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SEDIMENT DELIVERY TO THE CORDILLERAN FORELAND BASIN: INSIGHTS FROM U-Pb AGES OF DETRITAL ZIRCONS IN UPPER JURASSIC AND CRETACEOUS STRATA OF THE COLORADO PLATEAU

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ABSTRACT. In late Mesozoic time, the southern Cordilleran foreland basin was bounded on the west by the Sevier thrust belt and on the south by the Mogollon highlands. Paleocurrent indicators in fluvial and fluviodeltaic strata imply sediment delivery into the basin from both tectonic features. Ages of detrital zircons in sandstones of the basin provide insights into the nature of the sediment sources. Upper Jurassic and Lower Cretaceous fluvial strata were deposited as sediment blankets across the width of the basin but Upper Cretaceous marginal-marine facies were restricted to the basin margin, with marine facies in the basin interior. Most Upper Jurassic and Lower Cretaceous fluvial sandstones contain heterogeneous age populations of Precambrian and Paleozoic detrital zircons largely recycled from Jurassic eolianites uplifted within the Sevier thrust belt or antecedent highlands, and exposed as sedimentary cover over the Mogollon highlands, with only minor contributions of Mesozoic zircon grains from the Cordilleran magmatic arc along the continental margin. Sources in Yavapai-Mazatzal Proterozoic basement intruded by anorogenic Mesoproterozoic plutons along the Mogollon highlands were significant for the Westwater Canyon Member of the Upper Jurassic Morrison Formation and for early Upper Cretaceous (Turonian) fluviodeltaic depositional systems, in which arc-derived Cordilleran zircon grains are more abundant than in older and younger units composed dominantly of recycled detritus. Detrital zircons confirm that the Salt Wash and Westwater Canyon Members of the Morrison Formation formed separate foreland megafans of different provenance. Late Upper Cretaceous (Campanian) fluvial sandstones include units containing mostly recycled sand lacking arc-derived grains in the Sevier foredeep adjacent to the Sevier thrust front, and units derived from both Yavapai-Mazatzal basement and the Cordilleran arc farther east, with some mingling of sand from both sources at selected horizons within the Sevier foredeep. Evidence for longitudinal as well as transverse delivery of sediment to the foreland basin shows that paleogeographic and isostatic analyses of thrust-belt erosion, sediment loads, and basin subsidence in foreland systems need to allow for derivation of foreland sediment in significant volumes from sources lying outside adjacent thrust belts.

INTRODUCTION

The southern end of the late Mesozoic Cordilleran foreland basin (DeCelles, 2004) exposed on the Colorado Plateau was flanked on the west by the Sevier retroarc thrust belt of central Utah and on the south by the Mogollon highlands (fig. 1). The latter formed the northern rift shoulder of the Bisbee basin along the Border rift belt (Dickinson and Lawton, 2001). To address issues of sediment delivery to the foreland basin, we collected 21 samples of Upper Jurassic to Upper Cretaceous fluvial and fluviodeltaic sandstones on the Colorado Plateau from which we determined U-Pb ages of detrital zircon grains to help constrain the nature of sediment sources. A total of 1991 reliable U-Pb ages (concordant or nearly so) for individual zircon grains are available from the sample suite. Deposition of the sampled strata predated the

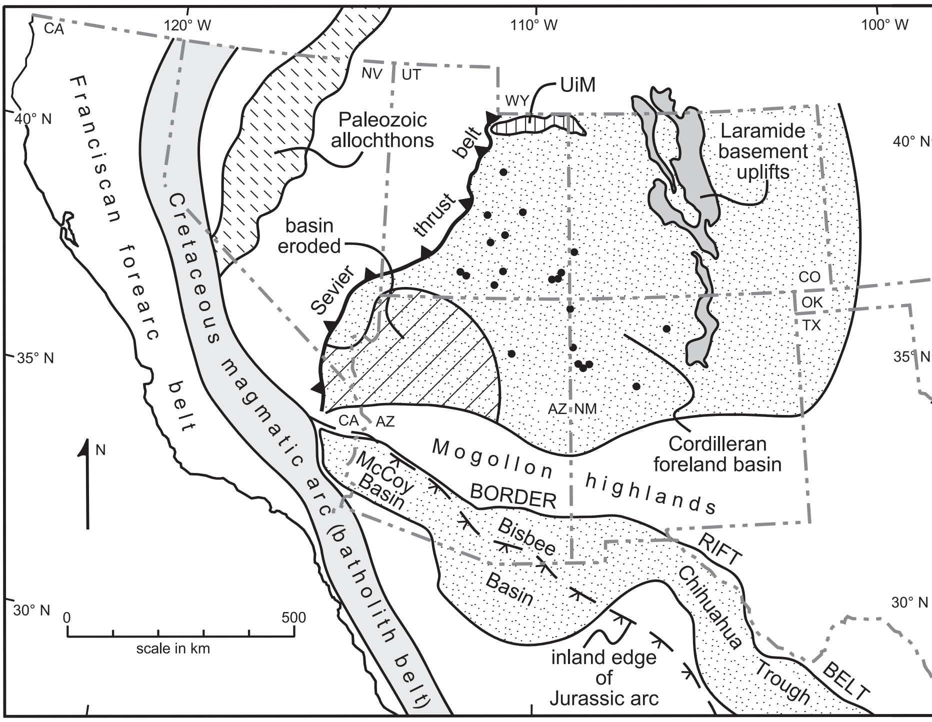

Fig. 1. Tectonic setting of southern end of Jurassic-Cretaceous Cordilleran foreland basin (with Gulf of California closed) showing areal distribution of detrital zircon samples (solid dots). Extent of foreland basin after DeCelles (2004). Border rift belt after Dickinson and Lawton (2001). Mogollon highlands underlain by Paleoproterozoic Yavapai-Mazatzal basement intruded by anorogenic Mesoproterozoic granitic plutons. Paleozoic allochthons in central Nevada after Dickinson (2006). UiM, Uinta Mountains Precambrian exposures (core of Laramide uplift marking north limit of Colorado Plateau). States: AZ, Arizona; CA, California; CO, Colorado; NV, Nevada; NM, New Mexico; OK, Oklahoma; TX, Texas; UT, Utah; WY, Wyoming.

emergence of Laramide basement uplifts that partitioned the southern Cordilleran foreland basin in latest Cretaceous to Paleogene time (fig. 1).

Paleocurrent indicators imply transport of sediment into the interior of the foreland basin from the directions of both the Sevier and Mogollon flanks of the basin. Samples of fluvial Upper Jurassic and Lower Cretaceous strata were collected from across the full span of the Colorado Plateau, but sampling of Upper Cretaceous strata was confined to fluviodeltaic facies exposed around the periphery of the basin near presumed sources in the Sevier thrust belt and Mogollon highlands. Cretaceous marine shoreface and shelf sandstones from the interior of the basin were not collected to avoid any effects of longshore sediment redistribution by strandline processes or marine currents that might confuse patterns of sediment delivery into the basin. Sampling of Upper Cretaceous strata was designed, however to test extant hypotheses for alternate transverse and longitudinal transport of sediment within the flexural foredeep that lay parallel to the Sevier thrust belt (Lawton, 1986b; Lawton and others, 2003).

Our results document derivation of sand in the foreland basin from both the Sevier thrust belt or its antecedents to the west and the Mogollon highlands to the south, in each case partly from recycling of Precambrian and Paleozoic zircon grains eroded from older Mesozoic and possibly Paleozoic strata. The durability of resistant zircon makes sediment recycling, as opposed to contributions directly from granitoid basement rocks, a possibility to be considered in all detrital zircon studies, and this study provides affirmation of its significance.

Descriptions of sample localities (including GPS coordinates) can be found in Appendix 1 and in the supplementary data depository at:
http://earth.geology.yale.edu/~ajs/SupplementaryData/2008/05DickinsonLocalities.pdf

U-Pb age data (full analytical results) for all 21 samples discussed in this paper can be found in the supplementary data repository at:
http://earth.geology.yale.edu/~ajs/SupplementaryData/2008/06DickinsonDataTable.xls

A concordia diagram for each sample and superimposed graphs of age-bin histograms and age-probability plots (age-distribution curves) for grains in each sample falling within the ranges of 0 to 4000 Ma, 0 to 800 Ma, and 800 to 2400 Ma can be found in the supplementary data repository at: http://earth.geology.yale.edu/~ajs/SupplementaryData/2008/07DickinsonPlots.pdf

Preliminary data were presented by Bressmer and others (2006), Hurd and others (2006), Eichler and others (2007), and McGraw and others (2007). Comparative data for the Wahweap Formation of the Kaiparowits Plateau have been reported by Roberts and others (2006) and Link and others (2007).

ANALYTICAL METHODS

Samples of sandstone were collected in plastic buckets of five-gallon capacity as 22 to 24 kg of rock chips <10 cm in largest dimension from selected areas or horizons of the outcrops specified in the accompanying data repository describing sample localities. Zircon grains 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 recovered grains (generally 1000–2000) was incorporated into a 1″ epoxy mount together with fragments of our standard Sri Lanka zircon and SRM 610 trace element glass. The mounts were sanded down to a depth of ~20 microns, polished, imaged, and cleaned prior to isotopic analysis.

For U-Pb analysis by laser ablation, target zircons are preferably >50μm (>0.05 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 grains are expected to be approximately one sand grade (phi size) 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 sand, but we were also able to date zircon grains recovered from the one-third of our samples composed of fine quartzose sand.

Age Determination

U-Pb geochronology of approximately 100 individual zircon grains per sample was conducted by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the Arizona LaserChron Center (Gehrels and others, 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 is carried in helium into the plasma source of a GVI Isoprobe, which is equipped with a flight tube of sufficient width that U, Th, and Pb isotopes are measured simultaneously. All measurements are made in static mode, using Faraday detectors with 10e11 ohm resistors for ^{238}U, ^{232}Th, ^{208}Pb, and ^{206}Pb, a Faraday detector with a 10e12 ohm resistor for ^{207}Pb, and an ion-counting channel for ^{204}Pb. Ion yields are ~1.0 mv per ppm. Each analysis consists of one 12-second integration on peaks with the laser off (for backgrounds), 12 one-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 is ~12 microns in depth.

For each analysis, the errors in determining $^{206}Pb/^{238}U$ and $^{206}Pb/^{204}Pb$ result in a measurement error of ~1 to 2 percent (at 2-sigma level) in the $^{206}Pb/^{238}U$ age. The errors in measurement of $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{204}Pb$ also result in ~1 to 2 percent (at 2-sigma level) uncertainty in age for grains that are >1.0 Ga, but are substantially larger for younger grains due to low intensity of the ^{207}Pb signal. For most analyses, the cross-over in precision of $^{206}Pb/^{238}U$ and $^{206}Pb/^{207}Pb$ ages occurs at ~1.0 Ga.

Common Pb correction is accomplished by using the measured ^{204}Pb and assuming an initial Pb composition from Stacey and Kramers (1975) with uncertainties of 1.0 for $^{206}Pb/^{204}Pb$ and 0.3 for $^{207}Pb/^{204}Pb$. Our measurement of ^{204}Pb is unaffected by the presence of ^{204}Hg because backgrounds are measured on peaks (thereby subtracting any background ^{204}Hg and ^{204}Pb), and because very little Hg is present in the argon gas (background ^{204}Hg = ~300 CPS).

Inter-element fractionation of Pb/U is generally ~20 percent, whereas fractionation of Pb isotopes is generally ~2 percent. In-run analysis of fragments of a large zircon crystal (generally every fifth measurement) with known age of 564 ± 4 Ma (2-sigma error) is used to correct for this fractionation. The uncertainty resulting from the calibration correction is generally 1 to 2 percent (2-sigma) for both $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{238}U$ ages.

Concentrations of U and Th are calibrated relative to our Sri Lanka zircon standard and to SRM 610 trace element glass, which contains ~460 ppm of each element.

Data Presentation

Full analytical data are reported in the accompanying data repository. Age uncertainties (at 1σ) for individual grains in the data table include only measurement errors. Interpreted ages are based on $^{206}Pb/^{238}U$ for <1000 Ma grains and on $^{206}Pb/^{207}Pb$ for >1000 Ma grains. 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 are older than ~1.0 Ga were filtered for discordance by comparison of $^{206}Pb/^{238}U$ and $^{206}Pb/^{207}Pb$ ages; analyses that are >30 percent discordant or >5 percent reverse discordant were not considered further. An average of 95 grain ages were retained per sample, and ovals of age uncertainty for >95 percent of accepted grain ages overlap concordia (see data repository), with others lying close to concordia. Although inclusion of slightly discordant analyses adds some increased scatter to age spectra, this has little impact on our interpretations of detrital zircon populations because all comparisons are based on clusters of grain ages rather than individual ages. This approach insures that inaccurate individual grain ages do not bias contrasts or correlations between age populations in different samples.

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 million years 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 are 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. In actuality, however, the reverse is the case. Age uncertainties for individual grains are commonly larger than the widths of the age bins for the histograms, which are accordingly selective plots of the analytical data incorporating only best estimates of grain ages. 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 to 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 and others, 1986, p. 472-474) to intersample comparisons using an in-house Excel program (available from www.geo.arizona.edu/alc). The K-S test mathematically compares two age distributions, taking the uncertainties of grain ages into account, to determine whether there is a statistically significant difference between the two. The K-S test determines a P-value, which assesses the probability that differences between two age-distribution curves could be due simply to random choice of grains during analysis. Where $P>0.05$, one cannot be 95 percent confident that two age populations were not selected randomly from the same parent population. Where this criterion is met, we conclude that the two age populations are statistically indistinguishable for purposes of assessing provenance relations.

STRATOTECTONIC SETTING

The southern end of the Cordilleran foreland basin occupied the angle between the retroarc Sevier thrust belt on the west and the Mogollon highlands rift shoulder of the Bisbee basin on the south (fig. 1). The most proximal basin fill near the join between those two potential sources of foreland sediment has been removed by erosion in the Grand Canyon region of northwestern Arizona (fig. 1). Remnants of the foreland basin fill preserved on the tectonic enclave of the Colorado Plateau were structurally isolated from eastern and northern extensions of the foreland basin by Laramide basement uplifts that formed in latest Cretaceous to early Paleogene time (Chapin and Cather, 1981, 1983). Intrabasinal thickness relations document initial growth of Laramide structures late in Campanian time (Lawton, 1986b; Cather, 2004), but lateral continuity of sedimentation within the foreland basin was not disrupted until Maastrichtian time (Dickinson and others, 1988).

Our sample array spanned >500 km from Utah just east of the Sevier thrust belt to New Mexico north of the Mogollon highlands (fig. 1). For sample collection, we targeted four horizons where correlative sandstone-rich lithofacies are present throughout the study area except where removed by Cenozoic erosion (fig. 2): (1) Upper Jurassic (Kimmeridgian) fluvial units of the lower Morrison Formation; (2) basal units (Barremian) of the Lower Cretaceous Cedar Mountain and Burro Canyon Formations; (3) Turonian members or lateral equivalents of the Mancos Shale; and (4) Campanian formations of the Mesaverde Group. By focusing on specific stratigraphic intervals within the basin, we sought to avoid potentially misleading comparisons of detrital-zircon age populations in non-correlative strata. Two additional samples were collected from sandstone-rich lithofacies equivalent to or overlying the upper Morrison (Tithonian) Brushy Basin Member to ascertain whether the ages of detrital zircons near the

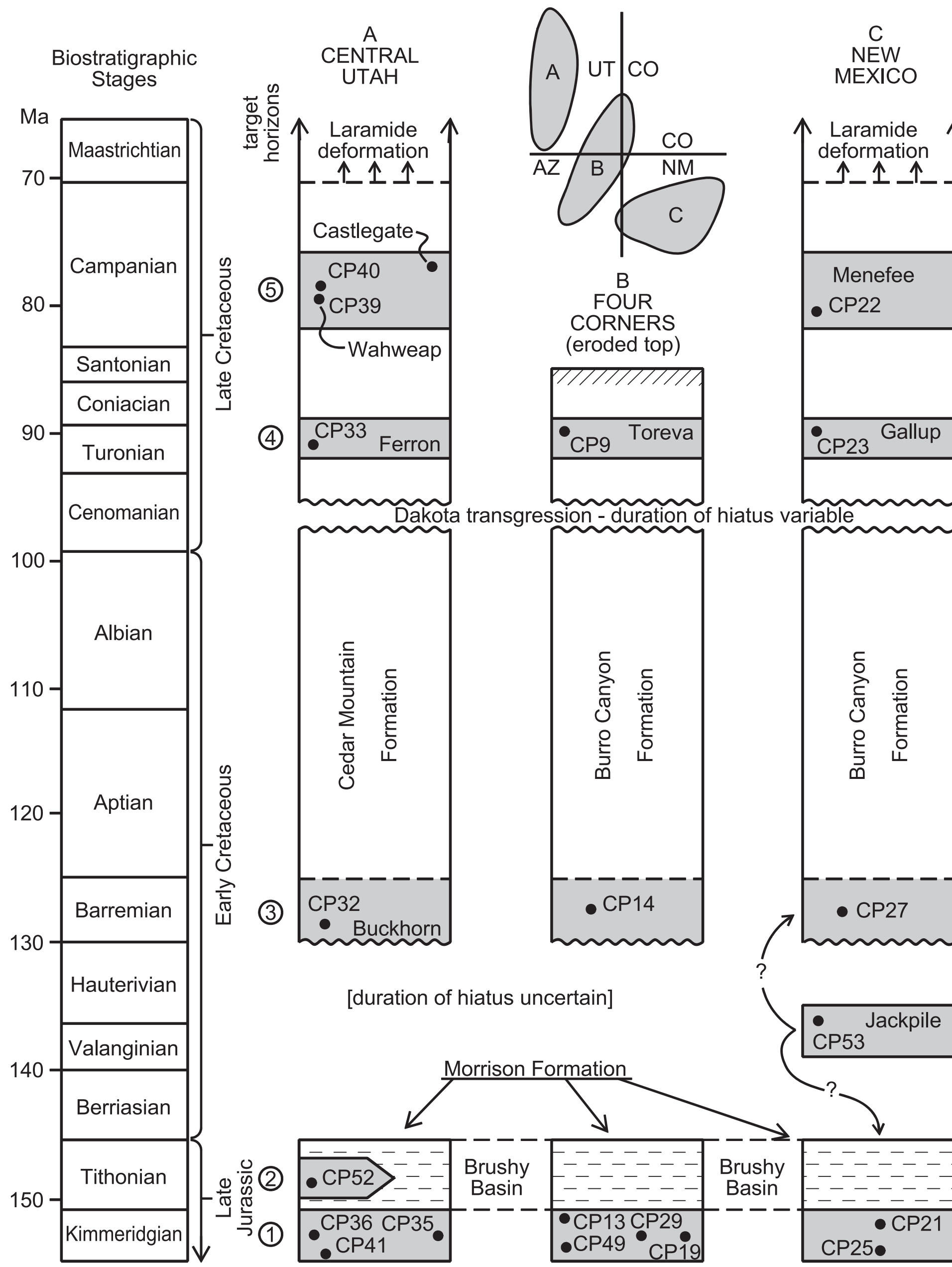

Fig. 2. Stratigraphic positions of detrital zircon samples (solid dots) in Upper Jurassic to Upper Cretaceous strata of the Colorado Plateau within five targeted time-stratigraphic intervals (shaded): (1) Kimmeridgian lower Morrison Formation (Tidwell, Salt Wash, Recapture, Westwater Canyon Members); (2) Tithonian upper Morrison Formation (Fiftymile Member, correlative with finer grained Brushy Basin Member); (3) Barremian basal Cedar Mountain (Buckhorn Conglomerate Member) and Burro Canyon Formations; (4) middle to upper Turonian sandstone tongues and lateral equivalents of lower Upper Cretaceous Mancos Shale; (5) lower to middle Campanian sandstone units of upper Upper Cretaceous Mesaverde Group. Designated stratal intervals are variously named local formations and members discussed in text (but Jackpile correlation uncertain). Sketch map at top center shows areal span of stratigraphic columns (AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah). Correlations adapted after Molenaar (1977, 1983), Peterson and Kirk (1977), Fouch and others (1982, 1983), Owen and others (1984), Tschudy

Jurassic-Cretaceous time boundary within the basin more closely resemble those in underlying or overlying strata.

The Morrison Formation (fig. 2) was deposited during the late phases of active rifting (165-145 Ma) along the keel of the Bisbee basin to the south (Dickinson and Lawton, 2001; Lawton, 2004). An uplifted rift shoulder forming the Mogollon highlands was a potential sediment source during Morrison deposition (Lawton, 2004; Lucas, 2004). Postrift thermotectonic subsidence of the Bisbee trough continued through Early Cretaceous time during a prolonged post-Morrison hiatus or interval of condensed sedimentation (fig. 2), and throughout succeeding Cedar Mountain–Burro Canyon sedimentation. The relict Mogollon highlands were not onlapped by sediment until the mid-Cretaceous Dakota transgression (fig. 2), hence may still have been partly emergent as a positive tectonic feature early in Late Cretaceous time during deposition of our Turonian target units, but were largely buried during deposition of our Campanian target units. Basal Upper Cretaceous marine strata also spread beyond the Mogollon highlands over at least the eastern remnants of the Bisbee basin (Lucas and Lawton, 2005). Later in Cretaceous time, the Bisbee basin was structurally inverted (Bayona and Lawton, 2003), and succeeded by multiple Campanian-Maastrichtian successor basins associated with Laramide magmatism (Dickinson and Lawton, 2001).

The timing of initial thrusting along the Sevier belt in Utah is controversial, with two opposing viewpoints: (1) Sevier thrusting was not initiated until Albian time (Bohannon, 1983; Cross, 1986; Heller and others, 1986; Villien and Kligfield, 1986; Yingling and Heller, 1992), or possibly Aptian time (Schwans, 1988; DeCelles and others, 1995), but in either case late in Early Cretaceous time; (2) thrusting along ancestral faults west of the frontal Sevier thrusts was initiated by Late Jurassic time (DeCelles and Currie, 1996). In the former interpretation, Morrison and basal Cedar Mountain sedimentation preceded active Sevier thrusting (Heller and others, 1988; Heller and Paola, 1989). In the latter interpretation, Morrison and Cedar Mountain strata were deposited in a subdued backbulge basin, with Cedar Mountain strata prograding eastward over the crest of a forebulge that migrated across the Colorado Plateau in Early Cretaceous time (Currie, 1997, 1998). The latter perspective relates the prolonged hiatus and condensation of section between Morrison and Cedar Mountain strata to forebulge migration.

The thickness of Cretaceous strata exceeds 3500 m in the flexural foredeep of central Utah adjacent to the Sevier thrust belt (Lawton, 1986a; DeCelles, 2004), with stratal thinning eastward to no more than half that thickness near the Utah-Colorado border. Subsidence to accommodate 1500 m of Cretaceous marine strata in the San Juan basin of northwestern New Mexico (Nummedal and Molenaar, 1995) adjacent to the northeastern flank of the Mogollon highlands (fig. 1) cannot be ascribed, however, to flexural effects of Sevier thrust loads emplaced 500 km to the northwest. Instead, a component of dynamic subsidence (Mitrovica and others, 1989), induced by the presence of a subducted slab beneath the foreland, can be invoked to account for the broad pattern of subsidence observed (Pang and Nummedal, 1995). Dynamic subsidence of a continental surface can extend 1000 km beyond the flexural foredeep (Burgess and Moresi, 1999).

Regressive lithofacies represented by the Turonian and Campanian fluviodeltaic sandstones that we sampled for detrital zircons occur in both the Sevier foredeep and

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and others (1984), Lawton (1986b), Eaton and others (1987), Eaton and Nations (1991), Kowallis and others (1991, 1998), Aubrey (1992, 1996), Shanley and McCabe (1993, 1995), Elder and Kirkland (1994), Kirkland and others (1997), Lucas and Anderson (1997), Litwin and others (1998), Turner and Peterson (1999), Lawton and others (2003), Nummedal (2004), and Kirkland and Madsen (2007).

the San Juan basin (fig. 2). As simultaneous tectonic events cannot readily be invoked to foster contemporaneous regressions in disparate tectonic settings, Nummedal (2004) inferred a eustatic influence on the shoreline migrations. Sequence stratigraphic charts for global eustasy afford no fully satisfactory match, however, for the observed plateau stratigraphy (Hardenbol and others, 1998). A rise in global sea level coincided with the mid-Cretaceous transgression associated with widespread deposition of the Dakota Sandstone (fig. 2), and falling sea level coincided with regressive upper Turonian lithofacies, but regressive lower to middle Campanian lithofacies coincided with a postulated rise in global sea level. If widespread aggradation of the latter is ascribed to eustasy, control must apparently be attributed to increased accommodation space.

STRATIGRAPHIC CONTEXT

Sampled stratigraphic intervals are discussed in three generic groups: (1) Upper Jurassic Morrison Formation, (2) Lower Cretaceous Cedar Mountain and Burro Canyon Formations, and (3) the Upper Cretaceous Mancos-Mesaverde succession.

Morrison Formation

The Upper Jurassic Morrison Formation (figs. 2 and 3) was deposited after drift of the Colorado Plateau northward from the subtropical arid zone into the mid-latitude belt of westerly winds (Dickinson, 2005). Fluvial paleosols record progressively more humid conditions during the course of Morrison sedimentation (Demko and others, 2004), but initial floodplains were dry enough to harbor local eolian deposits (Condon, 1998). Morrison strata form a sediment blanket 100 to 200 m thick over 150,000 km^2 of the Colorado Plateau from the Sevier foreland eastward to the Rio Grande rift, and paleocurrent indicators document consistent fluvial paleoflow toward the northeast and east (fig. 3).

The base of the Morrison Formation, overlying tidalite-sabkha and associated eolian strata of the San Rafael Group, is a surface commonly termed the J-5 unconformity (Pipiringos and O'Sullivan, 1978). Despite local scour at the contact beneath fluvial channel or sheetflood deposits, lack of evidence for substantial erosion of the substratum suggests that the contact may reflect the progradation of a fluvial system across marginal-marine environments without a marked hiatus in sedimentation. The onset of Morrison deposition coincided with the initial emergence of Cordilleran highlands which shed clastic detritus toward the northeast. Interpreting the contact in terms of sequence stratigaphy controlled by eustasy is unattractive because the paleoshoreline lay to the northwest during San Rafael sedimentation but to the northeast during Morrison sedimentation.

Over much of the area, the lower (Kimmeridgian) phase of Morrison sedimentation deposited a sandstone-rich succession (Salt Wash Member) favorable for collection of detrital zircons of sand size (fig. 2), but the upper (Tithonian) phase deposited an unfavorable sandstone-poor succession (Brushy Basin Member). The Morrison Formation is overlapped to the southwest by the mid-Cretaceous Dakota Sandstone (fig. 3), and its most proximal facies along the flank of the Mogollon highlands were removed by pre-Dakota erosion. Near the leading edge of the Sevier thrust belt, the Morrison Formation is overlapped westward by Lower Cretaceous strata of the Indianola Group (fig. 3), and it is not present within Sevier thrust sheets (Witkind and others, 1986; Lawton and Willis, 1987).

Salt Wash Member.—The Salt Wash Member includes lenticular, locally pebbly, and internally cross-bedded sandstone bodies, representing paleochannel complexes, which are intercalated with discontinuous siltstone-mudstone intervals representing slackwater and overbank deposition (Mullens and Freeman, 1957; Petersen and Roylance, 1982; Tyler and Ethridge, 1983; Peterson, 1984). Horizontally laminated sandstone

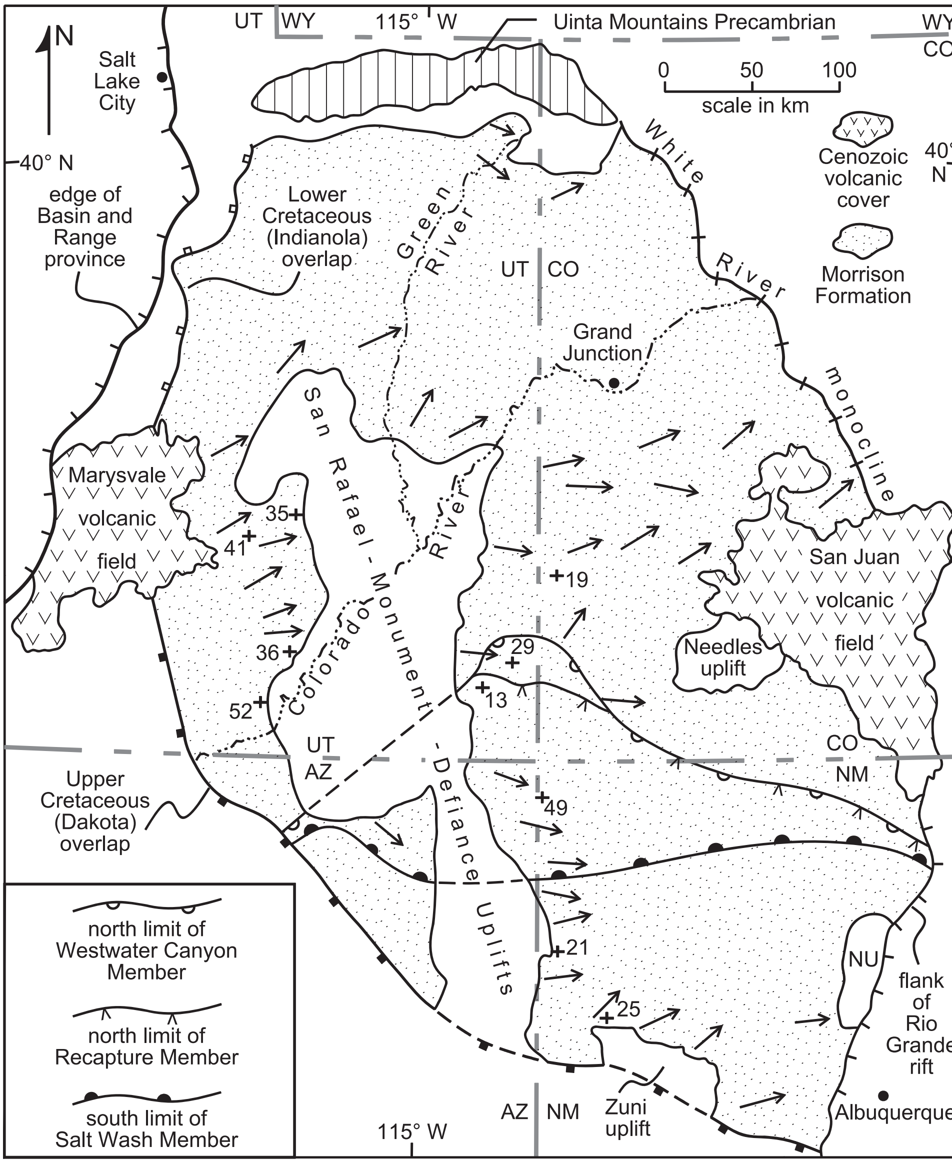

Fig. 3. Distribution of Upper Jurassic (Kimmeridgian-Tithonian) Morrison Formation (outcrop, subcrop, outliers) on Colorado Plateau (substratum is Middle to Upper Jurassic San Rafael Group). Crosses denote sample localities (prefix CP omitted from numbers) for detrital zircons. NU is Nacimiento uplift. Arrows are lower Morrison fluvial paleocurrent trends after Craig and others (1955), Peterson (1984), Currie (1998), and Robinson and McCabe (1998). Geographic limits of selected members near Four Corners (AZ-UT-CO-NM junction) adapted after Craig and others (1955), Beaumont and Dixon (1965), Ekren and Houser (1965), Huff and Lesure (1965), Cooley and others (1969), Lupe (1983), Condon and Peterson (1986), and Condon and Huffman (1994a, 1994b). States: AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah; WY, Wyoming.

intervals represent both intrachannel and crevasse-splay deposits, and local limestone lenses record lacustrine to palustrine deposition in isolated floodplain ponds and wetlands. Severely restricted occurrences of lateral-accretion bedding indicate limited stream sinuosity in a dominantly braided stream environment (Peterson, 1984; Robinson and McCabe, 1997, 1998). Areally, the Salt Wash Member forms a lobate body with its apex near the Colorado River (fig. 3) where its thickness is ≥125 m, and can be regarded as a foreland megafan (Leier and others, 2005) sourced in highlands lying to the southwest of the Colorado Plateau.

Brushy Basin Member.—The Brushy Basin Member forms an overlying blanket, 100 ± 30 m thick, of finer grained strata deposited on a muddy floodplain traversed by sluggish stream channels and dotted with floodplain lakes of varying size (Bell, 1986; Anderson and Lucas, 1997; Currie, 1998). To the southwest, the Brushy Basin Member grades laterally to the coarser grained Fiftymile Member (Peterson, 1988), sampled for this study, exposed only on the rim of the Kaiparowits Plateau near the Colorado River (fig. 4).

Recapture Member.—Facies changes led to differences in internal Morrison stratigraphy between the San Juan basin and areas to the north and northwest (fig. 4). Near the

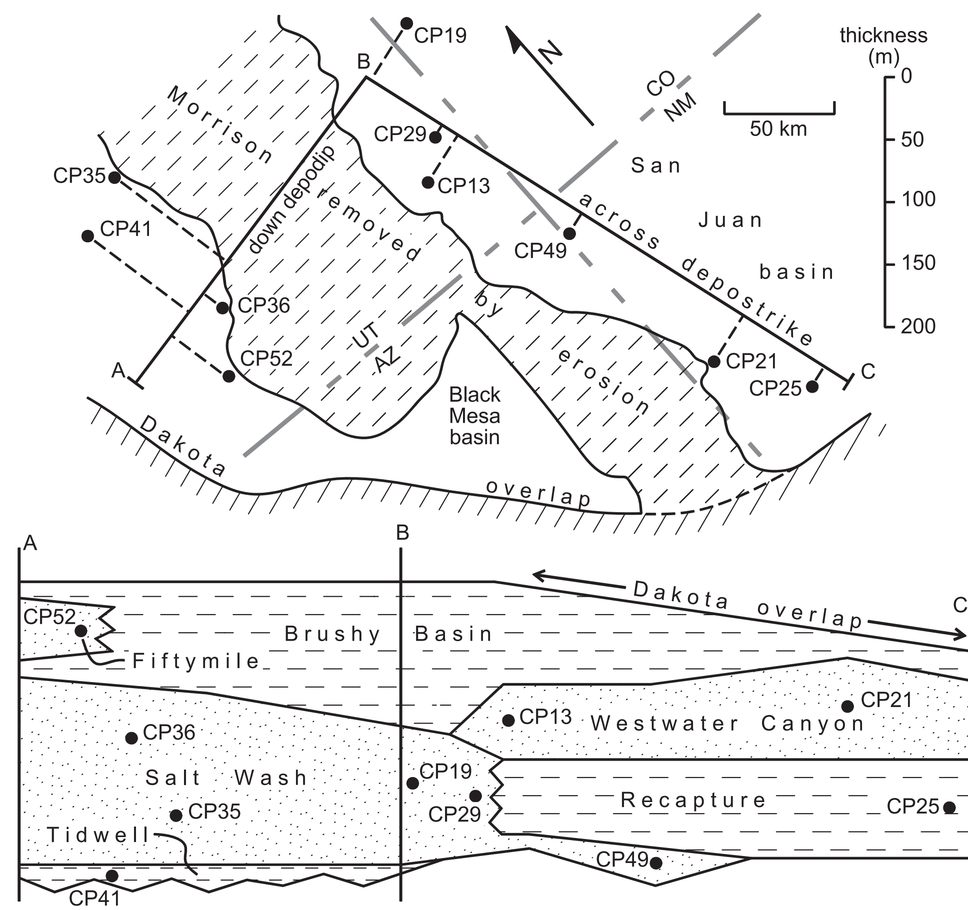

Fig. 4. Schematic stratal architecture (named members) of Upper Jurassic Morrison Formation from Sevier foreland (northwest) to San Juan basin (southeast). Samples projected arbitrarily at right angles to dogleg line of section. Thicknesses approximate. Stipples denote sandstone-rich units; dashes denote sandstone-poor units. Adapted after Craig and others (1955), Condon and Peterson (1986), Anderson and Lucas (1997, 1998), and Turner and Peterson (2004). States: AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah.

Four Corners juncture of AZ-CO-NM-UT (fig. 3), the Salt Wash Member grades southward by intertonguing into finer grained fluvial strata of the Recapture Member (Ekren and Houser, 1965; Huff and Lesure, 1965; Craig and Shawe, 1975; Turner and Peterson, 2004), within which channel sandstone lenses are dispersed in redbed overbank deposits, and is overstepped southward by the Recapture Member (Beaumont and Dixon, 1965; Cooley and others, 1969; Condon and Peterson, 1986). Regional paleocurrent trends (fig. 3) indicate that the Recapture Member is a lateral, rather than a downstream, facies of the Salt Wash Member.

Westwater Canyon Member.—Overlying the Recapture Member in the San Juan basin is a sandstone-rich succession termed the Westwater Canyon Member (figs. 3 and 4), which grades northward into the base of the Brushy Basin Member and perhaps into the uppermost Salt Wash Member as well (Huff and Lesure, 1965; Craig and Shawe, 1975). In stratigraphic terms, the Westwater Canyon Member has been treated as a tongue of the Salt Wash Member (Anderson and Lucas, 1997, 1998), but contrasts in petrofacies and detrital zircon content (see below) suggest deposition of the two members as separate foreland megafans. The Westwater Canyon Member is a composite sheet of multistory channel complexes, separated by thin intervals of finer grained overbank deposits, having an average thickness of 60 m that locally ranges upward to 90 m (Campbell, 1976; Turner-Peterson, 1986). Horizontal laminations indicative of the upper flow regime, crossbeds reflecting downstream accretion on intrachannel bars, and locally prominent lateral-accretion beds formed on point bars jointly imply deposition by intermittent streamflow of seasonal or multiannual recurrence (Miall and Turner-Peterson, 1989).

Tidwell Member.—In central Utah, channel complexes of the Salt Wash Member are underlain by the discontinuous Tidwell Member (fig. 4) of finer grained sheetflood and overbank strata with intercalations of lacustrine deposits (O'Sullivan, 1984; Peterson, 1988). Thicknesses are most commonly 15 to 25 m (Bernier and Chan, 2006), and the base of the Tidwell Member is commonly marked by a horizontally laminated sheetflood sandstone bed (termed "Bed A") <2 m thick. Above Bed A, thin sandstone bodies within the Tidwell Member are lenticular overbank lenses, unlike the laterally extensive thin sheets of sandstone within tidalite-sabkha successions of the underlying San Rafael Group. The top of the Tidwell Member is commonly marked by channel scour beneath coarser sandstone beds at the base of the overlying Salt Wash Member, but the two members locally intertongue. Deposition of the Tidwell Member reflected the spread of extrachannel crevasse splays and downstream sheetfloods from prograding Salt Wash channel complexes (Bernier and Chan, 2006). From a lithological standpoint with an emphasis on grain size, the Tidwell member can be viewed as an upward continuation of the underlying San Rafael Group (Lucas and others, 2006), but from a sedimentological standpoint is part of the Morrison fluvial system, and was accordingly sampled for this study.

Jackpile Member.—Near the southeastern extremity of the Colorado Plateau, the Jackpile Sandstone Member (Owen and others, 1984) overlies the Brushy Basin Member but is only locally preserved beneath the Dakota overlap (fig. 4). Long regarded as uppermost Morrison Formation (Condon and Peterson, 1986; Anderson and Lucas, 1996; Lucas and Anderson, 1998), the Jackpile has alternately been correlated with the Lower Cretaceous Burro Canyon Formation (Aubrey, 1992). As the unit is an important host for uranium ore (Moench and Schlee, 1967), we collected detrital zircons as a potential means to clarify its uncertain stratigraphic relationships.

Cedar Mountain-Burro Canyon Formations

Post-Morrison but pre-Dakota Lower Cretaceous fluvial strata (figs. 2 and 5) of the Colorado Plateau are by convention termed Cedar Mountain Formation and Burro Canyon Formation west and east, respectively, of the Colorado River (Tschudy and

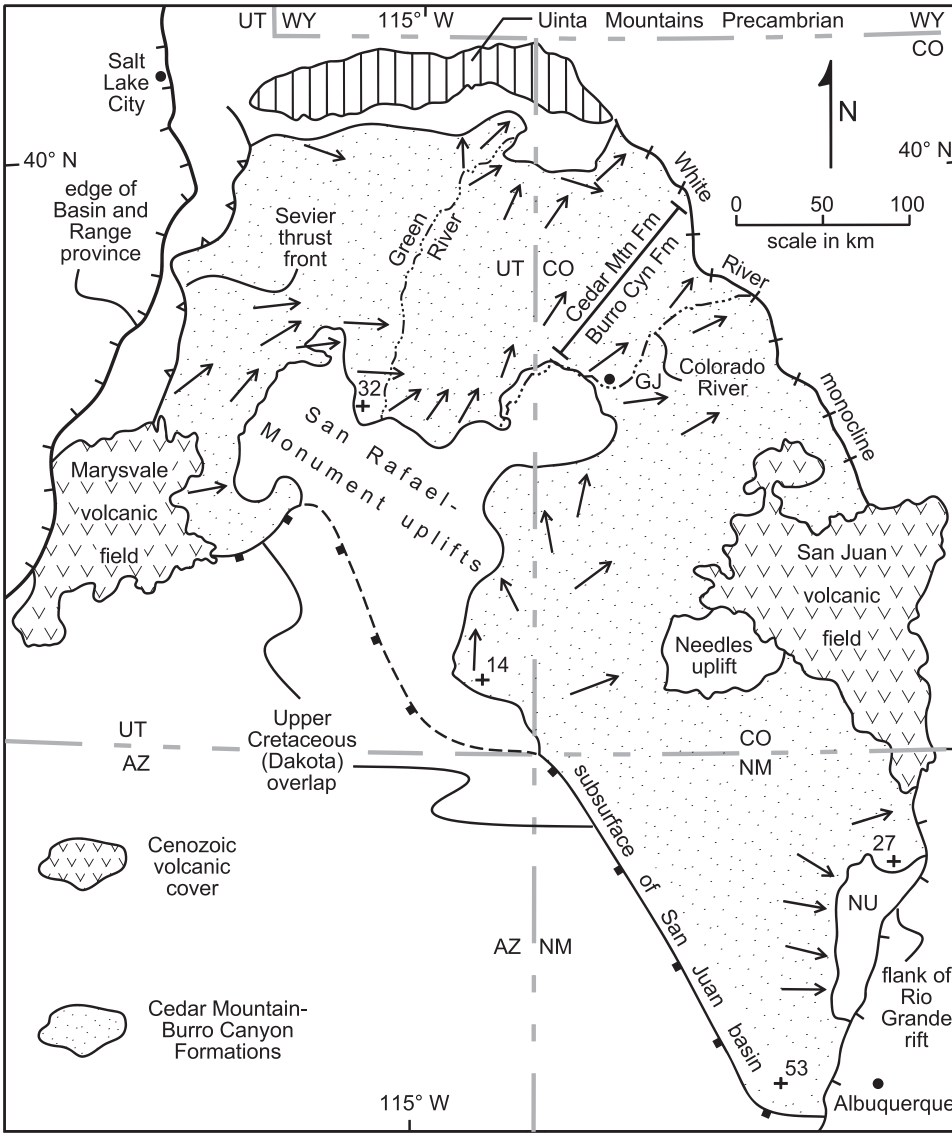

Fig. 5. Distribution of correlative Lower Cretaceous Cedar Mountain (northwest) and Burro Canyon (southeast) Formations on Colorado Plateau (substratum is Upper Jurassic Brushy Basin Member of Morrison Formation). Crosses denote sample localities (prefix CP omitted from numbers) for detrital zircons. GJ is Grand Junction; NU is Nacimiento uplift. Arrows are fluvial paleocurrent trends in Burro Canyon Formation and basal Buckhorn Conglomerate Member of Cedar Mountain Formation from Harris (1980), Craig (1981), Aubrey (1992), and Currie (1998, 2002). Position of Dakota overlap adapted after Cooley et al. (1969), Stuart-Alexander et al. (1972), Lupe (1983), Condon and Huffman (1994a, 1994b), and Kirkland and Madsen (2007). States: AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah; WY, Wyoming.

others, 1984; Aubrey, 1996; Kirkland and Madsen, 2007). Both formations include sandstone-conglomerate and mudstone-siltstone representing channel and overbank deposition, respectively (Shawe and others, 1968; Aubrey, 1996; Currie, 1997). Paleosols are present at multiple horizons both below and within the Cedar Mountain–

Burro Canyon succession (Kirkland and Madsen, 2007), and the hiatus of ~15 million years between Morrison and Cedar Mountain-Burro Canyon deposition (fig. 2) may be partly filled by condensed fluvial successions. Aptian-Albian faunas are most widespread in the Cedar Mountain–Burro Canyon interval (Tschudy and others, 1984; Currie, 1997; Lucas and Anderson, 1997), but local faunal evidence indicates that the succession also includes Barremian strata near its base (Kirkland and others, 1997; Eberth and others, 2006; Kirkland and Madsen, 2007). The Cedar Mountain Formation at least locally extends upward to include Cenomanian (lowermost Upper Cretaceous) strata by current calibrations of the Cretaceous timescale (Cifelli and others, 1997). Recently obtained palynological data (Currie and others, 2008) indicating a late Albian to early Cenomanian age for the overlying Dakota Formation has uncertain implications for the age span of the Cedar Mountain Formation. U-Pb ages for zircons from ash beds in the upper Cedar Mountain Formation range from 125 Ma to 110 Ma (Greenhalgh and others, 2006; Burton and others, 2007), consistent with Aptian-Albian deposition.

The Cedar Mountain Formation thickens from <50 m to >100 m toward the Sevier thrust belt into which stratal equivalents are incorporated (Sprinkel and others, 1999), but the Burro Canyon Formation forms a widespread sediment blanket ~50 m thick throughout its extent. Paleocurrent trends subparallel to the arbitrary stratal boundary (fig. 5) suggest that the two formations are lateral equivalents along depositional strike, rather than being upstream-downstream facies along depositional dip. Cedar Mountain derivation from the Sevier thrust belt and Burro Canyon derivation from the Mogollon highlands are implied. A greater proportion of sandstone within the Burro Canyon Formation (Craig, 1981) reinforces that inference because a fluvial system sourced in the Sevier thrust belt would be expected to become finer grained toward the east.

Both Lower Cretaceous formations are truncated by the Dakota overlap toward the southwest (Peterson and others, 1980; Owen and others, 2005; Kirkland and Madsen, 2007) along the northern flank of the Mogollon highlands (fig. 5). The duration of the hiatus at the contact is variable (Molenaar and Cobban, 1991), and uncertain in many places for lack of close faunal control (fig. 2). Incision of fluvial floodplains to depths of 10 to 25 m before or during Dakota transgression may reflect either structural relief on a migratory basin forebulge (Currie, 2002) or eustasy within the mid-continent seaway to the east (Aubrey, 1989). Barremian to Aptian (syn-Cedar Mountain–Burro Canyon) drawdown in global sea level was followed by Albian to Cenomanian (syn-Dakota) rise in sea level (Hardenbol and others, 1998).

Samples for detrital zircons derive from the basal Buckhorn Conglomerate Member of the Cedar Mountain Formation in central Utah and from sandstone bodies forming the base of the Burro Canyon Formation at two localities well to the southeast (figs. 2 and 5). A prominent calcrete paleosol separates Buckhorn Conglomerate from the remainder of the Cedar Mountain Formation (Currie, 1998), suggesting that the Buckhorn might represent a closing phase of Morrison sedimentation (Roca and Nadon, 2007), and an analogous calcrete horizon overlies basal sandstone bodies of the Burro Canyon Formation (Aubrey, 1998). The Buckhorn Conglomerate Member extends eastward, however, past an arbitrary change in nomenclature at the Green River, into the Poison Strip Sandstone Member, which overlies the Yellow Cat Member containing Early Cretaceous (Barremian) dinosaur remains (Kirkland and others, 1997; Kirkland and Madsen, 2007). Moreover, recent stratigraphic studies show that the Buckhorn Conglomerate Member and the Yellow Cat Member partly intertongue (Greenhalgh and others, 2007). These relations place Buckhorn and equivalent strata chronostratigraphically (fig. 2) within the Cedar Mountain–Burro Canyon succession. Nevertheless, gradational or intertonguing relationships have been described between the Brushy Basin Member of the Morrison Formation and the overlying Burro Canyon Formation (Shawe and others, 1968; Aubrey, 1992), leaving the formational assignment of sparsely fossiliferous strata in doubt over wide areas.

Mancos-Mesaverde Sedimentation

Except within the Henry Mountains and Black Mesa structural basins of Laramide age, exposures of post-Dakota marine Cretaceous strata are restricted to the periphery of the Colorado Plateau, and are masked by Tertiary strata beneath depocenters of the Laramide Uinta-Piceance and San Juan basins (fig. 6). Our samples of nonmarine sandstone derive from the Sevier foredeep in front of the Sevier thrust belt, and from proximal facies preserved in the Black Mesa and San Juan basins flanking the Mogollon highlands. Paleocurrents and paleoshoreline migration jointly imply sediment transport toward the interior of the southern Cordilleran foreland basin from both its Sevier and Mogollon margins (fig. 6).

Three Turonian samples (fig. 2) of comparable fluviodeltaic facies span nearly 500 km of the southwestern margin of the basin (fig. 6): (1) CP33 from a fluviodeltaic channel lens (Cotter, 1971) in the Ferron Sandstone (Ryer and Anderson, 2004; Xu, 2007), which intertongues with Mancos Shale (Peterson and Ryder, 1975) in the Sevier foredeep; (2) CP9 from a sheet of fluviodeltaic sandstone forming the progradational upper tier (Page and Repenning, 1958) of the lower Toreva Formation (Repenning and Page, 1956), a regressive succession overlying Mancos Shale in the Black Mesa basin (Eaton and Nations, 1991); (3) CP23 from the upper tier of progradational fluviodeltaic sandstone (Flores and others, 1991) in the Gallup Sandstone, which intertongues with Mancos Shale of the San Juan basin (Nummedal and Molenaar, 1995).

Three of four Campanian samples (fig. 2) derive from the Sevier foredeep, with an additional sample from the San Juan basin, but correlative strata have been removed by erosion from the intervening Black Mesa basin. The samples from the Sevier foredeep are fluvial sandstones associated with progradational advance of regressive Mesaverde facies into marine facies of the foredeep: (1) CP34 from the Castlegate Sandstone, deposited on a fluvial braidplain (Lawton, 1986b; Miall, 1993; Olsen and others, 1995; McLaurin and Steel, 2007) shed eastward from Sevier thrust sheets (Chan and Pfaff, 1991; Horton and others, 2004); (2, 3) CP39 and CP40 from the Wahweap Formation, the former from the upper member with paleocurrents from the southwest out of the syntaxis between the Sevier thrust belt and the Mogollon highlands (fig. 1), and the latter from the capping member with paleocurrents from the northwest off the nearby Sevier thrust belt (Lawton and others, 2003). The sample (CP22) from the San Juan basin derives from a lenticular fluviodeltaic sand body within the Menefee Formation, a tapering wedge of nonmarine deltaic strata enclosed by time-transgressive marine sandstone formations, regressive below and transgressive above (Nummedal, 2004).

SANDSTONE PETROGRAPHY

Table 1 and figure 7 list and plot the detrital modes (petrofacies) of the sandstone samples collected for detrital zircons. Most samples are sublitharenite in the classification of McBride (1963), but samples from the Westwater Canyon Member of the Morrison Formation and Turonian equivalents of the Mancos Shale are distinctly more feldspathic subarkose, and the Campanian Menefee sample is both less quartzose and more lithic than other samples. Table 2 shows the similarity of detrital modes for (1) Morrison quartzose (Upper Jurassic), Lower Cretaceous, and most Campanian (Upper Cretaceous) samples; and (2) Morrison feldspathic (Upper Jurassic) and Turonian (Upper Cretaceous) samples. Two of the three least quartzose sublitharenites in QmFLt space (fig. 7) contain abundant chert (Qp) grains (table 1), and would plot as

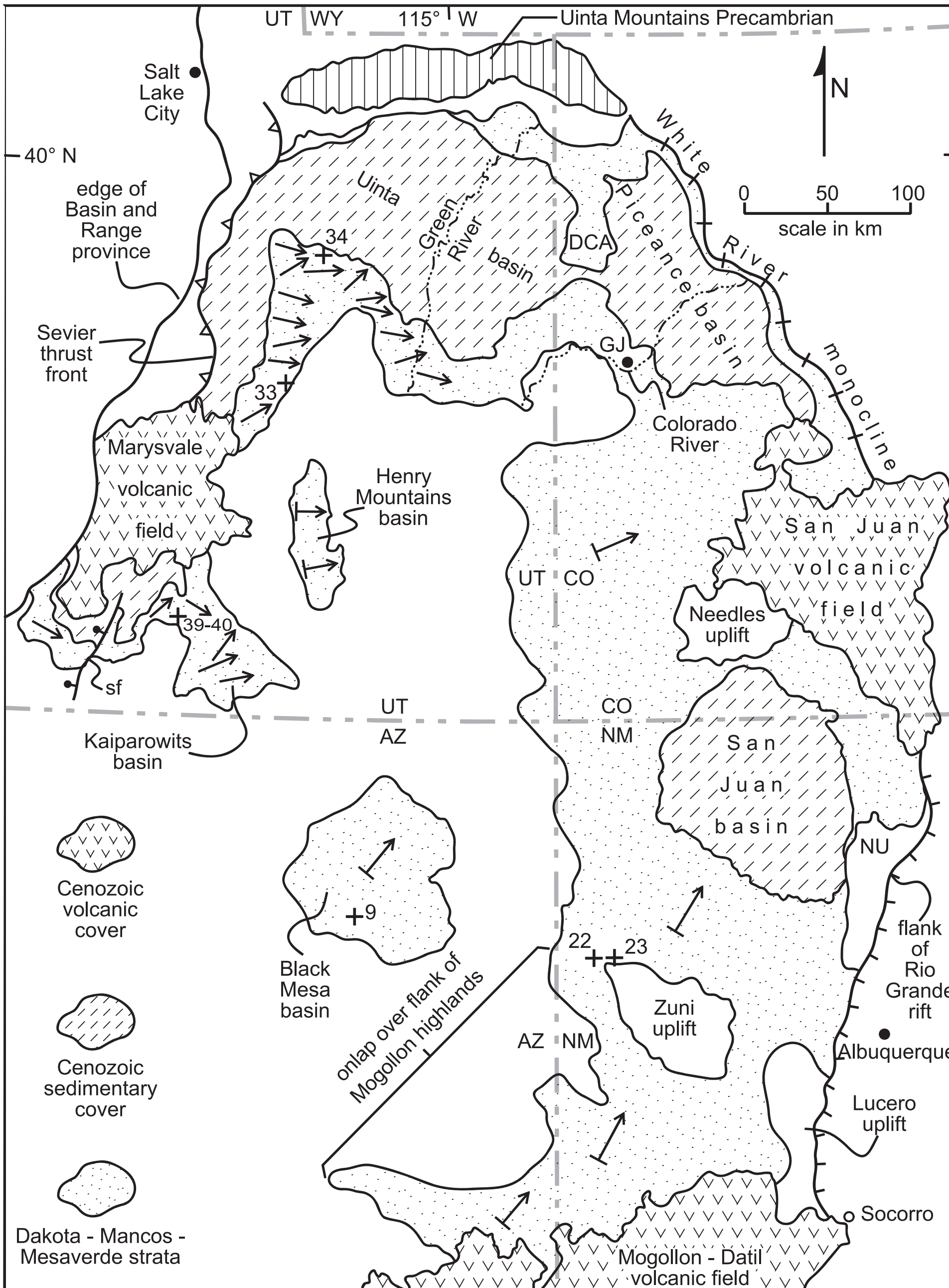

Fig. 6. Distribution of Upper Cretaceous Mancos Shale and Mesaverde Group (and correlatives) on Colorado Plateau including underlying mid-Cretaceous Dakota Formation. Crosses denote sample localities (prefix CP omitted from numbers) for detrital zircons. DCA, Douglas Creek arch; GJ, Grand Junction; NU, Nacimiento uplift; Sf, Sevier fault. Arrows without ticks indicate fluvial and fluviodeltaic paleocurrent trends in Utah after Van de Graaff (1972), Lawton (1986), Dickinson and others (1986), Olsen and others (1995), Robinson and Slingerland (1998), and Lawton and others (2003). Arrows with ticks on tails indicate directions of paleoshoreline migration during progradational regressions after Molenaar (1983). States: AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah; WY, Wyoming.

Table 1

Detrital modes[1] of detrital zircon samples[2] from Jurassic-Cretaceous strata of the Colorado Plate Detrital modes[1] of detrital zircon samples[2] from Jurassic-Cretaceous strata of the Colorado Plateau[3]

Morrison Formation (N=10)										
	A. Miscellaneous (N=3)[4]			B. Salt Wash Member (N=5)					C. Westwater Canyon Member (N=2)	
Grains[5]	CP41	CP52	CP25	CP36	CP35	CP29	CP49	CP19	CP13	CP21
Qm	79	87	85	90	83	88	81	91	67	71
Qp	5	3	2	3	14	3	2	3	1	2
Qt	84	90	87	93	97	91	83	94	68	73
P	2	2	5	1	tr	1	3	1	4	8
K	10	2	5	3	2	4	6	1	16	12
F	12	4	10	4	2	5	9	2	20	20
Lvm	2	3	1	2	tr	3	5	1	6	5
Lsm	2	3	2	1	1	1	3	3	6	2
L	4	6	3	3	1	4	8	4	12	7
Lt	9	9	5	6	15	7	10	7	13	9

Post-Morrison Formation (N=11)											
	D. Cedar Mountain–Burro Canyon–Jackpile (N=4)[6]				E. Mancos (N=3)[7] [Turonian]			F. Mesaverde (N=4)[8] [Campanian]			
Grains[5]	CP32	CP14	CP53	CP27	CP33	CP9	CP23	CP39	CP40	CP34	CP22
Qm	82	90	84	89	74	75	74	77	92	90	54
Qp	10	5	3	5	2	tr	1	7	4	3	9
Q	92	95	87	94	76	75	75	84	96	93	63
P	1	1	3	1	7	6	7	1	1	1	9
K	2	1	5	1	12	15	13	2	1	1	10
F	3	2	8	2	19	21	20	3	2	2	19
Lvm	2	1	2	1	3	2	2	3	1	2	13
Lsm	3	2	3	3	2	2	3	10	1	3	5
L	5	3	5	4	5	4	5	13	2	5	18
Lt	15	8	8	9	7	4	6	20	6	8	27

[1] Modes based on point counts of 400 QFL framework grains per sample.
[2] See Appendix 1 for sample localities (listed west to east within each group).
[3] N is number of samples in each tabulated group.
[4] CP41, Tidwell Member; CP52, Fiftymile Member; CP25, Recapture Member.
[5] Monocrystalline grains: Qm, quartz; P, Plagioclase; K, K-feldspar; F, total feldspar (P + K). Polycrystalline grains: Qp, polycrystalline quartz (dominantly chert); Lvm, volcanic and metavolcanic lithic fragments; Lsm, sedimentary and metasedimentary lithic fragments; L, total labile lithic fragments (Lvm + Lsm); Lt, total lithic fragments (L + Qp). Qt is total quartzose grains (Qm + Qp).
[6] Cedar Mountain (Buckhorn): CP32; Burro Canyon: CP14, CP27; Jackpile: CP53.
[7] Ferron: CP33; Toreva: CP9; Gallup: CP23.
[8] Wahweap: CP39, CP40; Castlegate: CP34; Menefee: CP22.

more quartzose in QtFL space (table 2). The detrital modes imply that subarkose samples contain larger contributions of immature basement detritus than other samples, but otherwise they afford little basis for judging provenance. The samples are also broadly similar texturally, as expected for derivation from outcrops of analogous fluvial to fluviodeltaic channel sandstones.

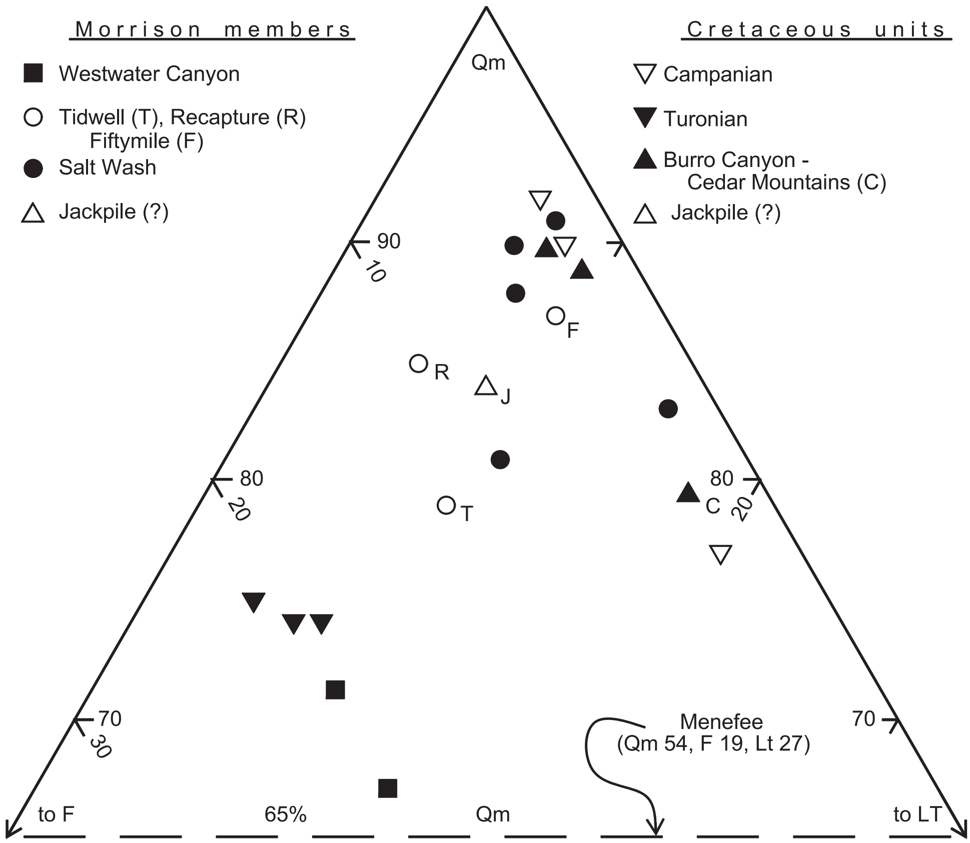

Fig. 7. Partial QmFLt diagram (note scale with base of plot at 65% Qm) of Jurassic-Cretaceous sandstone samples (table 1) from the southern Cordilleran foreland basin on the Colorado Plateau.

The Morrison samples contain moderately to well sorted aggregates of subrounded to subangular grains of medium to fine sand. The three most feldspathic of the quartzose Morrison sublitharenites (fig. 7) are finer grained than other samples of that group (table 1), being fine to medium rather than medium to fine (CP25, Recapture; CP41, Tidwell; CP49, Salt Wash). This relation suggests a dependence of quartz/feldspar ratio on grain size for the sublitharenite Morrison samples, rather than any difference in provenance. The Cedar Mountain–Burro Canyon samples are more varied texturally, ranging from fine to coarse in grain size, but without any apparent dependence of composition on grain size. The Mancos-equivalent (Turonian) fluviodeltaic samples contain moderately sorted aggregates of subangular to subrounded grains of medium to fine sand, but the Mesaverde (Campanian) fluvial and fluviodeltaic samples contain well sorted and subrounded aggregates of medium to fine sand.

DETRITAL ZIRCONS

Age populations of detrital zircons are varied in ways linked paleogeographically to sources in both the Sevier thrust belt, or its antecedents, and the Mogollon highlands, but those sources varied in both space and time. Provenance differences are also linked to sandstone petrofacies.

TABLE 2

Mean QFL compositions of generic groups of Jurassic-Cretaceous foreland sandstone samples[1]

	Morrison quartzose	Morrison feldspathic	Lower Cretaceous	Turonian	Campanian[2]	Menefee (Campanian)
	Table 1AB (N=8)	Table 1C (N=2)	Table 1D (N=4)	Table 1E (N=3)	Table 1F (N=3)	Table 1F (N=1)
Qm	86 ± 4	69 ± 2	86 ± 3	74 ± 1	86 ± 7	54
F	6 ± 4	20 ± 0	4 ± 2	20 ± 1	2 ± 1	19
Lt	8 ± 3	11 ± 2	10 ± 3	6 ± 1	11 ± 6	27
Qt	90 ± 5	70 ± 2	92 ± 3	75 ± 1	91 ± 5	63
F	6 ± 4	20 ± 0	4 ± 2	20 ± 0	2 ± 1	19
L	4 ± 2	10 ± 2	4 ± 1	5 ± 1	7 ± 5	18

[1] Data from Table 1 (± denotes standard deviation from the mean for N samples).
[2] Exclusive of Menefee Formation (right column).

Morrison Formation

Figures 8 and 9 include age-bin histograms and age-distribution curves for all samples from the Morrison Formation (fig. 8, Salt Wash Member; fig. 9, other members). Morrison sublitharenites (table 1AB) from various members (fig. 8; fig. 9ADE) contain similar heterogeneous detrital zircon age populations very different from the more restricted age populations in subarkoses (table 1C) of the Westwater Canyon Member (fig. 9BC). K–S analyses of detrital zircon age populations in the Morrison sublitharenites yield P-values >0.05 for 27 of 28 pairs, indicating lack of confidence at the 95 percent confidence level that the grain populations were not derived at random from the same parent population. The only pair with a marginally lower P-value (0.045) derives from comparison of one of five Salt Wash samples (fig. 8C) with the sample from the Fiftymile Member (fig. 9E), which is equivalent to the Brushy Basin Member (fig. 2) near the southwest limit of Morrison exposures (fig. 4). We conclude that all Morrison members except the Westwater Canyon Member were derived from similar sources.

Figure 10 provides confirmation of that conclusion by comparing the composite age populations for four samples (CP19, CP29, CP35, CP36) from the central axis of the Salt Wash megafan and four samples from underlying (CP41 Tidwell Member), overlying (CP52 Fiftymile Member), and laterally equivalent strata (CP25 Recapture Member and CP49 Salt Wash Member at Beclabito Dome). The P-value from K-S analysis of the two composite grain populations is 0.46 (statistically indistinguishable), and essentially the same principal age peaks appear on both age-distribution curves: 150 to190 Ma (Jurassic), 220 to 280 Ma (Permian-Triassic), 400 to 430 Ma (Silurian-Devonian), 600 to 620 Ma (Neoproterozoic), and 980 to 1180 Ma (Grenville-aged Mesoproterozoic). The latter is a broad peak with its crest at ~1090 Ma. The breadth of the Grenville age peak is probably an artifact of U-Pb isotopic systematics, for age uncertainties of grain ages are inherently greatest in the interval 1000 to 1050 Ma (Gehrels, 2000). Subordinate Proterozoic peaks are also present within the 1300 to 2150 Ma range, as are minor Archean peaks within the 2575 to 2775 Ma range.

Recycled grains.—The heterogeneous age populations of Morrison detrital zircons in sublitharenites of the Tidwell, Salt Wash, Recapture, and Fiftymile Members (figs. 8, 9ADE, and 10) could not be derived from Proterozoic bedrock exposed in southwest

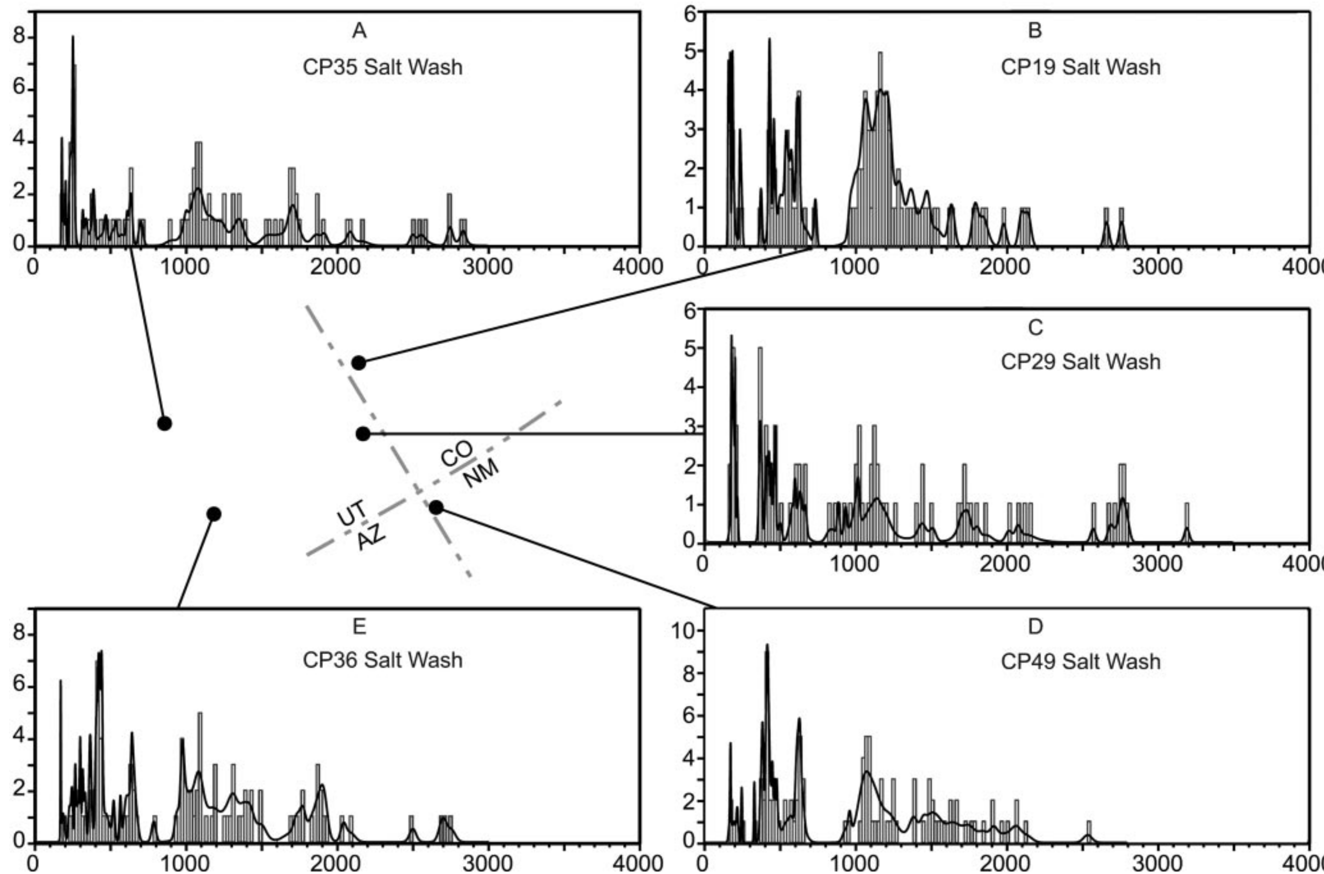

Fig. 8. Age-bin histograms (gray) and age-distribution curves (black) superimposed for samples of fluvial sandstone from the Salt Wash Member of the Upper Jurassic Morrison Formation keyed to collecting localities (also see figs. 3 and 4). Abscissas are grain ages (0-4000 Ma) and ordinates are numbers of grains (variable scales). See data repository for plots at larger scale. States: AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah.

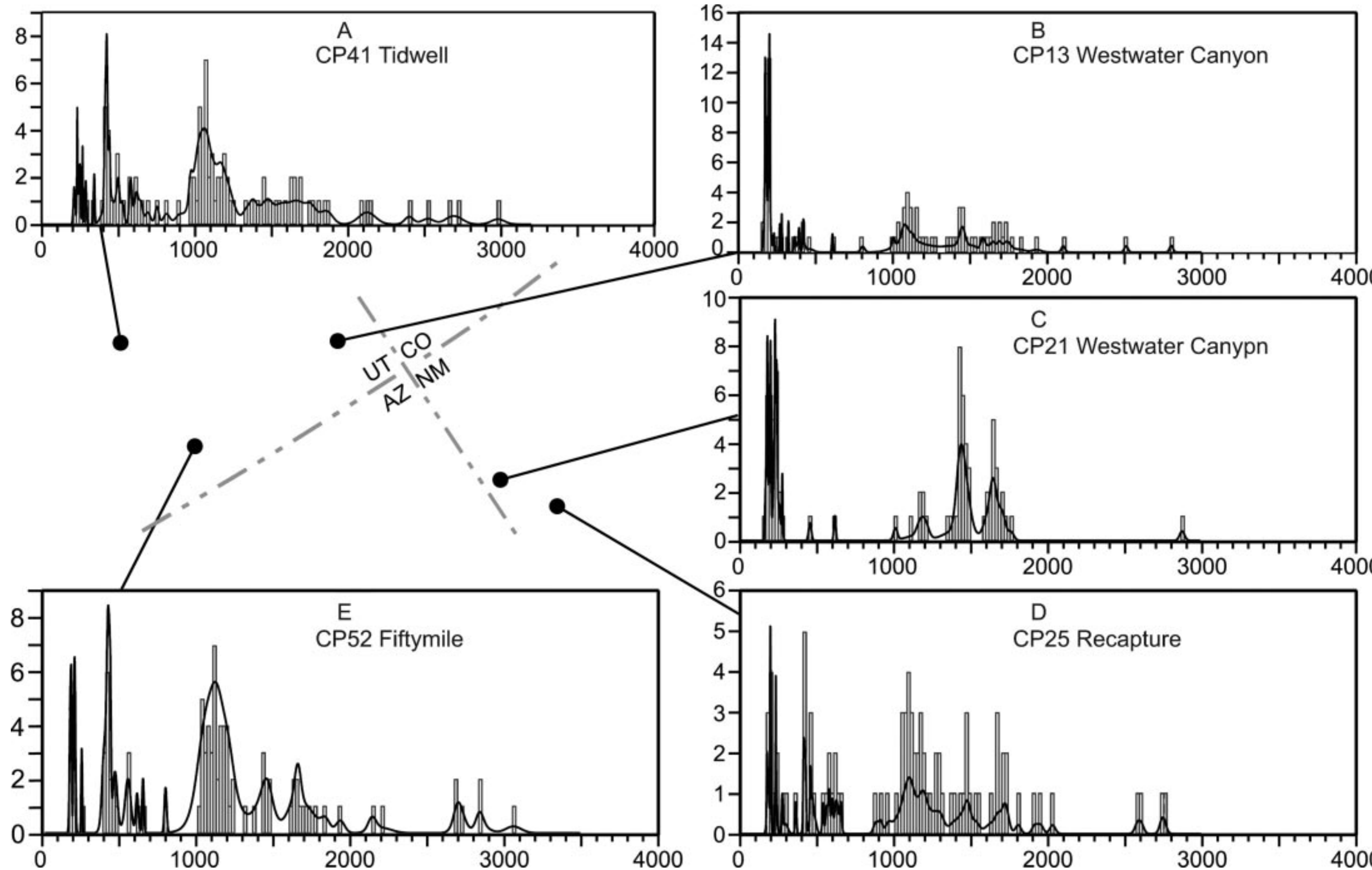

Fig. 9. Age-bin histograms (gray) and age-distribution curves (black) superimposed for samples of fluvial sandstone from the Tidwell, Recapture, Westwater Canyon, and Fiftymile Members of the Upper Jurassic Morrison Formation keyed to collecting localities (also see figs. 3 and 4). Abscissas are grain ages (0-4000 Ma) and ordinates are numbers of grains (variable scales). See data repository for plots at larger scale. States: AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah.

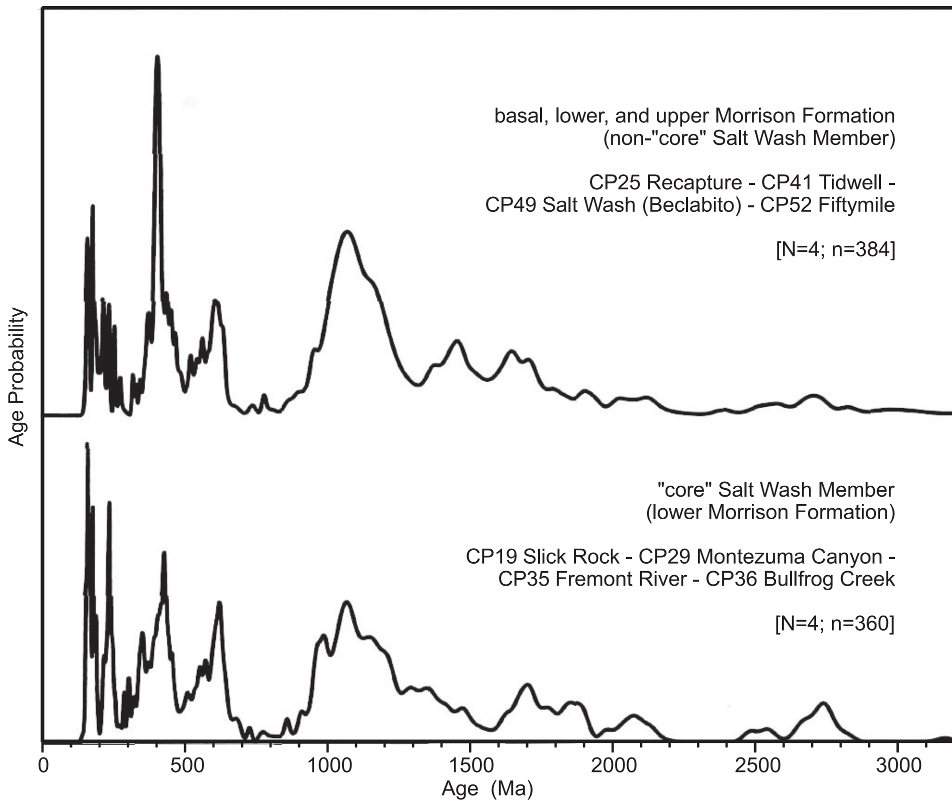

Fig. 10. Composite age-distribution curves for populations of detrital zircons in Salt Wash and related members of the Morrison Formation (table 1AB; figs. 8 and 9ADE). N = number of samples composited; n = number of grain ages plotted.

Laurentia upstream in relation to prevailing paleocurrents (fig. 3). From overall similarity to age populations in Jurassic eolianites of the Colorado Plateau (Dickinson and Gehrels, 2003, 2008), we infer that >295 Ma grains in sands from all these members were recycled from Jurassic eolianites uplifted on the Mogollon highlands or within the Sevier thrust belt. In all the sublitharenite samples, age gaps of 15+ million years are evident between <295 Ma grains and older grains. Testing for recycling by restricting comparison of eolianite and Morrison age populations to grains >295 Ma is dictated by knowledge that zircon populations in plateau eolianites are dominated by grains of that age derived from a transcontinental dispersal system tapping sources as distant as the Appalachian belt along the eastern margin of Laurentia (Dickinson and Gehrels, 2003, 2008). K–S comparison of composite >295 Ma age populations (fig. 11) in ten plateau eolianites and the Morrison sublitharenites yields a high P-value of 0.69, confirming that the latter could have been derived from erosion of the former. The close similarity of the composite age populations is also apparent from inspection of the grain-age peaks on figure 11. Despite a depositional age near 150 to 155 Ma (fig. 2), 90 percent of the detrital zircon grains in the Tidwell, Salt Wash, Recapture, and Fiftymile Members are part of the recycled >295 Ma (effectively >310 Ma) age population of figure 11.

It is notable that only 6 percent of the recycled zircon population in Morrison samples (fig. 11) falls within the age range of 1800 to 2100 Ma that could have been

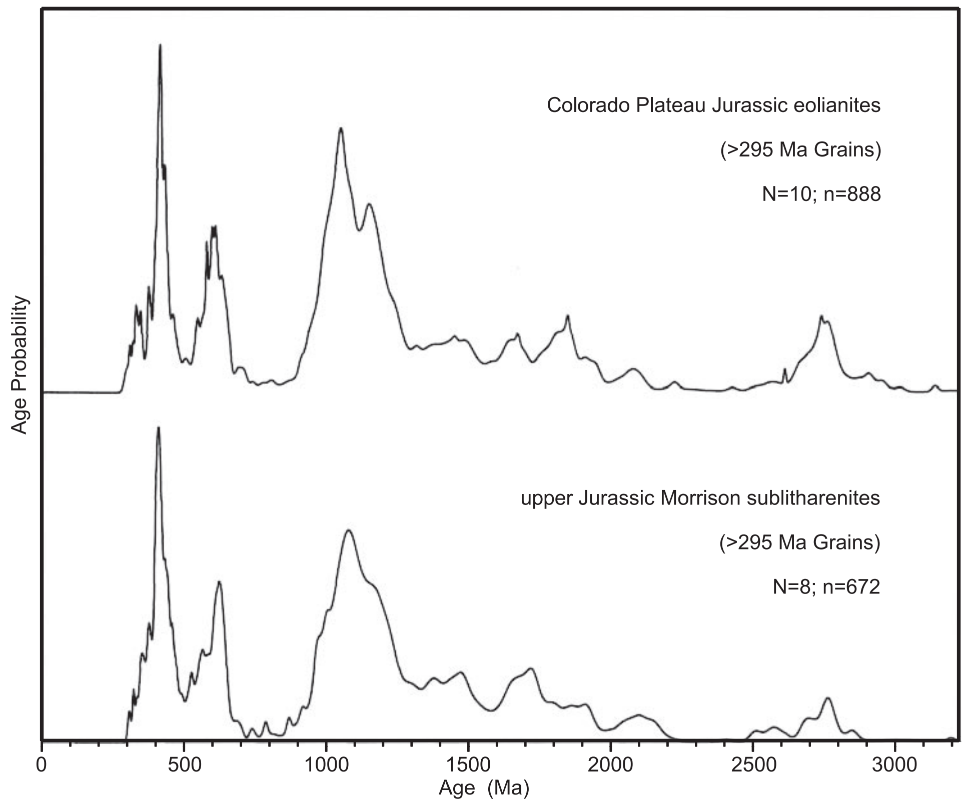

Fig. 11. Composite age-distribution curves for >295 Ma detrital zircon grains in Jurassic eolianites of the Colorado Plateau (Dickinson and Gehrels, 2008) and Upper Jurassic Morrison litharenite samples from the Salt Wash and related members (table 1AB; figs. 8 and 9ADE). N = number of samples composited; n = number of grain ages plotted.

recycled from Paleozoic allochthons of central Nevada (fig. 1), where grains of that age range are dominant in Paleozoic sandstones (Dickinson and Gehrels, 2000). Nor is any zircon contribution at all required from that provenance, for Paleoproterozoic detrital zircons falling within the same age range form 7 percent of the age population in Jurassic plateau eolianites (fig. 11).

Arc-derived grains.—Younger grains derived from the Cordilleran magmatic arc along the western margin of Laurentia form 5 percent to 17 percent of the detrital zircon grains in the Morrison sublitharenites (figs. 8 and 9ADE). Of those arc-derived grains, >85 percent fall within the age range of 155 to 245 Ma, appropriate for derivation from the Cordilleran arc for which ages of plutons as old as 235 to 245 Ma are known from the Mojave Desert region (Barth and Wooden, 2006). Fourteen age peaks defined by three or more grain ages in various of the samples fall within 158 to 162 Ma, 172 to 173 Ma, 183 to 194 Ma, 220 to 231 Ma, and 242 to 251 Ma, but it is uncertain whether those particular age clusters are significant or derive spuriously from the statistics of small datasets. The two subarkose samples from the Westwater Canyon Member (fig. 9BC) contain a distinctly higher proportion of arc-derived grains (33%-35%), with ~95 percent falling within the Cordilleran age range of 152 to 245 Ma, and eight age peaks defined by three or more grain ages fall within 164 to 165 Ma, 169 to 171 Ma, and 185 to 191 Ma. As these clusters of grain age lie partly between the age clusters for Salt Wash and related samples, we conclude provisionally that none of the specific grain-age clusters of arc-derived grains have geologic meaning.

Grain mixing.—Construction of the Morrison age population of detrital zircons by mixing of arc-derived grains with recycled eolianite detritus is compatible with the similarity of the overall composite age population of detrital zircons in the Morrison samples with the composite age population in Middle to Upper Jurassic eolianites (Entrada Sandstone and Bluff Sandstone) of the San Rafael Group (fig. 12). The latter were formed by depositional admixture of arc-derived grains with far-travelled grains (Dickinson and Gehrels, 2008). K–S comparison of the two composite age populations yields a high P-value of 0.68, indicating no significant statistical difference. Simple reworking of eolianite sand from the San Rafael Group into the Morrison Formation is precluded because paleocurrent trends show that the Salt Wash and related members were derived from southwest of the Colorado Plateau, whereas eolianites of the San Rafael Group containing arc-derived grains occur only on the eastern Colorado Plateau (Dickinson and Gehrels, 2008).

Basement sources.—Figure 13 shows the greater abundance of arc-derived grains in the Westwater Canyon Member than in other Morrison members, and also highlights a salient difference among >295 Ma grains. Proterozoic grain-age peaks at 1665 to 1660 Ma and 1455 to 1450 Ma are significantly higher relative to Grenville grain-age peaks at

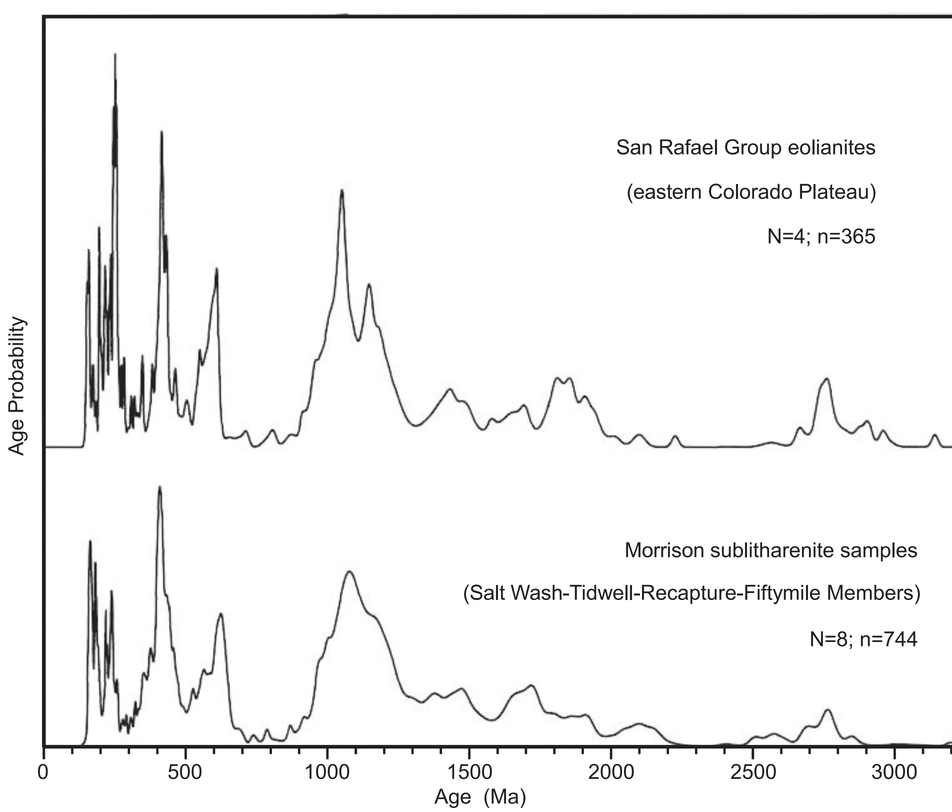

Fig. 12. Composite age-distribution curves for detrital zircon grains (full age populations) in Morrison litharenite samples (table 1AB; figs. 8 and 9ADE) and older eolianites of the San Rafael Group containing both arc-derived grains from western Laurentia and far-travelled grains from eastern Laurentia (Dickinson and Gehrels, 2008). N = number of samples composited, n = number of grain ages plotted.

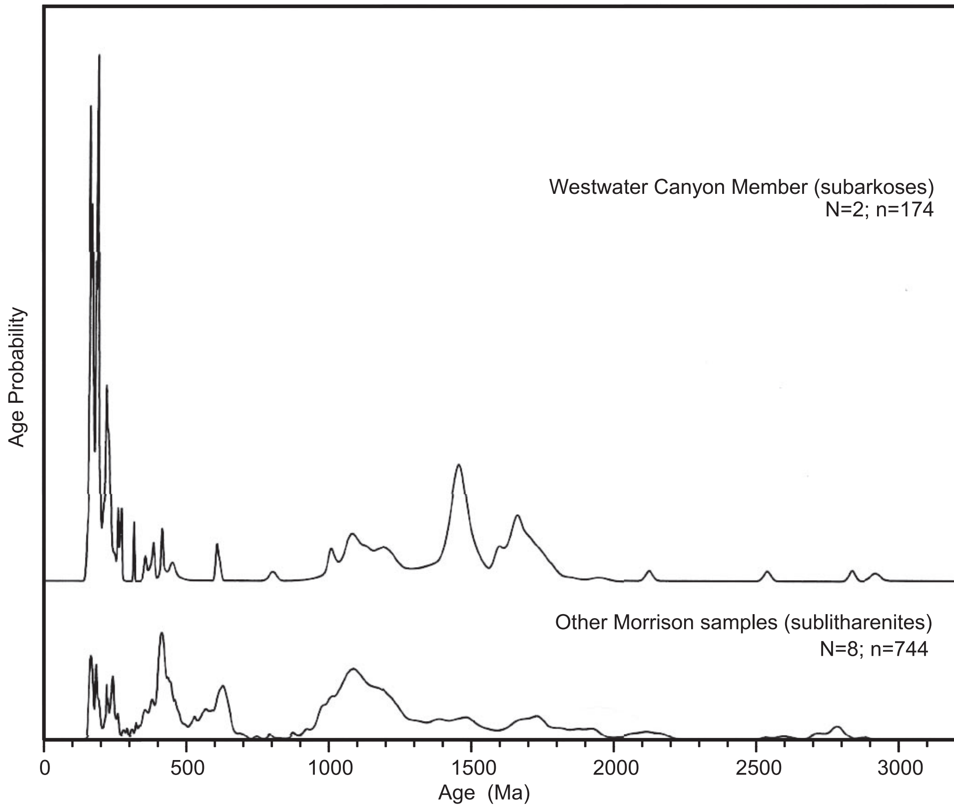

Fig. 13. Composite age-distribution curves for detrital zircon grains (full age populations) in Morrison subarkose samples from the Westwater Canyon Member (table 1C; fig. 9BC) and Morrison sublitharenite samples from the Salt Wash and related members (table 1AB; figs. 8 and 9ADE). N = number of samples composited; n = number of grain ages plotted.

~1100 Ma for the Westwater Canyon composite grain population as compared to the grain populations in other Morrison members. The two pre-Grenville Mesoproterozoic age peaks are inferred to reflect derivation of detritus from Yavapai-Mazatzal basement (Shaw and Karlstrom, 1999) intruded by anorogenic plutons (Anderson, 1983) along the nearby Mogollon highlands south of the Colorado Plateau (fig. 1). The ratio of Yavapai-Mazatzal (1775-1340 Ma) to Grenville (1335-950 Ma) age populations is >2:1 for the Westwater Canyon Member but only ~1:3 for other members.

Contributions of Yavapai-Mazatzal basement to the Westwater Canyon Member does not entirely preclude derivation of the older Salt Wash Member in whole or in part from the Mogollon highlands, from which an eolianite cover could have been stripped by recycling into Salt Wash sands before Westwater Canyon deposition (fig. 4). Persistence of the recycled eolianite signal into the Fiftymile Member, younger than Westwater Canyon Member (fig. 4), nevertheless suggests different provenance areas for the two contrasting zircon age populations in different Morrison members. Paleocurrent and thickness relations for the Salt Wash Member (fig. 3), and the limited exposure area of the Fiftymile Member (figs. 2 and 4), jointly suggest deposition of the recycled sand by a drainage system emerging from the tectonic syntaxis between the Sevier thrust belt and the Mogollon highlands where Tertiary erosion has removed all proximal Morrison facies (fig. 1). Alternate derivation of the recycled sand from antecedents of the Sevier thrust belt or from sedimentary cover over the Mogollon highlands, or from both sources, would in that case be a moot point. From both paleocurrent and facies relations (figs. 3 and 4), the Westwater Canyon Member was probably sourced farther east along the Mogollon highlands where basement-cover relations may have been different.

Twin megafans.—A different provenance for Salt Wash and Westwater Canyon Members has long been inferred from paleocurrent trends and sandstone compositions (Craig and others, 1955; Cadigan, 1967). Figure 14 shows the detrital modes of our samples in relation to the means and ranges of sandstone composition reported by others for the two members (Cadigan, 1967; Hansley, 1990). Although there is regional overlap in Salt Wash–Westwater Canyon petrofacies, net trends in composition parallel those of our samples, with mean QmFLt values from previous studies generally within 3 percent of means calculated from our samples, and in no case >7 percent different. The compositions of sandstones from the Recapture Member are intermediate for both our samples and for previous samples (fig. 14). The previous petrography was undertaken either during a study of diagenesis (Hansley, 1990) or before modern conventions for sand-grain categories were adopted (Cadigan, 1967), and our conversion of published data to QmFLt values (fig. 14) involved assumptions that may have led to imprecision. We cannot be sure whether or not further work will

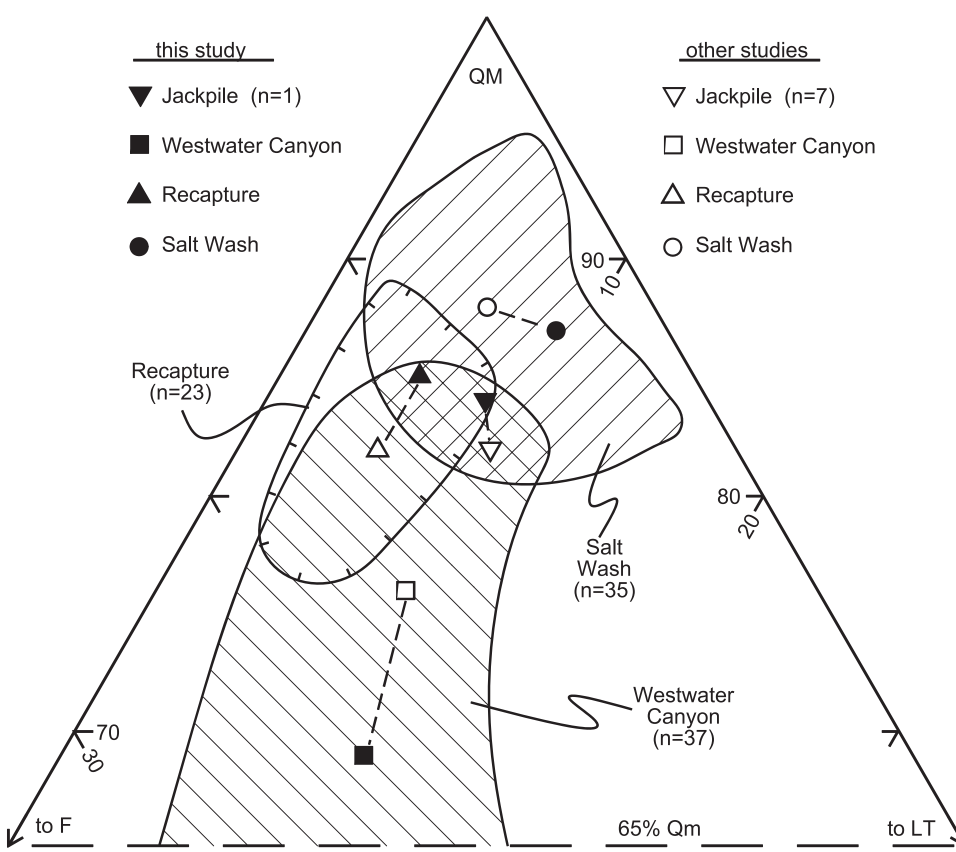

Fig. 14. Partial QmFLt diagram (note scale with base of plot at 65% Qm) of mean detrital modes and compositional ranges of sandstones from key members of the Morrison Formation after table 1ABC and previous studies (Cadigan, 1967; Hansley, 1990). Dashed lines connect means of our data and previous data.

reveal mixed zircon populations that we have not detected. We provisionally judge that result to be unlikely because some of our samples derive from the area where both Salt Wash and Westwater Canyon Members are present (figs. 3 and 4), and sediment mixing might be expected for those samples if operative anywhere.

Of the Cordilleran arc-derived grains in Morrison samples (5%-35% of total grains), only two grains have mean age estimates young enough (150-155 Ma) to have been derived from ash eruptions contemporaneous with Morrison sedimentation, and age uncertainties for even those grains are large enough not to preclude predepositional origin. For all or nearly all the arc-derived grains, therefore, sedimentary transport into the Cordilleran foreland basin by fluvial processes is indicated, rather than transport as airborne ash. If the Salt Wash and related members formed a foreland megafan built to the northeast from the tectonic syntaxis between the Sevier thrust belt and the Mogollon highlands, incorporation of detritus into the megafan from the arc assemblage along the California continental margin can be envisioned without difficulty (fig. 1). Delivery of arc-derived detritus to the Westwater Canyon megafan deposited farther east is somewhat more difficult to envision because the Border rift system (fig. 1) blocked the most direct pathway from the continental-margin magmatic arc to the depositional site. Easterly rather than northeasterly paleoflow for the Westwater Canyon megafan (fig. 3) suggests that both Yavapai-Mazatzal and arc-derived zircon grains in the Westwater Canyon Member were derived from the western segment of the Mogollon highlands where the Border rift system overprinted the northeastern flank of the Jurassic magmatic arc (fig. 1). Rifting may have uplifted the disrupted Jurassic arc assemblage along the rift shoulder, allowing erosion to contribute both basement and arc detritus to the Westwater Canyon megafan. The postulated derivation of Westwater Canyon detritus from the western part of the Mogollon highlands favors derivation of recycled eolianite detritus in the Salt Wash Member and related members from a different provenance lying within the Sevier thrust belt or its antecedents, rather than from the Mogollon highlands.

Cedar Mountain-Burro Canyon Formations

Figure 15 includes age-bin histograms and age-distribution curves for samples from correlative Cedar Mountain (fig. 15A) and Burro Canyon (fig. 15BC) Formations, which contain heterogeneous zircon age populations closely similar to those in quartzose sublitharenite samples from the Morrison Formation (fig. 16), but dissimilar to the more restricted array of grain ages in the more feldspathic subarkose samples from the Westwater Canyon Member (fig. 13). Petrofacies relations are comparable (table 2; fig. 7), and a provenance involving recycled eolianite sand is inferred.

In terms of both petrofacies and zircon content, the sample from the Jackpile Sandstone Member (table 1D; fig. 15D) closely resembles Cedar Mountain-Burro Canyon samples rather than Westwater Canyon samples. We accordingly treat the Jackpile Sandstone as a lateral equivalent of the Burro Canyon Formation (Aubrey, 1992), rather than as a member of the Morrison Formation (Owen and others, 1984). Its detrital zircon content precludes an origin from rejuvenation of Morrison Westwater Canyon sedimentation. K–S analyses of Cedar Mountain (Buckhorn)-Burro Canyon-Jackpile zircon ages indicate that five of six pairs of samples yield P-values (0.26-0.98) well in excess of the criterion of >0.05 above which age populations are not statistically distinguishable with confidence. Notably, P-values for the Jackpile sample (CP53) as compared to the Cedar Mountain and Burro Canyon samples are 0.32, 0.59, and 0.98, with the latter high value for Jackpile as compared to the Burro Canyon sample (CP27) from the nearby Chama Basin (fig. 5), where $P=1.0$ would indicate identity.

Paleocurrent patterns suggest derivation of the Burro Canyon Formation from the Mogollon highlands to the south, but derivation of the Cedar Mountain Formation from the Sevier thrust belt to the west (fig. 5). If both inferences are valid, the similar

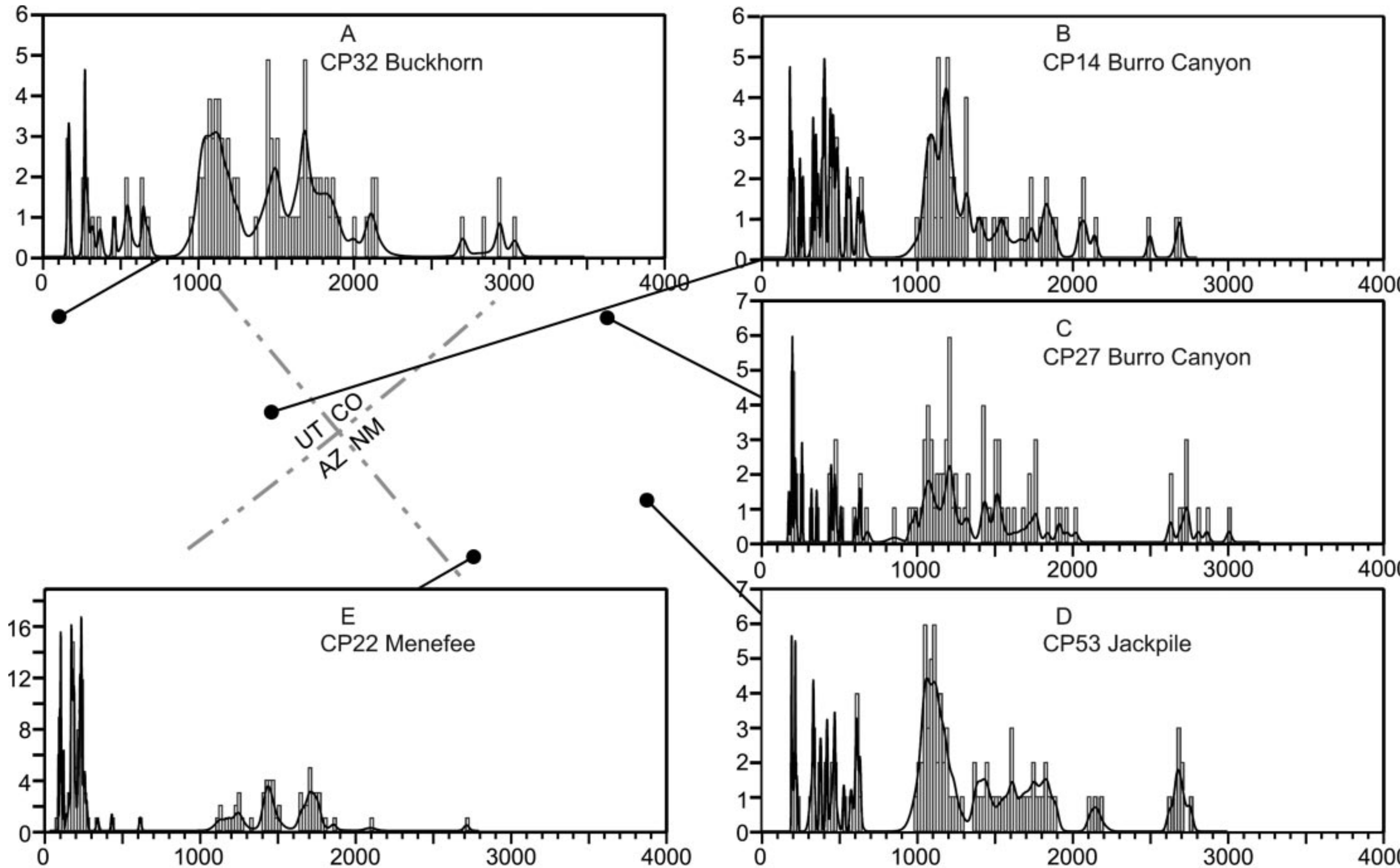

Fig. 15. Age-bin histograms (gray) and age-distribution curves (black) superimposed for samples of Lower Cretaceous Cedar Mountain–Burro Canyon Formations (including Jackpile Sandstone), and Upper Cretaceous Menefee Formation (see fig. 17 for other Upper Cretaceous samples) keyed to collecting localities (also see figs. 5 and 6). Abscissas are grain ages (0-4000 Ma) and ordinates are numbers of grains (variable scales). See data repository for plots at larger scale. States: AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah.

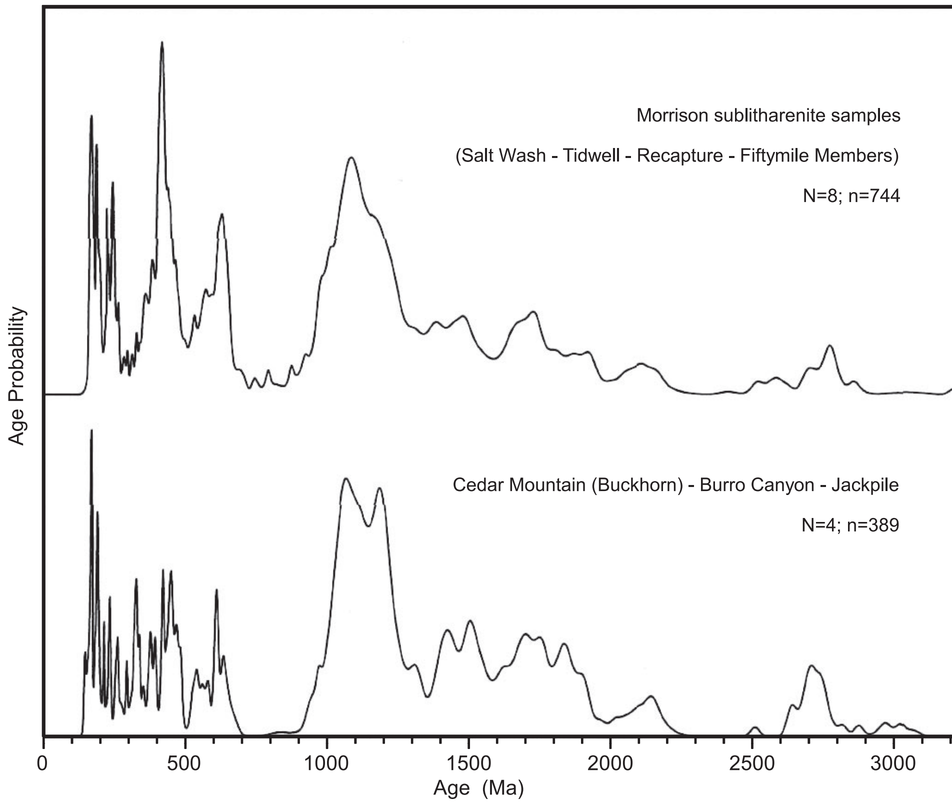

Fig. 16. Composite age-distribution curves for detrital zircon grains (full age populations) in litharenite samples from the Upper Jurassic Morrison Formation (table 1AB; figs. 8 and 9ADE) and Lower Cretaceous strata (table 1D; fig. 15ABCD). N = number of samples composited; n = number of grain ages plotted.

detrital zircon age populations in the two formations imply that detrital zircon studies cannot distinguish between eolianite sand recycled alternately from the Sevier thrust belt or its antecedents to the west, or from the Mogollon highlands to the south. Once a Jurassic blanket of eolian sand had been distributed across southwest Laurentia, erosion in multiple tectonic settings and sediment transport in multiple directions could achieve analogous redistribution of detrital zircons.

Arc-derived zircon grains are sparse (5%-10% of total zircon populations) in Cedar Mountain-Burro Canyon samples, as they are in Morrison samples of similar provenance, and afford no additional insight into sediment provenance. Apart from six isolated grain ages of uncertain significance, 80 percent of the 29 net grains <295 Ma in age fall within the age range of 154 to 253 Ma, appropriate for derivation from the Cordilleran magmatic arc, with age peaks defined by three or more grains in various samples at 155, 163, 168, and 185 Ma. The pathway or pathways of transport from the Cordilleran margin to the Colorado Plateau cannot be established, however, from our data.

There is a striking contrast between (1) the strong Yavapai-Mazatzal basement signal in the detrital zircons of the Upper Jurassic Westwater Canyon Member (fig. 13) of the Morrison Formation apparently derived from the western Mogollon highlands, and (2) the notable lack of a comparable basement signal (fig. 16) in the younger Burro Canyon (-Jackpile) Formation thought to derive from the eastern Mogollon highlands. Clearly, the same provenance could not have been stripped to basement in Late Jurassic time, and later yield recycled sand from sediment cover in Early Cretaceous time. Perhaps eastern and western segments of the Mogollon highlands experienced different erosional histories during Jurassic-Cretaceous time, with sediment cover stripped earlier on the west than on the east.

Cretaceous Mogollon Provenance

Populations of detrital zircons in samples of Turonian fluviodeltaic sandstone (fig. 17AB) of subarkosic composition (tables 1-2; fig. 7) from the Black Mesa (CP9 Toreva) and San Juan (CP23 Gallup) basins were collected from marginal-marine depositional systems associated with regressive progradation of paleoshorelines to the northeast off the flank of the Mogollon highlands. Both samples display prominent age peaks (1700-1750 Ma) controlled by grains derived from Yavapai-Mazatzal basement of the Mogollon highlands, and subordinate age peaks (1425-1435 Ma) controlled by grains derived from anorogenic granitic bodies intrusive into Yavapai-Mazatzal basement. Grains derived from the Cordilleran arc are minor (5%-15%), as expected because the relict rift shoulder of the Mogollon highlands and the Bisbee basin tended to screen the Black Mesa and San Juan basins from the magmatic arc (fig. 1). Age peaks controlled by three or more grains in the two samples represent both Jurassic (172 and 167 Ma) and Cretaceous (98 Ma) grain populations derived from the Cordilleran arc.

The detrital zircon population in a sample of Campanian deltaic sandstone (CP22 Menefee) from the San Juan basin (tables 1-2; figs. 7, 15E) displays comparable age peaks of grains derived from Yavapai-Mazatzal basement (1710-1715 Ma) and intrusive anorogenic granite (1440-1445 Ma), but also contains abundant arc-derived grains (~50% of total grain population). By Campanian time, the Bisbee basin was undergoing tectonic inversion, Dakota transgression had advanced across the remnant Mogollon highlands, and zircon grains could be delivered directly to the San Juan basin from the Cordilleran magmatic arc to the southwest by fluvial processes (Cumella, 1983). Major clusters of arc-derived grains in the Menefee sample fall into the ranges of 86 to 105 (n=10), 158 to 182 (n=19), and 190 to 240 (n=22) Ma, indicating derivation from varied components of the Cordilleran magmatic arc ranging from Middle Triassic to Late Cretaceous in age. A dozen age peaks, each defined statistically by three or more grain ages, fall into the ranges of 86 to 93 (n=2), 158 to 182 (n=5) and 190 to 239 (n=5) Ma, reflecting the same diverse origins.

The sample of Turonian sandstone (CP33 Ferron) from the Sevier foredeep (fig. 17A) is comparable in petrofacies (tables 1-2) to correlative sandstones from the Black Mesa and San Juan basins despite the proximity of the collecting site to the Sevier thrust belt. Much or most of the Ferron sand was probably transported longitudinally along the foredeep from sources in the Mogollon highlands to the southwest (Lawton, 1986b). The Ferron detrital zircon population displays a Yavapai-Mazatzal age peak (1680-1700 Ma), but also displays a less prominent Grenville age peak probably reflecting admixture of recycled zircon grains derived from the nearby Sevier thrust belt. Age peaks defined by three or more of the minor arc-derived grains (<15%) in the Ferron sample are controlled by both Triassic (~244 Ma) and Cretaceous (~97 Ma) grains.

Figure 18 compares age-distribution curves for all samples containing significant contributions of detrital zircons derived from Precambrian basement of the Mogollon highlands. The reasons for variation in the relative sizes of peaks for detritus derived from Yavapai-Mazatzal basement (1600-1800 Ma) and intrusive anorogenic granite (1400-1500 Ma) are unknown, but are not thought to be significant for regional paleogeography. The Cretaceous (Turonian-Campanian) samples contain zircon clusters younger than the depositional age of the Westwater Canyon samples (bottom). The relative prominence of a subdued Grenville peak (1000-1200 Ma) in the Ferron sample from the Sevier foredeep is also apparent.

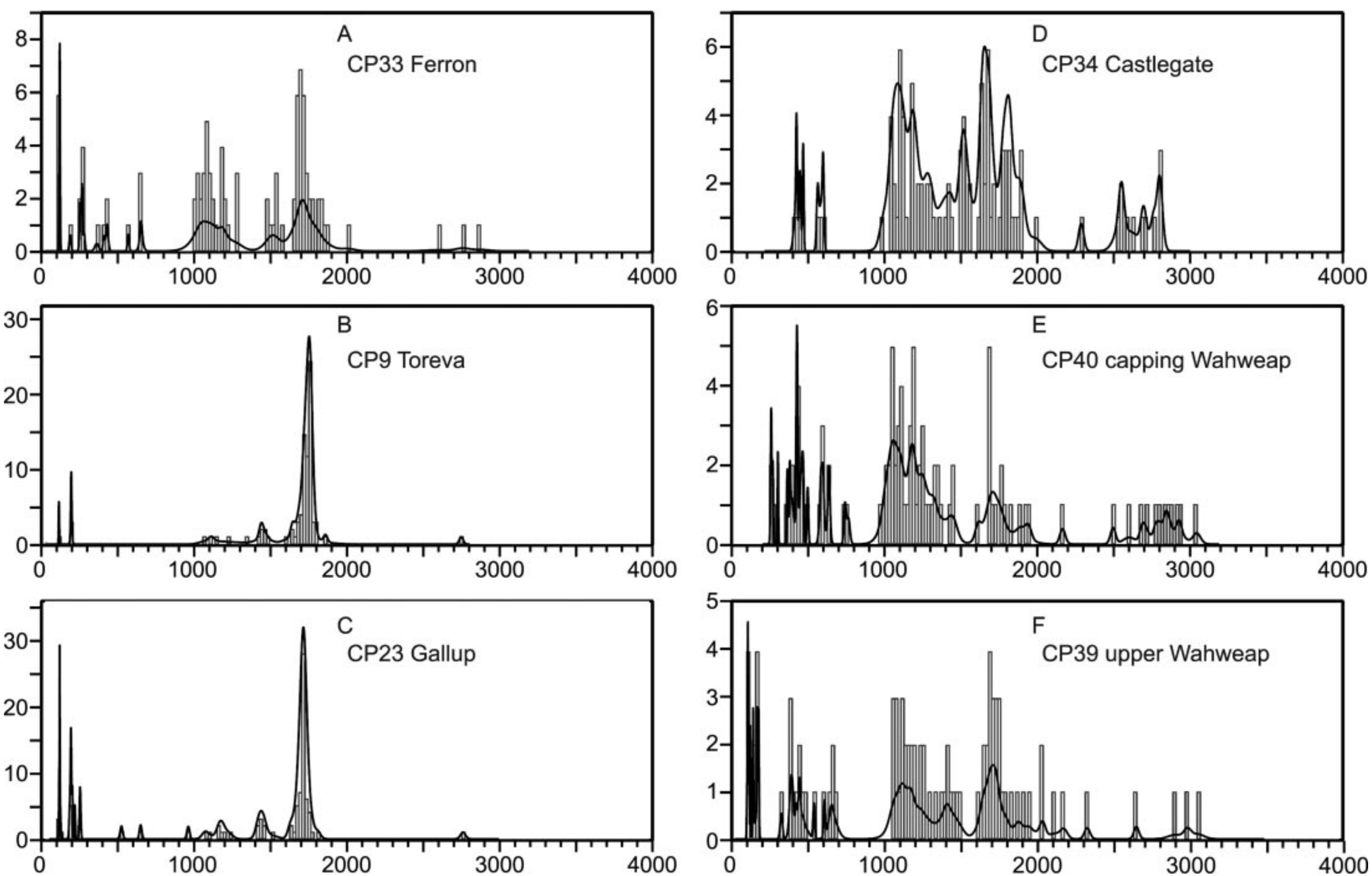

Fig. 17. Age-bin histograms (gray) and age-distribution curves (black) superimposed for samples of Upper Cretaceous Mancos-equivalent strata (fluviodeltaic Turonian) from Sevier foredeep (A), Black Mesa basin (B) and San Juan basin (C), and Mesaverde Group (Campanian) fluvial (DE) and fluviodeltaic (F) units in Sevier foredeep (see fig. 6 for collecting localities). Abscissas are grain ages (0-4000 Ma) and ordinates are numbers of grains (variable scales). See data repository for plots at larger scale. States: AZ, Arizona; CO, Colorado; NM, New Mexico; UT, Utah.

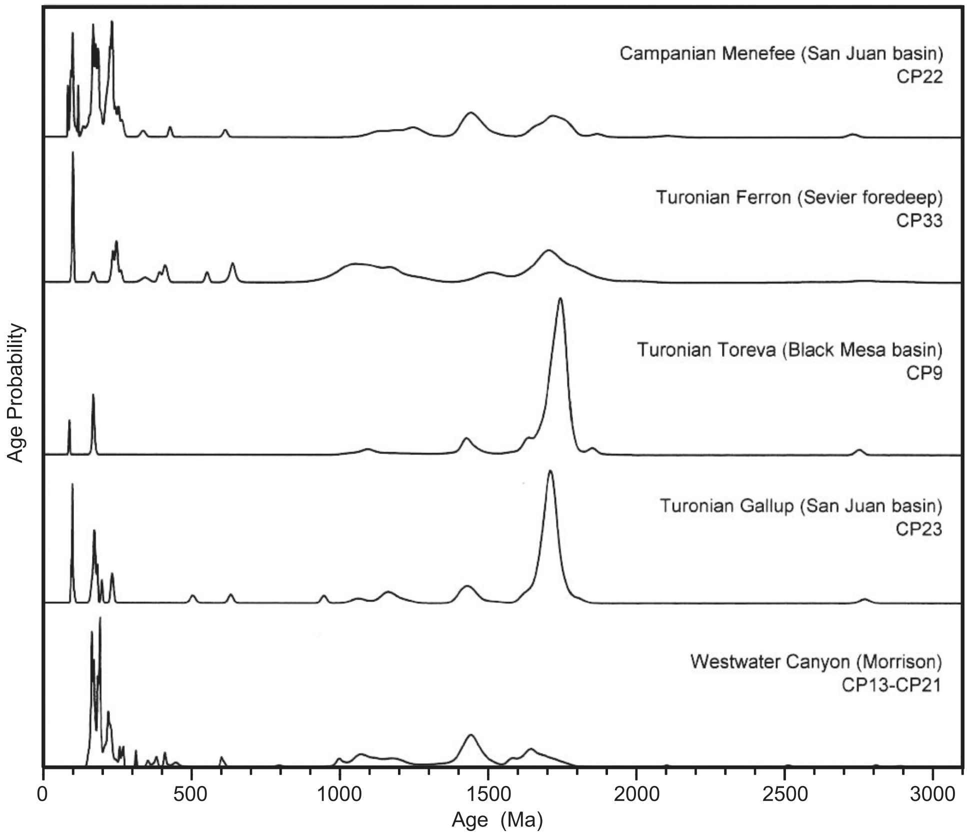

Fig. 18. Comparative age-distribution curves for detrital-zircon populations derived in large measure from Precambrian basement of the Mogollon highlands.

Cretaceous Sevier Provenance

Figure 19 compares age-distribution curves for heterogeneous age populations of detrital zircons that are thought largely to be recycled from Jurassic eolianites or other sedimentary strata within southwest Laurentia. Three are samples of quartzose (tables 1-2; fig. 7) Campanian sandstones (Wahweap Formation and Castlegate Sandstone) from the Sevier foredeep (fig. 16DEF). The prominence of a Grenville age peak (1000-1200+) Ma is evident on each plot, as is the absence or paucity of arc-derived grains in sands thought to have been derived exclusively from the Sevier thrust belt (CP34 Castlegate and CP40 capping Wahweap).

The prominent Yavapai-Mazatzal (1600-1800 Ma) age peak for the upper member of the Wahweap Formation (CP39), with indicators of paleoflow from the southwest, might be attributable to contamination of detritus from the Sevier thrust belt with detritus from the Mogollon highlands. The same argument cannot be applied, however, to the broadly comparable Yavapai-Mazatzal age peaks for the capping member of the Wahweap Formation and the Castlegate Sandstone with indicators of paleoflow to the southeast and east, respectively, off the Sevier thrust belt (fig. 6). These sands may incorporate recycled contributions from deformed pre-Mesozoic as well as Jurassic eolian strata in the thrust belt, for Yavapai-Mazatzal detritus is abundant in Precambrian and Paleozoic strata of the Cordilleran miogeocline west of the

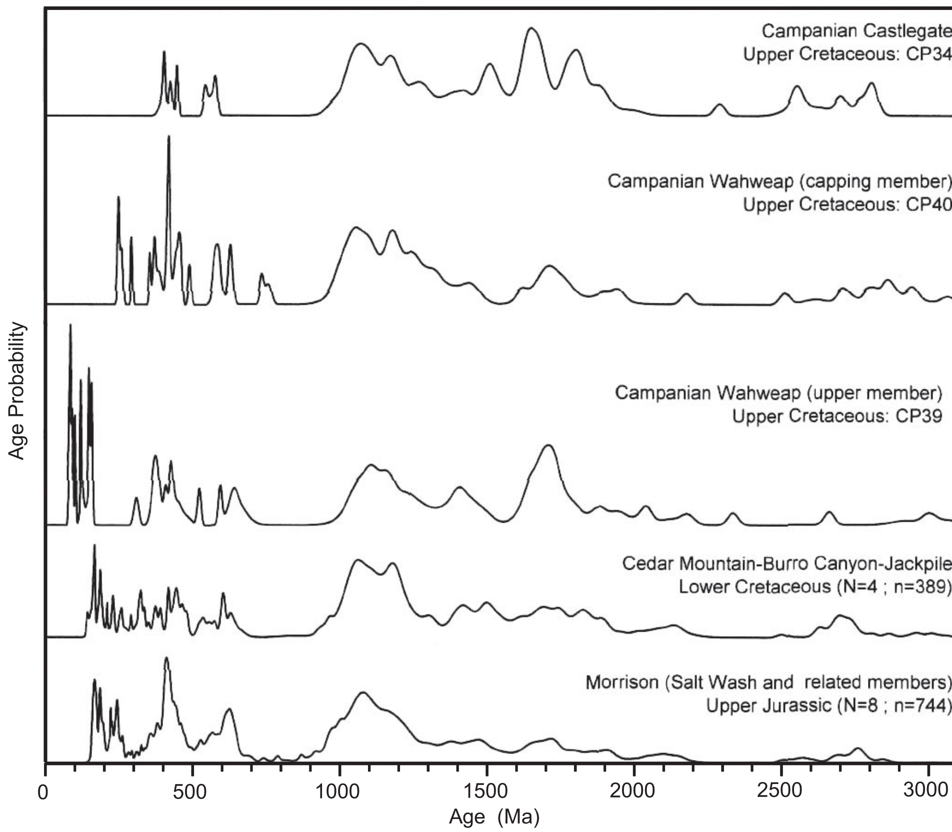

Fig. 19. Comparative age-distribution curves for detrital-zircon populations derived in large measure from recycling of Jurassic eolian sand (all three Campanian samples from the Sevier foredeep). N = number of samples composited; n = number of grain ages plotted (92-100 grain ages in each Cretaceous plot for an individual sample).

Colorado Plateau (Gehrels and Dickinson, 1995; Gehrels and others, 1995). Further ambiguity for sources of recycled detritus derived from the Sevier thrust belt is introduced by knowledge that some Neoproterozoic strata of the thrust belt contain detrital-zircon populations displaying prominent Grenville age peaks (Stewart and others, 2001). Campanian foredeep sandstones thus might contain detrital zircons recycled from varied Paleozoic miogeosynclinal strata as well from Jurassic eolianites.

Minor arc-derived grains (12% of total grains) in the upper member of the Wahweap Formation fall into the age ranges of 83 to 103, 122 to 124, and 146 to 160, with statistical age peaks defined by three or more grains each at 88, 150, and 159 Ma indicating derivation from Jurassic and Cretaceous components of the Cordilleran arc assemblage. Cretaceous arc-derived grains are not present in pre-mid-Cretaceous samples (fig. 19).

Cretaceous Mogollon-Sevier Relations

The detrital zircon data are inherently ambiguous with regard to Cretaceous recycling of pre-Mesozoic grains alternately from strata uplifted along the Sevier thrust belt or forming sedimentary cover over the Mogollon highlands. K-S comparisons for the eight Cretaceous samples dominated by recycled zircon grains yield P-values of 0.2

to 0.9 (for 15 sample pairs) that vary irregularly among samples collected within the Sevier foredeep, from the San Juan basin, and across the intervening basin sill. The lack of any systematic differentiation among the recycled zircon age populations underscores the inherent limitation of detrital zircon studies for determining provenance relations when zircon sources lie in laterally extensive sediment blankets rather than at discrete and areally circumscribed basement exposures.

SUMMARY OF SEDIMENTARY TECTONICS

Sands in Upper Jurassic and Lower Cretaceous fluvial systems of the Colorado Plateau largely contain zircons recycled from Jurassic eolianites exposed both within the Sevier thrust belt or its antecedents and along the Mogollon highlands. The foreland megafan of the Westwater Canyon Member of the Morrison Formation tapped a segment of the Mogollon highlands from which sediment cover had been stripped to expose Precambrian Yavapai-Mazatzal basement intruded by anorogenic Mesoproterozoic granite. Because the Jurassic eolianite sources formed a blanket over the region later occupied by the southern Cordilleran foreland basin and its periphery, age patterns in the detrital zircon record of Upper Jurassic and Lower Cretaceous strata in the basin interior cannot resolve issues of thrust initiation along the Sevier belt. Where zircon sources are laterally extensive, rather than areally restricted, patterns of age populations are not informative of provenance direction (Link and others, 2005).

The detrital zircon record suggests that Mancos-equivalent post-mid-Cretaceous (Turonian) fluviodeltaic systems of both the Sevier foredeep and areas of the southern Cordilleran foreland basin farther east (Black Mesa and San Juan basins) were largely fed longitudinally from sources along the Mogollon highlands lying south of the basin. Minor admixtures of sand from the Sevier thrust belt are apparent within the Sevier foredeep, but erosion of the thrust belt was not the prime control for pre-Campanian sedimentation within the downflexed foredeep. Detrital zircons in younger Cretaceous (Campanian) fluvial sandstone units that prograded across the foredeep are dominated by recycled detritus from the thrust belt to the west (Roberts and others, 2006; Link and others, 2007), but also include some admixture of sand derived from the Mogollon highlands to the south. East of the foredeep, sediment delivery into the interior of the foreland basin remained mainly longitudinal from south to north, rather than transverse from east to west, into Campanian time.

The detrital zircon evidence for prolonged longitudinal as well as transverse sediment delivery into the southern Cordilleran foreland basin sounds a cautionary note for the analysis of isostatic relations of thrust and sediment loads in foreland systems. In general, the assumption cannot be made that the volumes of rock eroded from the thrust belt and the volumes of sediment deposited in the foreland basin are balanced through time. The downflexed foredeep can attract depositional systems that import sediment from afar, and thereby add sediment volume to foreland basin fill apart from sediment generated by erosion of the nearby thrust belt.

ACKNOWLEDGMENTS

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Appendix 1

Sample Localities

(GPS=latitude-longitude coordinates from Global Positioning System)

CP9: Upper sandstone member of Toreva Formation at Shungopovi AZ. Cross-bedded fluviodeltaic sandstone near middle of 15 m (E-W) segment of distributary channel in roadcut at top of grade on AZ Highway 264 on east side of Hopi Second Mesa ~100 m east of sign for Shungopovi and 2.8 mi west of intersection of AZ Highway 264 with AZ Highway 87 at Second Mesa AZ. GPS (~1 m from white line marking north side of roadway directly below sample horizon): 35° 48.835′ N, 110° 31.677′ W.

CP13: Westwater Canyon Member of Morrison Formation near White Mesa UT. Crossbedded multistory fluvial sandstone on benchlands of Recapture Creek in roadcut on north side of UT Highway 262 at a point 1.3 mi east of junction with US Highway 191 (between Bluff and Blanding). GPS (at white line marking edge of roadway ~2 m from roadcut face and midway along sample horizon extending for ~10 m along strike): 37° 25.088′ N, 109° 27.011′ W.

CP14: Burro Canyon Formation near White Mesa UT. Trough cross-bedded and locally pebbly fluvial sandstone overlying Brushy Basin Member of Morrison Formation at edge of McCracken Mesa in roadcut on north side of UT Highway 262 at a point 4.9 mi east of junction with US Highway 191 (between Bluff and Blanding). GPS (adjacent to sample at white line marking edge of roadway ~ 2 m from roadcut face): 37° 26.163′ N, 109° 23.506′ W.

CP19: Salt Wash Member of Morrison Formation near Slick Rock CO. Massive trough-crossbedded fluvial sandstone of mid-member channel complex containing abundant mudchips in roadcut beside Dolores River on side road to Slick Rock 1.1 mi downstream from CO Highway 141 bridge over Dolores River and <0.1 mi downstream from old loading chute for ore at Burros Mine. GPS (at edge of pavement ~2.5 m from roadcut face): 38° 02.676′ N, 108° 53.617′ W.

CP21: Westwater Canyon Member of Morrison Formation near Todilto Park NM. Horizontally laminated and locally cross-bedded fluvial sandstone midway up steep hillside (middle of three bold sandstone ledges) northeast of dirt road to Twin Buttes from Todilto Park (north of gorge through hogback of Dakota Sandstone). GPS (on sidehill at sample): 35° 55.000′ N, 108° 55.615′ W.

CP22: Menefee Formation of Mesaverde Group near Gallup NM. Trough-crossbedded fluviodeltaic sandstone (sandy horizon ~ 1 m thick exposed 5-10 m along strike) within distributary-channel complex 6–8 m thick in roadcut on south side of US Highway 491 at crest of hill 3.5 mi south of junction with NM Highway 264 at Ya-Ta-Hey Junction. GPS (midway across spacing of ~7.5 m from edge of pavement to roadcut face): 35° 34.929′ N, 108° 45.632′ W.

CP23: Gallup Sandstone Member of Mancos Shale near Gallup NM. Cross-bedded and locally pebbly fluviodeltaic channel sandstone at top of progradational (sh to ss) marine-nonmarine transition on west flank of prominent hogback north of Interstate Highway I40 just east of Gallup NM (natural outcrop on hillock capping small spur on sidehill of ridge extending off frontage road reached by following Miyashiro Drive at Exit 22 of Interstate Highway I40). GPS (atop hillock ~2.5 m from sample): 35° 32.116′ N, 108° 41.596′ W.

CP25: Recapture Member of Morrison Formation near Gallup NM. Horizontally bedded and locally concretionary fluvial white sandstone (above redbeds and below eolianite) in low bluff off Church Rock Road (NM Highway 566) east of sweeping curve at foot of grade with summit 2.3 mi north of turnoff to Red Rock Park. GPS (ledge on outcrop ~1 m west of sample): 35° 33.623′ N, 108° 35.203′ W.

CP27: Burro Canyon Formation near Ghost Ranch NM. Trough cross-bedded fluvial sandstone of multistory channel complex (with green shaly partings between channel lenses), scoured into Brushy Basin Member of Morrison Formation and overlapped by marine Dakota Sandstone, in ledgy roadcut on west side of US Highway 84 at a point 5.4 mi south of intersection with NM Highway 115 to Canjilon. GPS (midway across spacing of ~10 m between edge of pavement and roadcut face): 36° 25.325′ N, 106° 28.033′ W.

CP29: Salt Wash Member of Morrison Formation in Montezuma Canyon UT. Trough-crossbedded fluvial sandstone in natural ledgy outcrop ~50 m west of San Juan County Road 246 (unpaved) in Montezuma Canyon SE of Monticello UT where SJC Road 246 crosses section line (Secs 25-26, T38S, R24E). GPS (atop ledge within 2-4 m of sample): 37° 32.720′ N, 109° 14.430′ W.

CP32: Buckhorn Conglomerate Member of Cedar Mountain Formation near Green River UT. Sandstone horizon of fluvial fining-upward cycle (~2.5 m thick from conglomerate base to shale above) in roadcut along south side of eastbound lanes of Interstate Highway I70 at a point 0.75 mi east of its intersection with UT Highway 24 and 20–25 m west of milepost 150. GPS (~5 m south of white line marking edge of roadway and ~4 m from roadcut face): 38° 55.646′ N, 110° 21.771′ W.

CP33: Ferron Sandstone Member of Mancos Shale in Dry Wash UT. Coarse sandstone in middle part (~3 m above base) of trough-crossbedded distributary-channel sandstone lens ~8 m thick in alcove of cliff beside Dry Wash Road at fenceline with cattleguard 3.1 mi toward Interstate Highway I70 from turnoff of Dry Wash Road off loop road through Moore UT (off UT Highway 10). GPS (on ledge ~1 m north of sample): 38° 56.070′ N, 111° 07.140′ W.

CP34: Castlegate Sandstone of Mesaverde Group on Willow Creek UT. Fluvial sandstone forming multiple stacked channel lenses within braided-channel complex (sample from prominent channel lens ~5 m thick) exposed on steep slope west of first bridge over Willow Creek (tributary to Price Canyon) on US Highway 191 north of its intersection with US Highway 6 in Price Canyon. GPS (on hillside outcrop within ±5 m along strike of composited sample): 39° 44.834′ N, 110° 50.034′ W.

CP35: Salt Wash Member of Morrison Formation near Hanksville UT. Trough-crossbedded fluvial sandstone containing lenticular pebble conglomerate lenses within multistory channel complex in roadcut on north side of UT Highway 24 up Fremont River 3.9 mi west of Hanksville UT. GPS (~1 m from white line marking edge of roadway and ~2 m from roadcut face): 38° 22.305′ N, 110° 45.945′ W.

CP36: Salt Wash Member of Morrison Formation near Bullfrog Creek UT. Trough-crossbedded fluvial sandstone and pebble conglomerate of compound stacked channel complex exposed beside Burr Trail Road 1.5 mi north of ford across Bullfrog Creek just above switchback at top of grade and on point of spur east of road in line with first rise in road above switchback. GPS (on bare rock outcrop ~1m from sample): 37° 36.809′ N, 110° 47.791′ W.

CP39: Upper Member of Wahweap Formation on Henrieville Creek UT. Fluviodeltaic channel sandstone (with convolute lamination locally) in roadcut on west side of UT Highway 12 just upstream from parking area beside Henrieville Creek 7.3 mi north of Senior Citizens Center in Henrieville UT. GPS (~1 m from white line marking edge of roadway and ~3 m from roadcut face): 37° 35.531′ N, 111° 54.161′ W.

CP40: Capping Member of Wahweap Formation on Henrieville Creek UT. Fluvial sandstone containing abundant pebble stringers and lenses in cliff on west side of Henrieville Creek across from end of 4WD track leading off UT Highway 12 at power pole 8.2 mi north of Senior Citizens Center in Henrieville UT and bearing right to fire circle beside Henrieville Creek opposite cliff face. GPS (on low ledge just west of tall conifer tree at base of cliff and ~5 m vertically below base of cliff): 37° 37.251′ N, 111° 53.562′ W.

CP41: Tidwell Member of Morrison Formation near Notom UT. Horizontally laminated and ripple cross-stratified sandstone bed ~ 1 m thick ~1 m above base of Tidwell Member (marked by green zone of discoloration at top of underlying red Summerville Formation) in roadcut near top of grade on back road from Notom toward Hanksville 0.4 mi uphill from paved road to Notom from Capitol Reef National Park. GPS (~1 m from eroded edge of sandstone bed exposed in roadcut): 38° 14.557′ N, 111° 06.797′ W.

CP49: Salt Wash Member of Morrison Formation near Beclabito NM. Trough-crossbedded fluvial sandstone on south flank of Beclabito Dome in roadcut on Navajo Route 63 (now largely abandoned) at locale 30–35 m uphill from sharp curve at foot of grade 3.2 mi south of US Highway 64 in Beclabito NM (turnoff 0.3 mi east of Beclabito Dome Historical Marker in front of Beclabito Trading Post). GPS (on slickrock slab in middle of roadway beside roadcut face): 36° 47.854′ N, 109° 00.515′ W.

CP52: Fiftymile Member of Morrison Formation at Fiftymile Bench UT. Trough-crossbedded and locally pebbly fluvial sandstone of sandy channel complex in roadcut at edge of Fiftymile Bench on Grand Staircase-Escalante National Monument (GSENM) Road 280 (the more southerly of two roads leading up to Fiftymile Bench from GSENM Road 200 from Escalante to Hole-in-the-Rock) at 35 m downgrade from cattle guard just below switchback 2.5 mi up GSENM Road 280 from GSENM Road 200. GPS (on flat orange rock beside road ~1 m from roadcut face): 37° 17.150′ N, 111° 03.417′ W.

CP53: Jackpile Sandstone Member of Morrison Formation near Paguate NM. Trough-crossbedded fluvial sandstone unconformably beneath overlapping Dakota Sandstone off east face of Clay Mesa south of Paguate NM in roadcut (0.1 m downhill from Dakota contact) on Old NM Highway 279 at a point 1.4 mi north of intersection with modern NM Highway 279 at turnoff 3.0 mi NE of junction of NM Highways 279 and 124 near Laguna Pueblo. GPS (~1 m from white line marking edge of roadway and ~2 m from roadcut face): 35° 05.766′ N, 107° 21.856′ W.

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