hatcher et al., 2007).

(2) The volume of rock eroded to supply a body of sediment no longer exists in the provenance. This principle comes into play because the Blue Ridge thrust sheet may once have extended farther westward, structurally above deformed strata of the Valley and Ridge province, before erosion of the gently dipping thrust sheet back to the present position of the Blue Ridge thrust front. To the east, the complex Blue Ridge and Inner Piedmont belts, composed of Grenville basement, overlying sedimentary cover, and both overthrust basement and intrusive plutons of Paleozoic age, are now jointly 70–120 km wide west of accreted peri-Gondwanan terranes (Hatcher et al., 2007), but may perhaps have been 100–150 km wide during Jurassic time.

If one postulates, based on the proportions of detrital zircons of various ages in plateau eolianites (Table 3), that 55% of the eolian sand was derived ultimately from Grenvillian and Paleozoic basement in the central and southern Appalachians, an estimate of the net depth of erosion in the provenance can be made. The calculation leaves aside the question of Neoproterozoic detrital zircons derived from accreted peri-Gondwanan terranes lying father to the east, which contributed an additional 11% of the detrital zircons to plateau eolianites (Table 3). A volume of quartzose Jurassic eolian sand of Grenvillian-Paleozoic origin of 95 ± 40 km³ (embracing minimum and maximum estimates) requires erosion of 245 ± 100 km³ of granitoid-gneissoid bedrock to produce. The indicated net depth of erosion into basement in the southern and central Appalachians is 4.5 ± 2.3 km if the geographic extent of eroded basement between the Blue Ridge thrust front and the western edge of accreted peri-Gondwanan terranes is taken to be 85–115 km (width) by 575 km (length). This estimate does not allow for enhanced zircon fertility of Grenvillian plutons (which would reduce the required depth of erosion), nor for derivation of some detritus from quartzose metasedimentary rocks (which would also decrease the required depth of erosion), nor for erosional removal of mafic or other rocks yielding little or no zircon or quartz (which would increase the inferred depth of erosion). Even without such adjustments, however, the figure derived for depth of erosion seems unexceptional for exposure of plutonic and metamorphic rocks in the core of a mature orogen, and it implies that no recycling of detritus from outside the Appalachian belt is required to explain the abundance of Grenvillian and Paleozoic detrital zircons in plateau eolianites.

Pre-Grenvillian Grains

None of the five age groups of pre-Grenvillian grains in plateau eolianites forms more than 10% of the net grain population (Table 3), and none is especially abundant in any of the eolianite samples (Fig. 5). In aggregate, however, they sum to approximately one-third of the detrital zircon grains, and this amount could not have been derived from the Appalachian region, although some of the pre-Grenvillian grains could represent recycling of zircons from Appalachian rift or foreland successions (Cawood et al., 2007; Thomas and Becker, 2007), or enclaves within the Grenville orogen (Fig. 9). Tributary contributions to the transcontinental paleriver having its principal headwaters in the Appalachian orogen are the most likely sources of the non-Appalachian detrital zircons.

Archean grains could have reached the trunk paleriver from northern tributaries draining the cratonic nucleus of Laurentia (Fig. 1). The
Wyoming province of Archean rocks immediately north of the Colorado Plateau (Fig. 1) is not a viable source because it was masked by sedimentary cover in Jurassic time, and it was also partly buried by the northern end of the Navajo-Nugget erg (Fig. 10). Most Paleoproterozoic grains could similarly have entered the dispersal system from northern sources, among which the Penokean belt near the Great Lakes is the most proximal (Fig. 1). Zircon grains older than 2000 Ma that are ascribed provisionally (Table 3) to sources in northwestern Laurentia (Dickinson and Gehrels, 2003) may have reached the terminus of the transcontinental paleoriver system by longshore transport along the Jurassic paleoshoreline of the Cordilleran margin (Figs. 1 and 10).

Early Mesoproterozoic Yavapai-Mazatzal (1.8–1.6 Ma) detritus (Fig. 1; Table 3) was probably contributed to the transcontinental paleoriver by southern tributaries draining residual highlands of the Ancestral Rocky Mountains lying immediately east of the Colorado Plateau. The coeval Central Plains Paleoproterozoic belt was masked by sedimentary cover in Jurassic time (Fig. 10). Contributions from anorogenic pre-Grenvillian granitic rocks (Table 3) intrusive into the Yavapai-Mazatzal belt, but present farther east as well, probably entered the sediment dispersal system from the same southern tributaries that contributed Yavapai-Mazatzal detritus. The anorogenic plutons (Anderson and Morrison, 2005) are widespread across the continental interior (Fig. 8), reaching as far east as the Grenville front (Van Bremen and David- son, 1988), but most were buried beneath platform cover in Jurassic time (Fig. 10). More easterly analogues were incorporated as deformed enclaves within the Grenville orogen (Rivers, 1997; Rivers and Corrigan, 2000), and some 1300–1500 Ma grains in plateau eolianites may have been derived from pre-Grenvillian sources incorporated into the Grenville orogen.

**Arc-Derived Grains**

Grains younger than 285 Ma in age could only have been derived from the Cordilleran region along the western flank of Laurentia (Fig. 1). Many interpretations are possible for the three solitary grains younger than 285 Ma in six eolianites from the western Colorado Plateau (Fig. 6), including analytical error, and they are not discussed further. Four eolianites of the San Rafael Group on the eastern Colorado Plateau (Fig. 6) contain a total of 49 grains that are younger than 285 Ma, but statistical analysis of their age distribution is challenging because half occur in just one sample (Fig. 5I). Statistical age peaks (n = 10), each defined by three or more grains in various of the four samples, range from 158 Ma to 261 Ma. The oldest known plu- tons of the Cordilleran magmatic arc along the western fringe of Laurentia are 245–235 Ma in the Mojave Desert region of southern California (Barth and Wooden, 2006), and older arc-derived grains (older than 245 Ma) are inferred to reflect contributions from the Permian-Triassic East Mexico magmatic arc (284–232 Ma) of Torres et al. (1999) along the Gondwana margin of Pangaea (Fig. 1).

Eolianites of the Upper Jurassic Bluff erg (Fig. 2B) were deposited by westerly winds that could have carried arc-derived grains directly from the Cordilleran orogen to the Colorado Plateau (Fig. 1). Notably, all four statistical age peaks for arc-derived grains (n = 19) in the two Bluff samples (Figs. 5H and 5J) are younger than 235 Ma, implying derivation from the Cordilleran rather than the East Mexico arc. Net grain populations in the Bluff samples also imply extensive recycling of older eolian sand into the Bluff erg of restricted areal extent (Fig. 2B).

Eolianites of the Middle Jurassic Entrada erg were deposited by winds blowing southwest across the Colorado Plateau toward the Cordilleran margin (Fig. 2B). Four of the six statisti- cal age peaks in the two Entrada samples from the eastern Colorado Plateau (Figs. 5G and 5I) are older than 245 Ma, suggesting important contributions from the East Mexico arc. Of the 30 arc-derived grains in the two samples, more than half are older than 245 Ma, the apparent age limit of the Cordilleran arc, and two-thirds are within the nominal age bracket (older than 232 Ma) for the East Mexico arc. Given the paleo- wind direction, these relations imply that detritus was transported north from the East Mexico arc where it was exposed in the headwaters of a southern tributary to the transcontinental trunk paleoriver (Fig. 10) and then blown southwest into the Entrada erg from sites of temporary storage on the interior plains. As the Cordilleran arc extended into northeastern Mexico (Fig. 1), a limited volume of arc-derived Cordilleran detritus could have accompanied the arc-derived East Mexico detritus northward.

**Arc-Flank Eolianite**

Local lenses of quartz-rich eolian sandstone are intercalated with Jurassic volcanic rocks along the inland flank of the Cordilleran magmatic arc southwest of the Colorado Plateau (Fig. 2B). To compare detrital zircons in arc-flank and Colorado Plateau eolianites, we collected a sample from an ~250-m-thick lens of quartzose eolianite in the Mount Wrightson Formation of southern Arizona (CP2 of Fig. 2B). Although exact correlations of the unfossilifer- ous eolian strata are contentious (Bilodeau and Keith, 1986; Bushy-Spera et al., 1990), our sample was collected less than a kilometer along strike from an ignimbrite body that yielded a markedly discordant U-Pb age, interpreted by modeling to reflect an emplacement age of 171 ± 2 Ma (Riggs et al., 1993). A statistical age peak of 164 Ma (n = 5 grains) for detrital zircons in the sample suggests that the discordant U-Pb age for the ignimbrite is unreliable, even with modeling corrections. The maximum depositional age implied by the detrital zircons invites correlation with the Entrada Sandstone (San Rafael Group) of the Colorado Plateau (Fig. 3) and suggests that transport of eolian sand southward to the flank of the Cordilleran arc occurred during multiple deflationary episodes recorded by the evolution of the Entrada erg (Kocurek, 1981; Carr-Crabaugh and Kocurek, 1998).

The ages of 25 arc-derived grains in the Mount Wrightson sample include two spurious ages (90 Ma; 140 Ma) that are younger than its depositional age, which is older than 155 Ma based on its unconformable position below the Bisbee Group (Dickinson and Lawton, 2001b). There are also two solitary outlier ages (251 Ma; 269 Ma), but most (n = 21) of the arc-derived grains span the age range of 235–160 Ma, with statistical peaks at 164 Ma (n = 5 grains), 178 Ma (n = 8 grains), and 219 Ma (n = 8 grains), which are compatible with derivation of zircon grains from igneous rocks of the associated Cordilleran arc assemblage. The other 64 detrital zircons (72% of the population) span the same general age range as non-Cordilleran grains in Colorado Plateau eolianites, but the two age spectra differ in detail (Fig. 11). Age peaks for Paleozoic, Neoproterozoic, and Archean grains are similar in both age and relative significance, but the Grenvillian age population is less prominent in the Mount Wrightson Formation, and peaks for older Proterozoic grains are broader. A comparison of the two age-distribution curves (Fig. 11) suggests that the content of zircons derived from the Yavapai-Mazatzal belt intruded by bodies of anorogenic granite was enhanced during transit of eolian sand across Yavapai-Mazatzal basement lying south of the Colorado Plateau (Fig. 1) but north of the sample site (Fig. 2B). Dilution of Appalachian-derived detritus with more local detritus is inferred to have been the factor that reduced the relative proportion of Grenvillian grains.

**CURTIS DETRITAL ZIRCONS**

Figure 12 displays age-bin histograms and age-distribution curves for samples of fluvial sandstone from the Glen Canyon Group and marine sandstone from the San Rafael Group (Fig. 3) to compare with plots in the same
format for eolianite samples (Fig. 5). Figure 13 compares composite grain populations in two samples of marine sandstone from the Curtis Formation (Figs. 12A and 12B) and two samples of eolian sandstone from the underlying Entrada Sandstone (Figs. 5E and 5G) at localities within 100 km of the southeastern limit of the Curtis transgression (Fig. 2B). The marine and eolian grain populations are closely similar, but they are not identical. A P value of 0.13 from K-S analysis for grains older than 175 Ma (= >205 Ma) in the two composite age populations indicates inability at the 95% confidence level to be certain that the Curtis zircon population was not largely recycled from the Entrada zircon population. On the other hand, a statistical age peak at 165 Ma for six grains in Curtis sample CP45 (Fig. 12B) is younger than any of the six age peaks in the range of 260–200 Ma for Entrada samples (Figs. 5G and 5I) collected both near and far from Curtis exposures (Fig. 2B).

The youngest zircon grains in the Curtis Formation control a sharp spike on the age-distribution curve at 165 Ma (Fig. 13) and probably derive from the backarc igneous province of northern Nevada and westernmost Utah (Fig. 2B). The Pony Trail Group (Wrightson, 1964) of that region contains ignimbrites produced by explosive eruptions that may have spread zircon grains eastward into the Curtis seaway. Abundant mica flakes (Tables 1 and 2) that are present in samples from the Curtis Formation but not the Entrada Sandstone also indicate some addition of non-Entrada detritus, perhaps transported by longshore currents along the southern margin of the Sundance seaway that lay northeast of the Colorado Plateau. On balance, however, the bulk of Curtis sand was apparently reworked from underlying Entrada Sandstone as the Curtis marine transgression proceeded. Although we did not sample eolian sandstone of the Moab Tongue (Figs. 2B and 3), there is no reason to suspect that its detrital zircons would not closely resemble the Curtis and Entrada zircon populations.

**FLUVIAL ZIRCON PROVENANCE**

The most widespread fluvial unit within the Glen Canyon Group is the Kayenta Formation (Fig. 3), which is more feldspathic than underlying and overlying eolian strata (Tables 1 and 2). Three samples collected from the Kayenta Formation at widely separated localities on the Colorado Plateau contain similar grain populations (Figs. 12D, 12E, and 12G), with comparative P values from K-S analysis of three sample pairs in the range of 0.25–0.83. The “Black Ledge” sandstone (Figs. 3 and 12C), exposed locally in Utah (Fig. 2A), is of somewhat different petrofacies than the Kayenta Formation (Table 2), but contains a similar grain population yielding a P value from K-S analysis of 0.12 when paired with a composite Kayenta grain population derived from three samples.

The Springdale Sandstone Member (Fig. 3) to the southwest (Fig. 2A) contains a distinctive grain population (Fig. 12F) dominated by arc-derived grains (n = 40 or 42.5% of total grains) for which discussion is deferred until after consideration of the Kayenta Formation. Our assignment of the “Black Ledge” sandstone to the Glen Canyon Group (Fig. 3) rather than to the underlying Chinle Group or Formation is supported by a “Black Ledge” statistical age peak (seven grains) of 203 Ma, which is younger than the Chinle depositional age of Carnian–Norian (Brack et al., 2005).

**Kayenta Fluvial Sands**

A comparison of age-distribution curves for Kayenta fluvial and Glen Canyon eolian samples (Fig. 14) indicates a close similarity in grain populations, except that the fluvial sandstones contain a significant proportion of arc-derived grains younger than 285 Ma. The P value for grains older than 285 Ma in the two composite grain populations is 0.65, indicating that the prearc grains in the Kayenta Formation and Glen Canyon eolianites are statistically indistinguishable. The overall Kayenta detrital zircon population can be interpreted as the result of mixing arc detritus with eolian sand redistributed from epeiric contemporaneous (or directly underlying) unconsolidated erg deposits.

Statistical age peaks (n = 8), each controlled by three or more grains in various of the Kayenta samples, fall within the range 288–231 Ma, suggesting derivation dominantly from the East Mexico arc (284–232 Ma) rather than the Cordilleran arc (younger than 245 Ma). Consistent paleocurrent trends toward the west and northwest for the Kayenta Formation are compatible with contributions from the East Mexico arc lying to the southeast of the Colorado Plateau (Fig. 1). Zircon grains of Grenvillian age in the Kayenta samples might also have been derived in part from source rocks lying to the southeast, but no apparent sources for the Archean and Paleoproterozoic grains are evident southeast of the Colorado Plateau (Fig. 1). Accordingly, redistribution of eolian sand is our preferred interpretation for the origin of all the
Figure 12. Age-bin histograms and age-distribution curves (superimposed) for samples of marine sandstone from the San Rafael Group (A–B) and fluvial sandstone from the Glen Canyon Group (C–G) keyed to collection localities on the Colorado Plateau (central map). Abscissas are grain ages (0–4000 Ma), and ordinates are numbers of grains (variable scales). See Supplementary Text 3 (see text footnote 1) for the same and additional plots including concordia diagrams at larger scale. States: AZ—Arizona; CO—Colorado; NM—New Mexico; NV—Nevada; UT—Utah.
Kayenta pre-arc grains. Lack of augmentation of Paleoproterozoic or early Mesoproterozoic zircon grains in the Kayenta Formation, as compared to Glen Canyon eolianites (Fig. 14), argues against significant contribution of detrital zircons to the Kayenta Formation from the Ancestral Rocky Mountains province lying immediately east of the Colorado Plateau. Ancestral Rockies bedrock (Figs. 1 and 8) is Yavapai-Mazatzal basement intruded by slightly younger anorogenic plutons.

The proportions of arc-derived detritus and redistributed eolian sand in the Kayenta Formation can be estimated in two ways. A mixing line from the mean detrital mode of Glen Canyon eolianites (Qt86-F10-L4 from Table 1), through the mean detrital mode of Kayenta sandstones (Qt76-F17-L7 from Table 1), to the mean detrital mode of first-cycle Paleogene arkoses (Qt40-F45-L15) in southern California (Dickinson, 1995) implies an admixture of 79% redistributed eolian sand and 21% arc detritus in Kayenta fluvial sandstone. The content of arc-derived zircon grains ($n = 30$ total or mean of 12%) in the Kayenta samples, as opposed to grains older than 285 Ma, implies a somewhat higher proportion of redistributed eolian sand (88%), but mature eolianites may contain a significantly higher proportion of zircon grains than juvenile arkosic detritus. In any case, the two mixing calculations yield similar estimates of admixture ($\sim 15\% \pm 5\%$ arc detritus). Kayenta paleoflow across the Colorado Plateau from the east and southeast implies the existence of an Early Jurassic sand blanket available for reworking from areas where erosion has since removed all traces of its former presence (Fig. 2A). The redistribution of eolian sand into the Kayenta Formation suggests widespread intraregional recycling of durable zircon grains of dominantly Appalachian origin once mature sand of Appalachian provenance had been spread across southwest Laurentia.

The presence of detrital zircons apparently derived from the East Mexico arc in both fluvial sandstones of the Kayenta Formation (Glen Canyon Group) and eolian sandstones of the San Rafael Group invites comparison of the two sample sets (Fig. 15). The only salient difference is the presence of 11 grains younger than 195 Ma in the composite San Rafael population. These young grains derived from the Cordilleran arc define a sharp age spike on the San Rafael plot that is not present on the plot for older Kayenta sandstones (Fig. 15). The P value from K-S comparison of grains older than 195 Ma in the two populations is 0.28, indicating a lack of statistical distinction. Higher P/F ratios in detrital modes (Table 2) appear to be a subtle but reliable guide to the presence of arc

![Figure 13. Composite age-distribution curves for detrital zircon grains in marine Curtis (Figs. 5E and 5G) and eolian Entrada (Figs. 11A and 11B) samples from Utah (N = samples; n = grain ages).](image)

![Figure 14. Composite age-distribution curves for detrital zircon grains in samples of Glen Canyon eolianites (Figs. 5B–5D, and 5F) and fluvial Kayenta Formation (Figs. 11D, 11E, and 11G) of Glen Canyon Group (N = samples; n = grain ages).](image)
detritus in both San Rafael eolian and Kayenta fluvial sandstones.

Springdale Sandstone Member

The Springdale Sandstone Member of the Moenave Formation has been correlated with the Kayenta Formation, but the contrasting Springdale suite of detrital zircons (Fig. 12F) makes the relationship equivocal because Springdale and Kayenta depositional systems tapped different provenances. The abundance of Springdale arc-derived grains, coupled with the absence of any Paleozoic–Neoproterozoic grains or any grains older than 1850 Ma, suggests derivation from a provenance in southwest Laurentia lying directly south of Springdale exposures (Fig. 1). All arc-derived Springdale detrital zircons ($n = 40$) are younger than 245 Ma in age, as expected for derivation from the Cordilleran magmatic arc, with the only age peaks controlled by three or more grains at 210 Ma, 217 Ma, and 235 Ma. By contrast, more than half the Kayenta arc-derived grains are 281–247 Ma, indicative of derivation from the older East Mexico magmatic arc.

There is, however, an areal variation in Kayenta zircon populations that suggests the Springdale and Kayenta fluviatile systems may have followed parallel courses flowing from ESE to WNW across a joint floodplain, with Springdale detritus derived from southwest of the provenance for Kayenta detritus. The most southwestern Kayenta sample (CP10) contains arc-derived zircon grains ($n = 7$ or 9% of total grains) that may be exclusively of Cordilleran derivation (younger than 241 Ma), with an age peak defined by three grains at 231 Ma. The other two Kayenta samples (CP1, DOL) contain arc-derived zircon grains ($n = 21$), of which 75% are older than 245 Ma (range 281–247 Ma), with age peaks defined by 5–10 grains of 246 Ma, 251 Ma, 265 Ma, and 280 Ma (indicative of sources in the East Mexico arc). Kayenta streams farthest toward the northeast on the compound floodplain evidently redistributed eolian sand, to which East Mexico arc detritus was added from the southeast, whereas Kayenta streams toward the southwest may have redistributed eolian sand to which Cordilleran arc detritus was added from the south. Springdale streams still farther to the southwest mixed detritus from Yavapai-Mazatzal basement of southwest Laurentia with arc-derived Cordilleran detritus without contributions from the East Mexico arc.

SUMMARY AND CONCLUSIONS

U-Pb ages of detrital zircons in Jurassic ergs and associated deposystems of the Colorado Plateau support the following conclusions: (1) plateau eolianites are composed dominantly of detritus derived ultimately from bedrock sources in eastern Laurentia rather than the Cordilleran orogen or the Ancestral Rocky Mountains province; (2) the non-Cordilleran detritus was transported to a position upwind from the Colorado Plateau by a transcontinental paleoriver system having its headwaters in the Appalachian belt, with contributions of non-Appalachian detritus delivered to the trunk stream by both northern and southern tributaries during transit of sediment across the continent; (3) subordinate detritus in the eolian sands was derived from the Permian-Triassic East Mexico magmatic arc as well as the Triassic-Jurassic Cordilleran magmatic arc; (4) arc-flank eolianite south of the Colorado Plateau is composed of plateau eolian sand contaminated with contributions from intervening basement and the enclosing arc assemblage; (5) marine Curtis sand was largely reworked from underlying Entrada eolian sand; (6) fluvial Kayenta sand is an admixture of redistributed eolian sand and younger arc detritus; (7) Springdale provenance in the Cordilleran arc and its basement was distinct from Kayenta provenance; and (8) the youngest detrital zircons in the “Black Ledge” sandstone confirm its affinity with the Glen Canyon Group rather than the Chirle Formation or Group.

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Figure 15. Composite age-distribution curves for samples of Entrada-Bluff (San Rafael Group) eolian sandstone (Fig. 5GJ) and Kayenta (Glen Canyon Group) fluvial sandstones (Figs. 11D, 11E, and 11G) containing arc-derived Cordilleran grains younger than 285 Ma ($n =$ samples; $N =$ grain ages).