Interactions between axial and transverse drainage systems in the Late Cretaceous Cordilleran foreland basin: Evidence from detrital zircons in the Straight Cliffs Formation, southern Utah, USA

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ABSTRACT

New detrital zircon geochronologic data from the Straight Cliffs Formation of southern Utah provide insight into the controls on stratigraphic architecture of the Western Interior Basin during Turonian–Campanian time. Detrital zircon ages (N = 40, n = 3650) derived from linked fluvial and shallow-marine depositional systems of the Kaiparowits Plateau indicate the majority of zircons in fluvial strata were derived from the Mogollon Highlands (1.25–1.90 Ga, 67% of fluvial zircons), with subordinate contributions delivered from the Sevier fold-and-thrust belt (265–1250 Ma, 17%) and Cordilleran magmatic sources (81–265 Ma, 16%). Integration of these data with fluvial facies distributions, petrography, clast counts, and evidence of magmatic arc sources from the Mohave region of California implies the presence of a northeast-flowing, axial fluvial system. This system was fed by rivers draining the Mogollon Highlands to the south and by transverse drainages from the Sevier fold-and-thrust belt to the west. Compared to the fluvial deposits, shallow-marine sandstones have a greater proportion of Sevier fold-and-thrust belt–derived zircons (42%), which were delivered via longshore currents from the north. Shallow-marine samples also contain less Mogollon input (44%) compared to contemporaneous fluvial systems, and similar input from the magmatic arc (14%). Although Proterozoic zircons associated with the Mogollon Highlands are also present in the Sevier fold-and-thrust belt, several lines of evidence argue for a distinct southerly source for the Straight Cliffs Formation. These include (1) moderate proportions of feldspar and angular quartz grains in fluvial sandstones, which favor a felsic intrusive source, and (2) prominent 1.4 and 1.7 Ga zircon populations. The 1.4 and 1.7 Ga peaks are the only dominant Proterozoic peaks in samples from the Straight Cliffs Formation, whereas samples derived more directly from the Sevier fold-and-thrust belt tend to have a broader distribution of Proterozoic age peaks.

Up-section architectural trends in the Straight Cliffs Formation are linked to trends in detrital zircon geochronologic data, underscoring the likelihood of common drivers and controls. The axial system depositing Straight Cliffs fluvial strata was primarily fed by drainages originating in the Mogollon Highlands during a pulse of tectonic activity in the Maria fold-and-thrust belt and generally high subsidence rates in the foreland basin (Turonian–Santonian). Over time, activation of the Paxton duplex in the Sevier fold-and-thrust belt (early Campanian) exhumed proximal foreland basin strata and enabled drainage systems from the Sevier fold-and-thrust belt to feed into the basin more prominently. The results presented here underscore the potential significance of axial fluvial systems and their complex interplay with transverse drainage networks in foreland basins.

INTRODUCTION

Modern foreland basin systems contain both transverse and axial rivers (generally oriented orthogonal and parallel to the fold-and-thrust belt, respectively) that deliver and redistribute sediment throughout the basin. To date, most studies of Cordilleran foreland basin architecture have focused on transverse fluvial deposits (Lawton, 1983, 1986; Fillmore, 1989, 1991; Goldstrand, 1994; Olsen et al., 1995; Horton et al., 2004; DeCelles et al., 1995; DeCelles and Cavadza, 1999; DeCelles, 2004; Edwards et al., 2005; May et al., 2013), and related stratigraphic architecture with variations in relative sea level (Olsen et al., 1995; Van Wagoner, 1995), climate (Drummond et al., 1996), autogenic patterns (Wang et al., 2011), and tectonic subsidence associated with fold-and-thrust belt development (Robinson and Slingerland, 1998; Horton et al., 2004; Edwards et al., 2005).

Factors governing axial fluvial architecture have remained largely unstudied in Cordilleran foreland strata, but new detrital zircon geochronologic data from the Turonian–Campanian Straight Cliffs Formation help to elucidate the relationship between source rocks and basin sedimentation. Approximately 10 m.y. of fluvial and alluvial deposition are preserved in the Straight Cliffs Formation in the Kaiparowits Plateau of southern Utah (Figs. 1 and 2; Table 1), enabling detailed investigation into the controls on fluvial architecture. Among the challenges associated with linking fluvial architecture to potential driving factors is the difficulty of distinguishing between axial and transverse deposition, not only spatially throughout the basin, but also as the systems evolve through time. Resolving the detrital zircon provenance of these Cordilleran foreland basin deposits remains a challenge due to overlap between zircon age populations in the likely source areas on the basin margins. However, by integrating new detrital zircon geochronologic data with sandstone petrology, paleocurrent measurements, and clast counts, the ambiguity of source rock provenance signatures adjacent to the foreland basin can be reduced, and axial fluvial deposits can be more clearly differentiated from their transverse counterparts.

Previous studies of the Straight Cliffs Formation (e.g., Peterson, 1969a, 1969b; Shananey and McCabe, 1991, 1993, 1995; Hettinger, 1995, 2000; Allen and Johnson, 2010a, 2010b, 2011; Gallin et al., 2010; Gooley, 2010; Dooling, 2013; Pettinga, 2013; Fig. 3) provide a necessary framework in which to relate controls on
Detrital zircon geochronology, provenance, and evolution of Late Cretaceous fluvial systems, southern Utah

REGIONAL GEOLOGY

The Straight Cliffs Formation records fluvial and marginal marine deposition adjacent to several prominent paleogeographic features during Turonian–early Campanian time (Fig. 1). A major source area for these depositional systems is presumed to be the Sevier fold-and-thrust belt, a mountain chain situated at the easternmost extent of the Cordilleran hinterland that trended northeast through southern Utah (Armstrong, 1968; DeCelles, 2004). Approximately 300 km south of the Kaiparowits Basin were the Mogollon Highlands, a northwest-trending topographic high in central Arizona and New Mexico that was uplifted during several tectonic events throughout Mesozoic time (Bilodeau, 1986; Salem, 2009). West of these mountain belts, there was the Cordilleran magmatic arc, an active volcanic chain of subduction-related magmatism spanning the western margin of the North American plate (Barth and Wooden, 2006). The eastern edge of the Kaiparowits Plateau was marked by the Coniacian–early Campanian shoreline of the Western Interior Seaway, an epicontinental sea that connected the Gulf of Mexico to Arctic Canada throughout much of Late Cretaceous time (Kauffman, 1977).

Sevier Fold-and-Thrust Belt

Late Cretaceous subduction of the Farallon plate beneath the western margin of the North American plate induced east-west crustal shortening through most of present-day Nevada and western Utah (Burchfiel and Davis, 1972, 1975). More than 300 km of shortening was accommodated by large horizontal-offset (>100 km) thrust faults in the Sevier fold-and-thrust belt (DeCelles and Coogan, 2006). The easternmost extent of the Sevier fold-and-thrust belt during Turonian–early Campanian time was located ~100 km west of the Kaiparowits Plateau (Fig. 1; Allmendinger, 1992; Burchfiel et al., 1992; DeCelles, 2004). During this time, thin-skinned deformation and erosion of the Paxton, Pavant, fluvial and marginal marine architecture to the sedimentary source terranes adjacent to the Cordilleran foreland basin. With strong facies control across the Kaiparowits Plateau, it is possible to identify variability in sediment sources and delivery within distinct stratigraphic intervals and depositional environments. Additionally, changes in provenance through time can be related to tectonic processes in both the Sevier fold-and-thrust belt and Mogollon Highlands, which heavily influenced the evolution of fluvial systems in the Kaiparowits region of the foreland basin.

Figure 1. Paleoreconstruction of southwestern North America during Coniacian–Santonian time (after DeCelles, 2004). The Kaiparowits Basin (KB) was situated between the Sevier fold-and-thrust belt to the west and the shoreline of the Western Interior Seaway to the east. The Mogollon Highlands were located south of the Kaiparowits Plateau in central Arizona. The Cordilleran magmatic arc extended from southern Arizona, through California, and continued north along the continental margin. Primary detrital zircon ages associated with each source terrane are labeled in shaded regions. Age data compiled from Chen and Moore (1982), Schermer and Bushy (1994), Gerber et al. (1995), Coleman and Glazner (1997), Ferguson et al. (2004), Barth and Wooden (2006), Amato et al. (2008), Dickinson and Gehrels (2009), Lawton et al. (2010), and Spencer and Pecha (2012). Present-day exposures of Upper Cretaceous foreland basin fill are designated by light-gray shading. Abbreviations: BMT—Blue Mountain thrust; CNTB—Central Nevada thrust belt; CR—Canyon Range thrust; ESTB—Eastern Sierra thrust belt; KB—Kaiparowits Basin; KMM—Keaney/Mollusk Mine thrust; KT—Keystone thrust; PV—Pavant thrust; PX—Paxton thrust; WW—Wah Wah thrust. States: AZ—Arizona, CA—California, CO—Colorado, NM—New Mexico, NV—Nevada, UT—Utah, WY—Wyoming.
and Canyon Range thrust sheets in central Utah and the Blue Mountain, Wah Wah, and Keystone thrusts in southern Utah and Nevada (Fig. 1) exposed Proterozoic through Mesozoic sedimentary and metasedimentary units throughout the Sevier fold-and-thrust belt (Miller, 1966; Armstrong, 1968; DeCelles and Coogan, 2006). Mogollon Highlands

In addition to the Sevier fold-and-thrust belt, topography was present along the southern margin of the Cordilleran foreland basin in the Mogollon Highlands. Initial uplift of the region was triggered by Early Cretaceous rifting in southeastern Arizona and New Mexico, which formed a northwest-trending topographic high in central Arizona known as the Mogollon Highlands (Fig. 1; Bilodeau, 1986). Northeastward tilting and uplift of early Mesozoic and Paleozoic strata adjacent to the rift basin formed the southwestern margin to the Cordilleran foreland basin in northern Arizona. During Early Cretaceous time, Mesozoic and Paleozoic sedimentary rocks exposed in the Mogollon Highlands were eroded and transported southeast into the Bisbee and McCoy Basins and northeast into the Cordilleran foreland basin (Bilodeau and Lindberg, 1983; Bilodeau, 1986). Prolonged exhumation of this relict rift shoulder through Late Cretaceous time resulted in the exposure of 1.3–1.9 Ga Yavapai-Mazatzal basement rock in central Arizona (Wasserburg and Lanphere, 1965; Ferguson et al., 2004; Spencer and Pecha, 2012). Although the Mogollon Highlands remained relatively inactive throughout Late Cretaceous time, minor episodes of crustal shortening may have aided in the exhumation of Proterozoic basement rocks throughout the region (Fig. 1; e.g., the Maria fold-thrust belt; Knapp and Heizler, 1990; Spencer and Reynolds, 1990; Salem, 2009). Regional correlations of Cordilleran foreland basin strata document significant unconformities beneath Upper Cretaceous strata in Arizona and Utah, further implying that the Mogollon Highlands persisted as a topographic high into Late Cretaceous time (Hayes, 1970; Peterson and Kirk, 1977).

Figure 2. Map of the Kaiparowits Plateau in southern Utah. Shaded regions represent present-day exposures of the Straight Cliffs Formation. Black circles indicate locations where detrital zircon samples, paleocurrents, clast counts, and/or petrographic samples were collected. Heward Creek is located on the eastern edge of the Paunsaugunt Plateau.

TABLE 1. DETRITAL ZIRCON SAMPLE FACIES AND LOCATIONS

<table>
<thead>
<tr>
<th>Facies</th>
<th>Heward Creek</th>
<th>Bull Canyon</th>
<th>Tibbet Canyon</th>
<th>Kelly Grade</th>
<th>Left Hand Collet</th>
<th>Buck Hollow</th>
<th>Total</th>
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<td>2 (5%)</td>
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<td>5 (13%)</td>
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<td>5 (13%)</td>
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<td>1 (3%)</td>
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<td>1 (3%)</td>
<td>9 (23%)</td>
<td>10 (25%)</td>
<td></td>
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Note: Numbers indicate quantity of samples collected. Abbreviations: TCM—Tibbet Canyon Member; SHM—Smoky Hollow Member; JHM—John; Henry Member; DTM—Drip Tank Member.
Subduction-related magmatism along the Cordilleran magmatic arc between roughly 260 and 81 Ma (Chen and Moore, 1982; Miller et al., 1995; Barth and Wooden, 2006) led to the development of an additional topographic high along the western margin of the North American plate (Fig. 1). Triassic through Cretaceous volcanic and plutonic detritus from southern California, Arizona, and central Nevada was likely carried by a network of drainages flowing eastward into the Cordilleran foreland basin (Dickinson and Gehrels, 2009). Three primary pulses of subduction-related magmatism occurred in the Cordilleran magmatic arc during Mesozoic time (225–200 Ma, 186–144 Ma, and 125–88 Ma; Bateman, 1983), but episodes of localized magmatism also took place within the arc (e.g., in the Mojave region of southern California around ca. 147 Ma; Schermer and Busby, 1994; Gerber et al., 1995; Walker et al., 2002).

The Straight Cliffs Formation is well exposed throughout the Kaiparowits Plateau, located in the Grand Staircase–Escalante National Monument of south-central Utah (Fig. 2). Approximately 300–500 m of Turonian–Campanian siliciclastic sedimentary deposits are exposed throughout the Kaiparowits Basin of south-central Utah, providing a nearly complete record of the marginal marine environment present during the initial retreat of the Western Interior Seaway. The earliest stratigraphic correlations of the Straight Cliffs Formation were performed by Peterson (1969a, 1969b). In doing so, he subdivided the formation into the Tibbet Canyon (TCM), Smoky Hollow (SHM), John Henry (JHM), and Drip Tank Members (DTM; Fig. 3).

The lowermost Tibbet Canyon Member (Fig. 3) consists of ~20 m of mainly shoreface strata deposited along the margin of the Western Interior Seaway (Peterson, 1969b). The Tibbet Canyon Member marks a transition from offshore mudstone and limestone deposition to sandstone and siltstone deposition in the Kaiparowits Basin of south-central Utah. Shanley and McCabe (1991) interpreted fluvial incision at the top of the Tibbet Canyon Member to mark a sequence stratigraphic boundary.

The Smoky Hollow Member (Fig. 3) is composed primarily of ~20–30 m of isolated fluvial sandstone bodies interbedded with carbonaceous floodplain mudstones and thin coal seams (Peterson, 1969b). These fine- to coarse-grained terrestrial deposits represent a basinward shift of facies, perhaps resulting from a regional drop in base level (Bobb, 1991; Shanley and McCabe, 1991). The top of the Smoky Hollow Member is commonly distinguished by the presence of a coarse-grained, white and orange, braided fluvial sandstone interval known as the Calico bed. This regionally extensive gravel sheet is composed of laterally and vertically amalgamated fluvial deposits, and it records...
deposition during a period of decreased accommodation relative to sediment supply (Bobb, 1991). Shanley and McCabe (1991) proposed a sequence stratigraphic boundary at the base of the Calico bed, where a regionally extensive, erosive contact marks a drop in relative sea level.

The John Henry Member is the thickest (200–500 m) and most laterally variable of the four members (Fig. 3). The base of the John Henry Member is marked by a landward shift in facies recording a transgression that occurred after deposition of the Smoky Hollow Member. In the southern and western Kaiparowits Plateau, the John Henry Member consists primarily of multi-story and single-story fluvial channel belts interbedded with carbonaceous floodplain mudstones and coals (Shanley and McCabe, 1991, 1993, 1995; Titus et al., 2005; Gooley, 2010; Pettinga, 2013). In these areas, basal John Henry Member strata contain evidence for tidally influenced deposition, including inclined heterolithic strata, herringbone cross-stratification, flaser and wavy-bedded sandstones, and brackish-water ichnofossils such as Teredolites and Gastrochaenolites (Shanley et al., 1992; Hettinger, 1995; Gallin et al., 2010). Easternmost exposures of the John Henry Member consist of offshore through intertidal facies, and these represent the latest episode of Western Interior Seaway deposition in southern Utah. Peterson (1969b) subdivided marine exposures of the John Henry Member into seven shoreface units (A–G), which were used by subsequent studies to document stratigraphic architecture in the eastern Kaiparowits Plateau (Fig. 3; Allen and Johnson, 2010a, 2010b, 2011; Johnson et al., 2011; Dooling et al., 2012).

The uppermost Drip Tank Member consists of 30–100 m of coarse-grained fluvial sandstones and channel lag conglomerates (Fig. 3). The Drip Tank Member gradationally overlies the John Henry Member and records a basinward shift in facies. Shanley and McCabe (1991) proposed a sequence boundary at the base of the Drip Tank Member, but more recent studies have suggested that the sequence boundary lies near the middle of the Drip Tank Member (Lawton et al., 2003; Schellenbach, 2013; Lawton et al., 2014). Channel bodies in the Drip Tank Member are both vertically and laterally amalgamated, and floodplain deposits are rare.

**Stratigraphic Architectural Trends**

Previous studies investigated fluvial strata from the Straight Cliffs Formation to identify possible controls on alluvial architecture (Shanley and McCabe, 1991, 1993, 1995; Little, 1997). Subsequent studies documented trends in average channel widths, grain size, sandstone:shale ratio, channel clustering, channel stacking, and paleoflow direction throughout the Kaiparowits Plateau (Fig. 3; e.g., Gallin et al., 2010; Gooley, 2010; Johnson et al., 2011, 2013; Pettinga, 2013). Fluvial strata near the base of the Straight Cliffs Formation (Smoky Hollow Member and lower John Henry Member) indicate northeast-directed paleoflow and show an up-section decrease in average grain size with a reduction in channel widths, lateral and vertical channel amalgamation, and sandstone:shale ratio. The middle John Henry Member consists of laterally restricted channel belts with abundant coals and floodplain mudstones. The upper John Henry Member and Drip Tank Member document a reversed trend of increasing grain size with wider channels, more amalgamation of channel belts, and higher sandstone:shale ratio (Gallin et al., 2010). The capping strata in the Drip Tank Member consist of a braided fluvial gravel sheet with paleocurrent indicators showing mainly east-directed flow (Lawton et al., 2014).

**METHODS**

This study focuses on detrital zircon U-Pb geochronologic data from 40 sandstone samples collected from five locations in southern Utah (Heward Creek, Bull Canyon, Kelly Grade, Left Hand Collet, and Buck Hollow; Figs. 2 and 4; Table 1). At each location, sandstone samples were taken from representative facies in each of the stratigraphic members exposed in the section. Heward Creek (in the easternmost Paunsaugunt Plateau) and Bull Canyon (southwestern Kaiparowits Plateau) are located in western exposures of the Straight Cliffs Formation and expose fluvial and tidally influenced channel deposits. Samples collected from Kelly Grade are mainly from tidal channel deposits and tidal bar forms at the coastal margin. Left Hand Collet and Buck Hollow are positioned at the Coniacian–early Campanian shoreline, and detrital zircon samples were derived from lower-middle shoreface and tidal channel sandstones (Table 1).

Zircons were isolated using traditional density and magnetic methods and were mounted in 25 mm epoxy plugs. For each sample, 120 zircons were randomly selected for U-Pb geochronologic analysis using laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS). Analyses were conducted at the University of New Brunswick in Fredericton, New Brunswick, Canada, following the method described by Archibald et al. (2013). Analyses were obtained using a Resonetics RESOlution™ series 193 nm excimer laser equipped with an S-155 two-volume Laurin Technic Pty ablation cell. The two-volume low-volume cell ensures identical ablation anywhere within the cell as well as fast-washout of the ablated aerosol. The laser was connected to an Agilent 7700x quadrupole ICP-MS via 4 mm nylon tubing, with a Laurin Technic Pty “Squid” smoothing device connected in-line just before the ICP-MS. Standards and unknowns were loaded together, and the cell was prepared for ablation by repeated evacuation and backfilling with high-purity He. A typical ablation sequence consisted of at least 120 detrital zircons interspersed with 15 primary standards (1065 Ma zircon 91500), up to five consistency standards (e.g., 416 Ma Temora zircon), as well as four analyses of NIST610 glass. Ablation was conducted in a mixed He (350 mL/min) and Ar (930 mL/min) atmosphere at conditions of ~4 J/cm² fluence, 19 or 26 μm crater diameter (depending on grain size of detrital zircon population), 4.5 Hz repetition rate, and 30 s ablation with 25 s background. Data were reduced offline using Iolite v2.31 (Paton et al., 2011) and VisualAge (Petrus and Kamber, 2012), and data were plotted using Isoplot v3.75 (Ludwig, 2012). With the exception of young grains (younger than 500 Ma), ages more than 5% discordant were rejected. Analyses yielding anomalously high concentrations of U and depleted concentrations of Th were discarded because these grains can be highly susceptible to Pb loss (Dickinson and Gehrels, 2009).

Zircon age distributions were compared using the Kolmogorov-Smirnov (K-S) test, which assigns a $p$ value to sample pairs based on the similarity of their cumulative density functions (Press et al., 1986). High $p$ values ($p > 0.05$) indicate a statistically significant likelihood that two samples may have been derived from sources with the same zircon age distributions. Low $p$ values ($p < 0.05$) suggest the samples were sourced by statistically distinguishable distributions of zircon ages.

Detrital zircon ages were analyzed in addition to paleocurrent measurements, sandstone modal analyses, and clast counts derived from well-studied stratigraphic intervals of the Straight Cliffs Formation. Paleocurrent measurements were obtained from trough cross-stratified fluvial sandstones, planar cross-stratified accretion sets, laterally and longitudinally accreting bar forms, ripples, and flute casts. Paleoflow measurements were obtained using a Brunton compass oriented along the axis of trough cross-stratified bed forms and in the dip direction of accreting foresets. Sandstone petrographic samples were point-counted to obtain relative proportions of monocrystalline and polycrystalline quartz (Qm + Qp), feldspar (plagioclase [P] and...
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RESULTS

Paleocurrent Measurements

Paleocurrent measurements \( n = 4568 \) and accretion set measurements \( n = 2040 \) are presented from fluvial strata at Rock House Cove, Bull Canyon, and Kelly Grade, as well as tidal, estuarine, and shoreface strata at Kelly Grade and Left Hand Collet (Figs. 2 and 5).

Fluvial PaleocurrentDirections

Paleocurrent measurements in fluvial strata were obtained from trough cross-stratified sandstones, planar cross-stratification, and ripple cross-laminated strata (Gooley, 2010). Accretion sets were measured from laterally and longitudinally accreting bar forms. These are distinguished to help grossly differentiate between different modes of bar form accretion (e.g., downstream vs. lateral accretion; McLaurin and Steel, 2007).

Near the base of the John Henry Member at Rock House Cove (\( n_{\text{total}} = 1577 \)), the average paleoflow direction trends northeast (\( n = 1577 \)), and accretion sets are oriented obliquely toward the north (Fig. 5). Middle John Henry strata record a shift toward southeastward flow, with laterally accreting bar forms advancing south and east. Paleocurrent data from the upper John Henry Member imply flow resumed its northeast trajectory, this time with a predominance of longitudinally accreting bar forms instead of the lateral accretion common in lower John Henry Member strata.

At Bull Canyon, paleocurrent data (\( n = 1869 \); Fig. 5) consist of ripple cross-lamination, trough cross-stratification, planar cross-stratification, laterally and longitudinally accreting bar forms, and imbricated mud clasts (Pettinga, 2013). At the base of the John Henry Member, mean paleoflow measurements are directed toward the northeast and show a preference for downstream accretion toward the northeast. Data from the middle John Henry Member imply paleoflow was oriented toward the east, with accretion sets primarily toward the northeast. In the Drip Tank Member, paleoflow was directed toward the southeast, and bar forms were accreting toward the northeast.

At Kelly Grade, fluvial paleoflow measurements (\( n = 1565 \); Fig. 5) in the upper John Henry Member indicate paleoflow was directed toward the northeast, and bar forms accreted toward the north (Gallin et al., 2010). Measurements from the Drip Tank Member imply flow direction was oriented toward the east. Paleocurrent measurements at Kelly Grade, Bull Canyon, and Rock House Cove do not follow the same up-section trends, but this is likely due to the sinuous nature of meandering fluvial systems. However, in all three locations, the overall trend is consistently toward the east-northeast, which is subparallel to the Sevier thrust front at this latitude.
Tidal and Marine Paleocurrent Directions

Tidal paleocurrent indicators from Kelly Grade (n = 929; Fig. 5) are generally oriented toward the northeast and consist of trough and planar cross-stratification, herringbone cross-stratification, ripple cross-lamination, and both laterally and longitudinally accreting bar forms (Gallin et al., 2010). Tidal strata in the lower John Henry Member contain mostly unidirectional indicators oriented toward the north and accretion sets directed toward the east. Tidal paleocurrent indicators from the middle John Henry Member imply that high-sinuosity and bidirectional flow was directed toward the east and west with accretion sets advancing eastward.

Paleocurrent data from Left Hand Collet (n = 668; Fig. 5) were measured from tidally influenced trough and planar cross-stratified sandstones, ripple cross-laminations, herringbone cross-stratification, and tidal bar forms (Dooling, 2013). Measurements from the lowermost A and B progradational shoreface successions (Fig. 3) indicate northeastward flow with southeastward accretion sets. Retrogradational shoreface successions (C, D, E) provide evidence for southeastward flow with accretion sets advancing to the northeast (C), southeast (D), and southwest (E). Aggradational to progradational shoreface successions at the top of the John Henry Member indicate flow toward the northeast (F) and accretion toward the east (F and G).

Sandstone Petrology

Sandstone modal analyses were conducted for 122 samples from all members of the Straight Cliffs Formation across the Kaiparowits Plateau (Table DR1 in the GSA Data Repository1; Allen and Johnson, 2010a, 2010b; Gallin et al., 2010; Gooley, 2010; Pettinga, 2013; this study). Petrographic data from each location (Rock House Cove, Bull Canyon, Kelly Grade, Left Hand Collet, and Rogers Canyon) are plotted on traditional ternary diagrams (Fig. 6). The end members on each ternary diagram represent total quartz (Qt), feldspar (F), and unstable lithic fragments (Lu; Dickinson, 1985).

Sandstones in the Straight Cliffs Formation are typically composed of mono- and poly-crystalline quartz, potassium and plagioclase feldspar, chert, and unstable volcanic, metamorphic, and sedimentary lithic fragments. Using the relative proportions of total quartz (Qt), feldspar (F), and unstable lithic fragments as a metric, Dickinson (1985) subdivided the QtFLu plots into seven categories representing various types of sedimentary source terranes. Sandstone compositional data from all Straight Cliffs Formation samples plot in the recycled orogen, craton...
The ratio of monocrystalline quartz to polycrystalline quartz for fluvial sandstones averages 40, which is characteristic of interior cratonic sources (Dickinson, 1985). Shoreface samples from the Tibbet Canyon Member (Bull Canyon, Kelly Grade, and Left Hand Collet) and John Henry Member (Left Hand Collet and Rogers Canyon; Fig. 2) cluster in the recycled orogen category but generally contain more rounded quartz grains and smaller proportions of feldspar than fluvial samples, implying recycled sedimentary rocks were a more significant source terrain for marine strata than fluvial strata (Allen and Johnson, 2010a).

Figure 7 shows temporal trends in sandstone modal compositions. Generally, samples document an up-section increase in total quartz from the Tibbet Canyon Member through the Calico bed at the top of the Smoky Hollow Member. The transition into the John Henry Member records a decrease in total quartz with an increase in feldspar. At Rock House Cove, Bull Canyon, and Kelly Grade, total quartz decreases up section through lower and middle John Henry strata, and then increases through the upper John Henry and Drip Tank Members. In contrast, the proportion of unstable lithic grains increases through the lower and middle John Henry Member and decreases through the remainder of the formation. The proportion of feldspar remains relatively consistent through the John Henry Member but decreases in the Drip Tank Member. At Left Hand Collet and Rogers Canyon, the John Henry Member records an up-section decrease in total quartz with an increase in unstable lithic grains. Feldspar content at Left Hand Collet decreases up section but remains relatively consistent at Rogers Canyon.

The up-section trends noted in fluvial samples indicate that cratonic and transitional continental detritus is more prominent in Smoky Hollow and lower John Henry samples (consisting of abundant angular to subangular quartz and feldspar grains), whereas upper John Henry and Drip...
Tank strata contain an increased abundance of recycled orogenic detritus (well-rounded quartz grains, detrital carbonate, and chert; Fig. 7). In shoreface samples, the up-section trends are less apparent but signal a minor increase in craton-derived feldspars and lithic fragments through time. This can be attributed to an increase in fluvial influence at the shoreline as fluvial facies prograded eastward through time.

Clast Counts

Clast count data \((N = 8, n = 1025; \text{Table 2})\) were collected from channel lag deposits in the Calico bed at Kelly Grade, Buck Hollow, and Main Canyon (Fig. 2). Clasts were also counted from shoreface strata in the basal John Henry Member at Main Canyon. Braided fluvial strata of the Calico bed contain well-rounded pebbles of chert (81% of clasts), quartzite (16%), and sandstone (3%). These proportions are consistent across the Kaiparowits Plateau and do not show any significant spatial trends. In comparison to the Calico bed, clasts from basal John Henry Member shoreface deposits show a decrease in chert (56%), with an increase in quartzite (43%), and a minor decrease in sandstone (1%).

U-Pb Geochronology

Detrital zircon geochronologic data from the Straight Cliffs Formation \((N = 40 \text{ samples}, n = 3650 \text{ individual analyses}; \text{Table 1; Fig. 4})\) are presented using age histograms superimposed on relative probability plots (Figs. 8 and 9).

Figure 7. Relative proportions of total quartz (Qt), feldspar (F), and unstable lithic fragments (Lu) from several stratigraphic intervals spanning the Kaiparowits Plateau. Fluvial samples (denoted by gray background shading) from Rock House Cove, Bull Canyon and Kelly Grade record two up-section trends in sandstone composition. Calico and lower John Henry strata show an up-section decrease in total quartz with an increase in unstable lithic fragments. Feldspar content remains relatively consistent. Upper John Henry and Drip Tank samples show a reversed trend with increased quartz content and a decrease in feldspar and unstable lithic fragments. Marine samples (denoted by white background) show an up-section decrease in quartz and an increase in unstable lithic fragments. Abbreviations: TCM—Tibbet Canyon Member; JHM—John Henry Member; DTM—Drip Tank Member.

Figure 8. Relative probability plot containing ages from all detrital zircons in this study \((N = 40 \text{ samples}, n = 3650 \text{ grains})\). Left vertical axis corresponds to number of grains in each age bin (age bins span 100 m.y.). Age populations are denoted by white and gray shaded bars. Population C constitutes the largest percentage of all ages from the Straight Cliffs Formation (59% of all grains), followed by population B (25%), population A (13%), and population D (3%).

<table>
<thead>
<tr>
<th>Table 2. Clast Count Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Calico bed</td>
</tr>
<tr>
<td>Basal John Henry Member shoreface</td>
</tr>
</tbody>
</table>

Downloaded from https://pubs.geoscienceworld.org/gsa/gsabulletin/article-pdf/127/3-4/372/421813/372.pdf by guest on 18 January 2019
Figure 9. Relative probability histograms for each detrital zircon sample from the Straight Cliffs Formation. Samples are grouped vertically according to location and horizontally by stratigraphic interval. The name, facies, and number of grains corresponding to each sample are labeled. Background shading designates age populations A (81–265 Ma), B (265–1250 Ma), C (1.25–1.90 Ga), and D (1.9–3.0 Ga). Abbreviations: SFTB—Sevier fold-and-thrust belt; WIS—Western Interior Seaway; TCM—Tibbet Canyon Member; SHM—Smoky Hollow Member; JHM—John Henry Member; DTM—Drip Tank Member.
Data are also presented in Table 3, Table 4, and Table DR2 in the GSA Data Repository (see footnote 1). Fluvial detrital zircon samples \( (N = 19) \) were predominantly taken from the John Henry Member at Bull Canyon and Heward Creek (Fig. 2). Additional fluvial samples were collected from the Smoky Hollow and Drip Tank Members at Bull Canyon, Left Hand Collet, and Buck Hollow. Tidal samples \( (N = 11) \) were collected from the John Henry Member at Bull Canyon, Kelly Grade, and Buck Hollow. Shoreface samples \( (N = 10) \) were obtained from the John Henry Member at Left Hand Collet and Buck Hollow. Additionally, shoreface samples were collected from the Tibbet Canyon Member at Bull Canyon, Kelly Grade, Left Hand Collet, and Buck Hollow. Detrital age spectra have been subdivided into four age populations (A–D). Each population may be linked with one or more potential source regions exposed near the Cordilleran foreland basin during Turonian–Campanian time. The characteristics of each age population are outlined in this section, followed by a discussion of spatial and temporal trends observed in the data set.

### Population A: Mesozoic Ages (81–265 Ma)

Mesozoic ages account for 13% of all Straight Cliffs ages (Fig. 8) and have major peaks at 96 Ma, 147 Ma, and 225 Ma. Mesozoic ages are present in all samples and range from 1% of ages in marine strata at Kelly Grade (TS-11, Tibbet Canyon Member; Fig. 9) to 43% of ages in fluvial strata at Buck Hollow (TS-25, John Henry Member; Fig. 9). Late Paleozoic ages (250–265 Ma) commonly accompany the Mesozoic distribution and have been included in population A.

Population A zircons originated within volcanic and plutonic sources in the Cordilleran magmatic arc of southwestern Arizona and southern California (Fig. 1), which was active between ca. 81 and 260 Ma (Chen and Moore, 1982; Miller et al., 1995; Barth and Wooden, 2006). Turonian–Campanian zircons compose only 7% of the total Mesozoic arc-derived population. The majority of Mesozoic zircons originating from the magmatic arc define 96 Ma, 147 Ma, and 225 Ma peaks, indicating many of these arc-derived zircons were remobilized and reworked prior to deposition in the Kaiparowits Basin. Latest Jurassic ages composing the 147 Ma peak were likely derived from 147 Ma intrusions in the Mojave Desert region of southern California (Schermer and Busby, 1994; Gerber et al., 1995; Walker et al., 2002), and the Late Cretaceous ages forming the 96 Ma peak were originally derived from the Sierra Nevada batholith (Coleman and Glazner, 1997). Zircons of these ages may have been derived directly from their original magmatic sources, but they may also have come from proximal foreland basin deposits and wedge-top basins (e.g., Iron Springs Formation) that were uplifted and exhumed during episodes of thrust belt propagation (Goldstrand, 1994). Mesozoic foreland basin strata containing arc-derived zircons are a likely source for the 225 Ma age peak (Dickinson and Gehrels, 2009). The resultant maximum depositional ages with 95% confidence for each member are 94.3 ± 1.4 Ma (top Tibbet Canyon Member), 89.1 ± 6.3 Ma (top Smoky Hollow Member), and 81.2 ± 2.5 Ma (top John Henry Member), and 81.2 ± 2.5 Ma (top John Henry Member).

### Table 3. Detrital Zircon Ages in Each Population

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Location</th>
<th>Interval</th>
<th>Facies</th>
<th>n</th>
<th>(%)</th>
<th>(%)</th>
<th>(%)</th>
<th>(%)</th>
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<td>JHM &quot;A&quot;</td>
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<td>8</td>
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</table>

**Note:** Abbreviations: TCM—Tibbet Canyon Member; SHM—Smoky Hollow Member; L JHM—Lower John Henry Member; M JHM—Middle John Henry Member; U JHM—Upper John Henry Member; DTM—Drip Tank Member.

### Table 4. Means and Standard Deviations for Each Age Population

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<tr>
<th>Age Interval</th>
<th>A (%)</th>
<th>B (%)</th>
<th>C (%)</th>
<th>D (%)</th>
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</thead>
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<tr>
<td>Marine</td>
<td>10 ± 6</td>
<td>40 ± 5</td>
<td>45 ± 10</td>
<td>5 ± 3</td>
</tr>
<tr>
<td>Tidal</td>
<td>9 ± 6</td>
<td>26 ± 10</td>
<td>63 ± 13</td>
<td>2 ± 2</td>
</tr>
<tr>
<td>Fluvial</td>
<td>17 ± 9</td>
<td>17 ± 8</td>
<td>63 ± 16</td>
<td>3 ± 2</td>
</tr>
<tr>
<td>Total</td>
<td>13 ± 5</td>
<td>25 ± 12</td>
<td>59 ± 15</td>
<td>3 ± 3</td>
</tr>
</tbody>
</table>
Population B: Paleozoic through Mesoproterozoic Ages (265–1250 Ma)

Paleozoic through Mesoproterozoic ages compose 25% of all Straight Cliffs Formation zircons (Fig. 8) and form a prominent Paleozoic peak (414 Ma) and Grenville peak (1076 Ma). Grains from population B range from 4% of all grains in isolated fluvial channel sandstones in the middle John Henry Member at Bull Canyon (SEM-004) to 51% of all grains in marine strata of the upper John Henry Member at Buck Hollow (TS-29).

Zircons representing population B were primarily derived from sedimentary and metasedimentary units within the Sevier fold-and-thrust belt (Dickinson and Gehrels, 2009; Lawton et al., 2010). The Canyon Range, Pavan, Paxton, Blue Mountain, and Wah Wah thrust sheets in southern Utah (Fig. 1) exposed Proterozoic sedimentary rocks to erosion, but patches of laterally extensive Paleozoic and Mesozoic sedimentary deposits adjacent to exposures of Yavapai-Mazatzal basement rocks (Bilodeau, 1986). During Early Cretaceous time, uplift and tilting of the Bisbee rift shoulder subjected the sedimentary rocks to erosion, but patches of remaining sedimentary cover blanketed parts of the Mogollon Highlands during Late Cretaceous time. Triassic through Early Cretaceous rocks in southern Utah and Arizona (Moenkopi, Chinle, Navajo, Morrison, Cedar Mountain, Burro Canyon and Dakota Formations) contain zircons derived from the Yavapai-Mazatzal basement rocks. Grenville and Paleozoic magmatic bodies exposed in eastern Laurentia (Dickinson and Gehrels, 2008a, 2008b), and the Cordilleran magmatic arc (Bilodeau, 1986).

Population C: Mesoproterozoic and Paleoproterozoic Ages (1.25–1.90 Ga)

Mesoproterozoic and Paleoproterozoic ages between 1.25 and 1.90 Ga represent 59% of all detrital zircons from the Straight Cliffs Formation (Fig. 8). Ages in this population compose two significant peaks. The more prominent age peak is centered at 1.68 Ga and contains 76% of zircons in this age population. A smaller peak centered at 1.40 Ga represents the remaining 24% of ages in this population. Compared to one another, the relative heights of the 1.40 and 1.68 Ga peaks vary among various samples, but there is no obvious pattern relating the heights of these peaks with relative positions in the Kaiparowits Plateau or specific time intervals in which the samples were deposited. The 1.68 Ga peak is present in 95% of Straight Cliffs samples and is nearly absent in three shoreface samples in the John Henry Member (TS-25, TS-26, TS-29) at Buck Hollow (Fig. 9). The 1.40 Ga peak is prominent in only 50% of all samples, most of which are fluvial sandstones.

Detrital zircons representing population C (59% of all Straight Cliffs zircons) are predominately derived from the Mogollon Highlands in central Arizona (Fig. 1). The 1.6–1.8 Ga and 1.4 Ga age peaks identified in most Straight Cliffs Formation samples are correlative with Yavapai-Mazatzal basement rocks in central Arizona (Wasserburg and Lanphere, 1965; Lanphere, 1968; Anderson and Bender, 1989; Gleason et al., 1994; Hawkins et al., 1996; Spencer and Pecha, 2012), as well as many sedimentary units in the Sevier fold-and-thrust belt and throughout the southwestern United States (Dickinson and Gehrels, 2008a; Laskowski et al., 2013). The original source of the 1.6–1.8 Ga zircons is an extensive metamorphosed magmatic belt that developed as a result of plate convergence during
the Paleoproterozoic Mazatzal orogeny (Amato et al., 2008). The expansive distribution of this magmatic belt resulted in widespread exposures of 1.6–1.8 Ga in the Mogollon Highlands. The 1.4 Ga intrusions present in the Mogollon High- lands were emplaced during a smaller orogenic event relative to the Mazatzal orogeny (Gleason et al., 1994; Nyman et al., 1994; Daniel et al., 2013); as a result, the distribution of these smaller magma bodies is more localized than that of the 1.6–1.8 Ga intrusions.

Population D: Paleoproterozoic and Archean Ages (1.9–3.0 Ga)

The remaining 3% of Straight Cliffs zircons are represented by the Paleoproterozoic and Archean age population. These ages form small peaks at 1.9 and 2.7 Ga and are most common in tidal samples from the John Henry Member at Kelly Grade and shoreline samples from Left Hand Collet (Fig. 9). The primary source for these grains was Mesozoic, Paleozoic, and Pre cambrian units in the Sevier fold-and-thrust belt (Fig. 1; Dickinson and Gehrels, 2009; Lawton et al., 2010).

DISCUSSION

Results from detrital zircon geochronology, sandstone petrography, and paleocurrent analyses provide evidence for sediment delivery from the Mogollon Highlands, Sevier fold-and-thrust belt, and Cordilleran magmatic arc into the Turonian–Campanian foreland basin of southern Utah (Fig. 1). Integration of these three data sets reduces the ambiguity associated with each provenance tool and enables source rocks with similar provenance signatures to be differentiated from one another.

Evidence for an Axial Drainage System

Fluvial paleocurrent measurements from the Straight Cliffs Formation show an overall east-northeastward orientation for rivers in the Kaiparowits Basin. This segment of the drainage system has an oblique orientation compared to the north-northeast strike of the Sevier thrust front at this latitude. However, rivers entering the Kaiparowits Basin are only one small part of the greater axial drainage network. It is possible that these rivers were redirected from the main axial drainage orientation due to backwater influences as they approached the shoreline, which was oriented nearly perpendicular to the overall paleocurrent direction (Johnson et al., 2013; Pettinga, 2013). The axial river system was further influenced by raised coal mines in the central plateau that impeded direct outputs to the shoreline (McCabe and Shanley, 1992; Hettinger, 2000; Allen and Johnson, 2010b) and redirected the rivers into lagoons or estuaries in the central plateau (Gallin et al., 2010; Dooling, 2013), or northward into a major north-trending fluvial-deltaic system (Chenmik et al., 2014; Mulhern et al., 2014).

The presence of an axial fluvial system upstream of the Kaiparowits Basin is supported by detrital zircon data, including the presence of 147 Ma zircons in the Straight Cliffs Formation (Fig. 8). This signature implies that 147 Ma intrusions and volcanics in the Mojave region were supplying detritus to the foreland basin. Because igneous rocks of this age are locally restricted to the Mojave region (Lahren et al., 1990; Schermer and Busby, 1994; Gerber et al., 1995; Walker et al., 2002), the river system in the Kaiparowits Basin must have been fed by drainages originating in southern California and southernmost Nevada, transporting sediment into the basin subparallel to the Sevier fold-and-thrust belt.

Further evidence for axial fluvial systems includes the abundance of population C detrital zircons (1.25–1.90 Ga) and petrographic data from Straight Cliffs Formation sandstones. Although the source for population C zircons can be traced to several potential regions spanning the basin margin (including the Mogollon Highlands, Sevier fold-and-thrust belt, and reworked Cretaceous foreland basin deposits), several lines of evidence indicate that the Mogollon Highlands were the primary source for population C zircons, and therefore that an axial drainage system transported sediment northeastward into southern Utah.

The abundance of potassium feldspar in Straight Cliffs fluvial strata (7%–26% of all grains, average 18%) requires that the source for these rocks contained an equal or greater percentage of feldspar. In the case of the Mogollon Highlands, the Yavapai-Mazatzal basin rock is largely composed of granitic and granodioritic intrusive bodies (Amato et al., 2008) containing up to 54% feldspar (Jagger and Palache, 1905), which is greater than the proportion observed in fluvial sandstones in the Straight Cliffs Formation. Strata in the Sevier fold-and-thrust belt typically yield smaller proportions of feldspar than what is observed in fluvial strata of the Straight Cliffs Formation (Otto and Picard, 1976; Uygur and Picard, 1980; Allen and Johnson, 2010a; Trendell et al., 2012). Other Late Cretaceous foreland basin deposits in southern Utah (Iron Springs Formation) and central Utah (Indianola Group, Blackhawk Formation) that were primarily sourced from the Sevier fold-and-thrust belt contain an average of ~3% feldspar (Lawton, 1986; Goldstrand, 1992; Horton et al., 2004). These lines of evidence indicate that recycled sedimentary sources in the Sevier fold-and-thrust belt were not supplying sufficient quantities of feldspar to account for the amounts present in Straight Cliffs Formation strata.

First-order sediment derivation from the Mogollon Highlands is also supported by the angular to subangular quartz grains that compose most fluvial deposits in the Straight Cliffs Formation (Allen and Johnson, 2010a; Allen et al., 2012; Gooley, 2010; Pettinga, 2013). The angularity of these grains is inconsistent with what would be expected from recycled sedimentary sources within the Sevier fold-and-thrust belt. Previous studies (Otto and Picard, 1976; Picard, 1977a, 1977b; Beitler et al., 2005) demonstrated that quartz grain morphologies within potential Mesozoic source rocks tend to be of equal or greater roundness than what is indicated by Straight Cliffs Formation petrography (Allen et al., 2012). Prominent Jurassic eolianites are composed of well-rounded spherical quartz grains that are likely present in Drip Tank samples (Lawton et al., 2003, 2014) but are otherwise rare or absent in the rest of the Straight Cliffs Formation. It is possible that angular quartz grains could have been sourced from quartzites exposed in the Sevier fold-and-thrust belt; however, due to the relatively low abundance of quartzite clasts present in fluvial lag deposits (16% of all clasts), it is unlikely that these quartzites were major sediment sources for the Straight Cliffs Formation.

Finally, the distribution of Proterozoic zircon ages in the Sevier fold-and-thrust belt is generally broader than what is observed in Straight Cliffs fluvial strata and Mogollon Highlands basement rock. To date, there have been no reported age signatures from the Sevier fold-and-thrust belt that contain primarily 1.4 Ga and 1.7 Ga peaks resembling those in the Straight Cliffs Formation and the Mogollon Highlands. Strata that do contain these two peaks also contain prominent Grenville, Paleoproterozoic, and Archean peaks that are not well represented in Straight Cliffs fluvial samples (Fig. 11; Dickinson and Gehrels, 2009; Lawton et al., 2010, 2014; Laskowski et al., 2013). Several Proterozoic quartzite units in the Sevier fold-and-thrust belt have prominent 1.4 Ga and 1.7 Ga peaks matching those seen in the Straight Cliffs Formation (Fig. 11; Lawton et al., 2010), but due to the relative scarcity of quartzite clasts in fluvial lag deposits, it is unlikely that these quartzites were the dominant source of 1.4 and 1.7 Ga zircons. Although these lines of evidence do not exclude the Sevier fold-and-thrust belt as a sediment source, they serve to support the Mogollon Highlands as the primary source for population C zircons present in Straight Cliffs fluvial strata.
Detrital zircon ages from Sevier fold-thrust belt correlative strata

Figure 11. Detrital zircon ages from stratigraphic units locally correlative to Sevier fold-and-thrust belt strata. Mesozoic strata contain an abundance of ages from populations A (not shown), B, and D. Precambrian strata from the Canyon Range thrust sheet contain zircons from populations B, C, and D. Figure is modified from Dickinson and Gehrels (2009) and Lawton et al. (2010).

Spatial Provenance Trends

Detrital zircon age signatures vary spatially across the Kaiparowits Plateau, and this is primarily linked to changes in depositional processes and sediment delivery mechanisms associated with each environment. There is a higher proportion of sediment derived from the Sevier fold-and-thrust belt (populations B and D) in samples from the northern and eastern plateau (Left Hand Collet, Buck Hollow, and Kelly Grade; Fig. 9) relative to samples collected in the western plateau (Bull Canyon and Heward Creek; Fig. 9). Up to 35% of zircons from Left Hand Collet are represented by populations B and D, and individual samples include as many as 54% (TS-10, basal shoreface deposits in the John Henry Member). At Buck Hollow and Kelly Grade, a similarly high proportion was observed, with 31% and 29% of all ages corresponding to populations B and D, respectively.

By comparison, populations B and D represent only 19% of ages at Bull Canyon and 15% at Heward Creek (Fig. 9). Spatial variations in detrital zircon U/Pb age distributions are linked to the transition from fluvial deposition in the southern and western Kaiparowits Plateau to tidal and marine deposition in the northern and eastern plateau (Fig. 12). The fluvial sections at Heward Creek and Bull Canyon were primarily fed by rivers draining the Mogollon Highlands, with subordinate input from the Sevier fold-and-thrust belt and Cordilleran magmatic arc (Fig. 13). The higher proportion of population B and D zircons in shoreface and tidal samples implies additional sediment was derived from Sevier sources and transported to the Kaiparowits Basin via longshore currents. When compared using Kolmogorov-Smirnov (K-S) statistics (Press et al., 1986), the resultant $p$ values for fluvial-tidal, fluvial-marine, and tidal-marine comparisons are 0.002, 0.000, and 0.000, respectively. $p$ values less than 0.05 imply that the age signatures are not similar enough to have been derived from the same source distributions.

Age signatures from the two fluvial-dominated successions (Bull Canyon and Heward Creek; Fig. 9) are similar and record only minor spatial variations in fluvial provenance. Samples near the base of the John Henry Member at Heward Creek (HC-2) and Bull Canyon (SEM-002) yield a K-S $p$ value of 0.898, implying a statistically significant likelihood that these zircons were derived from the same sources. Detrital zircon ages from both locations show similar proportions of each age population. At Heward Creek, 74% of ages correspond with population C, 13% with population B, 11% with population A, and 2% with population D. At Bull Canyon, 74% correspond with population C, whereas 15%, 8%, and 2% correspond with populations B, A, and D, respectively.

Temporal Provenance Trends

Detrital zircon ages record up-section trends that coincide with temporal variations in stratigraphic architectural elements and petrologic data (Fig. 14). In general, temporal trends reveal that fluvial successions (Heward Creek and Bull Canyon) record an up-section decrease in...
Mogollon Highlands–derived sediment through the John Henry Member, with an increase in sediment derived from the Sevier fold-and-thrust belt and volcanic sources. The quartz-rich, highly amalgamated fluvial deposits of the Calico bed and lower John Henry Member contain a predominance of Mogollon Highlands–derived zircons. This provenance signature is maintained through lower and middle John Henry Member strata, despite a higher proportion of feldspar and unstable lithic grains in the isolated channel deposits. The compositional change in the middle John Henry Member in the southwestern plateau is likely due to an increase in basin accommodation rates and, subsequently, a higher preservation potential for these unstable mineralogies. The highly amalgamated and braided fluvial deposits of the upper John Henry and Drip Tank Members show an increase in zircons derived from the Sevier fold-and-thrust belt. At Bull Canyon, the Drip Tank Member (TS-20) contains 53% of zircons from population C (Fig. 9), whereas population C in the Calico bed near the base of the section (TS-17) is represented by 77% of zircons in the sample.

In tidal- and marine-dominated successions (Kelly Grade, Left Hand Collet, and Buck Hollow), populations A and C show up-section increases, whereas populations B and D decrease in relative abundance. The temporal increase in Mogollon Highlands and magmatic arc detritus is likely due to the increase in fluvial influence at the shoreline as fluvial facies prograded eastward through time.

**Tectonic Controls on Provenance and Stratigraphic Architecture**

The stratigraphic architecture of the Straight Cliffs Formation was heavily influenced by the interactions between the axial and transverse river systems draining the Mogollon Highlands and Sevier fold-and-thrust belt. Stratigraphic architectural trends in Straight Cliffs Formation strata can be tied to variations in basin subsidence rates, sedimentation rates, and eustatic sea level, which in turn influenced basin accommodation rates and the behavior of drainage systems. Generally, the Straight Cliffs Formation can be subdivided into three stratigraphic intervals defined by architectural, compositional, and detrital zircon geochronologic trends. Each interval roughly coincides with the member stratigraphy and corresponds to synchronized trends in the aforementioned variables, which are driven by fluctuations in basin accommodation and sediment supply. These trends are summarized in Figure 15.

Fluvial provenance in the Straight Cliffs Formation was controlled by several factors, but it appears to have been most influenced by the interplay between tectonically driven sediment supply and foreland basin subsidence rates. In the Mogollon Highlands, evidence suggests that periods of tectonic activity in the Maria fold-and-thrust belt (Salem, 2009) broadly coincided with pulses of population C zircons and coarse-grained quartzofeldspathic sediment into the Kaiparowits Basin (Fig. 15, lowermost trend). During late Turonian time, active thrusting in the Maria fold-and-thrust belt (Salem, 2009) and related uplift in the Mogollon Highlands

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**Figure 12.** Detrital zircon ages corresponding to shoreface, tidal, and fluvial facies. Pie charts show relative proportion of ages from each population. Fluvial ages are dominated by grains from population C (63%), with a moderate presence of population B (17%) and A (17%) zircons. Tidal samples show an increase (relative to fluvial samples) in ages from population B (26%), and a decrease in population A (9%). Compared to both fluvial and tidal samples, marine samples record a more significant provenance shift, with population B increasing (40%) and population C decreasing (45%).
Figure 13. Paleogeographic reconstruction of the Cordilleran foreland basin during Santonian time. A large axial fluvial system was fed by transverse drainages emerging from the Sevier fold-and-thrust belt, but the majority of sediment feeding into the axial system was derived from the Mogollon Highlands and the Cordilleran magmatic arc. In the Kaiparowits Basin, backwater effects from the Western Interior Seaway and raised coal mires near the shoreline locally diverted the axial system from its northeast trajectory, ultimately resulting in a series of east-flowing rivers that terminated in lagoonal and estuarine settings. The location of a cross section through the Sevier fold-and-thrust belt and Kaiparowits Basin (Fig. 16) is indicated on the map. Abbreviations: CMA—Cordilleran magmatic arc; KP—Kaiparowits Plateau; MH—Mogollon Highlands; SFTB—Sevier fold-and-thrust belt; WIS—Western Interior Seaway. States: AZ—Arizona, CA—California, NV—Nevada, UT—Utah.

Figure 14. Relative proportions of each detrital zircon age population are plotted for each sample according to location and stratigraphic interval (population D not shown due to relatively low percentages). Fluvial samples are denoted by gray background shading. Samples generally show an up-section increase in population C from the Tibbet Canyon Member (TCM) through the Smoky Hollow Member (SHM) to the Calico bed. At Heward Creek and Bull Canyon, population C decreases through the John Henry Member (JHM) into the Drip Tank Member (DTM). Samples from Kelly Grade, Left Hand Collet, and Buck Hollow show an overall increase in population C through the John Henry Member. In general, populations B and C are inversely proportional to one another, and population A shows a gradual up-section increase. Standard deviations for each population are in Table 4. FTB—fold-and-thrust belt.
exposed Yavapai-Mazatzal source rocks, which were subsequently eroded and transported into the foreland basin (Fig. 16). Estimates for the timing of initial thrusting in the Maria fold-and-thrust belt (Knapp and Heizler, 1990; Barth et al., 2004; Salem, 2009) and Paxton thrust sheet in the Sevier fold-and-thrust belt (DeCelles and Coogan, 2006). Activation of the Maria fold-and-thrust belt coincides with an influx of population C zircons from the Mogollon Highlands (Calico bed). Increased basin subsidence rates during deposition of the lower and middle John Henry Member were likely driven by activation of the Paxton thrust sheet, which increased crustal loading in the proximal foreland basin. The upper John Henry and Drip Tank Members were deposited when the Paxton duplex was activated, which uplifted proximal foreland basin strata and enabled rivers draining the Sevier fold-and-thrust belt to deliver more sediment into the axial fluvial system. Time-scale divisions are from Gradstein et al. (2012).

Figure 15. Comparison of up-section trends in detrital zircon ages, sandstone modal compositions, and basin accommodation rates with potential eustatic and tectonic drivers. Data from fluvial strata (solid lines) and marginal marine strata (dotted lines) are presented. Trends show a weak correlation with eustatic sea-level curves but are more closely linked with activation of the Maria fold-and-thrust belt (Knapp and Heizler, 1990; Barth et al., 2004; Salem, 2009) and Paxton thrust sheet in the Sevier fold-and-thrust belt (DeCelles and Coogan, 2006). Activation of the Maria fold-and-thrust belt coincides with an influx of population C zircons from the Mogollon Highlands (Calico bed). Increased basin subsidence rates during deposition of the lower and middle John Henry Member were likely driven by activation of the Paxton thrust sheet, which increased crustal loading in the proximal foreland basin. The upper John Henry and Drip Tank Members were deposited when the Paxton duplex was activated, which uplifted proximal foreland basin strata and enabled rivers draining the Sevier fold-and-thrust belt to deliver more sediment into the axial fluvial system. Time-scale divisions are from Gradstein et al. (2012).

<table>
<thead>
<tr>
<th>Age</th>
<th>Member</th>
<th>Mogollon-Derived Zircons (% Population C)</th>
<th>Sandstone Modal Composition (% Total Quartz)</th>
<th>Accommodation Relative to Sediment Supply</th>
<th>Eustatic Sea Level</th>
<th>Major Thrusting Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>John Henry</td>
<td>Drip Tank</td>
<td>30%</td>
<td>80%</td>
<td>Low</td>
<td>High</td>
<td>Pavant Thrust</td>
</tr>
<tr>
<td>Coniacian</td>
<td>Smoky Hollow</td>
<td>83.6</td>
<td>100%</td>
<td></td>
<td></td>
<td>Paxton Thrust</td>
</tr>
<tr>
<td>Santonian</td>
<td>Tibbet Canyon</td>
<td>86.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cretaceous</td>
<td></td>
<td>89.8</td>
<td></td>
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</tr>
</tbody>
</table>

In early Campanian time, the Paxton thrust sheet began to deform in duplex style (DeCelles and Coogan, 2006); as a result, the rapid vertical stacking of Mesozoic strata in the Paxton thrust sheet began to uplift the overlying proximal foreland basin strata, thereby increasing transverse sedimentation rates (Fig. 16). The influx of sediment from the Sevier fold-and-thrust belt into the axial fluvial system caused channel systems to become highly amalgamated (upper John Henry Member) and eventually braided (Drip Tank Member, Fig. 15, uppermost trend). By middle Campanian time, fluvial systems draining the Sevier fold-and-thrust belt prograded basinward, displacing the axial system eastward (Lawton et al., 2014).

Although the timing of thrust belt activity and accommodation development appears to coincide, other potential driving factors cannot be disregarded. In general, the up-section trends in stratigraphic architecture show little convincing correlation to known eustatic sea-level changes (Fig. 15), implying eustasy was not a primary control on the evolution of fluvial and marine stratigraphy during this time. However, eustatic excursions at the Turonian-Coniacian boundary (Hardenbol et al., 1998; Miller et al., 2005) may have contributed to the reduction in accommodation space during deposition of the Calico bed and Drip...
Additionally, the effects of climate change on sedimentation rates must also be considered. The increase in sediment input from the Sevier fold-and-thrust belt during the early Campanian might imply warmer, wetter climate conditions. However, several studies indicate the Santonian–Campanian climate in North America gradually cooled through time (Wolfe and Upchurch, 1987; Huber et al., 1995). A cooler climate would generally imply drier conditions through time and lower sedimentation rates in the Campanian, thus favoring tectonics as a primary driving force behind increasing sediment delivery rates. Nonetheless, the influence of microclimates on foreland basin sedimentation may have evolved independently of global climatic trends, warranting further investigation.

CONCLUSIONS

Detrital zircon geochronological data from the Turonian–Campanian Straight Cliffs Formation of southern Utah provide insight into the interactions between axial and transverse drainage systems in the Cordilleran foreland basin. The abundance of Proterozoic zircons (1.25–1.90 Ga, 67% of all fluvial ages), Phanerozoic and Grenville zircons are also present in Straight Cliffs fluvial sandstones (17%) and provide evidence for addi-
tional sediment input from the Sevier fold-and-thrust belt in southwestern Utah. Subordinate Mesozoic zircons (16%) signal a minor influx of sediment from the Cordilleran magmatic arc or reworked volcanic material from Mesozoic sedimentary rocks in the Sevier fold-and-thrust belt and Mogollon Highlands.

Population C zircons (1.25–1.90 Ga) in the Straight Cliffs Formation were predominantly derived from the Mogollon Highlands. The abundance of feldspars in fluvial sandstones (average 18%), angular quartz grains, and prominent 1.4 Ga and 1.7 Ga age peaks are consistent with first-order sediment derivation from Proterozoic igneous bodies in the Mogollon Highlands. Zircons of this age are present in the Sevier fold-and-thrust belt, although strata in the thrust belt typically contain insufficient feldspars and angular grains to have sourced the quartzofeldspathic fluvial sandstones in the Kiparowits Basin. Additionally, units in the Sevier fold-and-thrust belt contain many age peaks that are absent or insignificant in the Straight Cliffs Formation, and they rarely yield exclusively the 1.4 Ga and 1.7 Ga peaks present in Straight Cliffs fluvial strata. The broad range of ages present in the Sevier fold-and-thrust belt is found in marine strata, where longshore currents transported Sevier fold-and-thrust belt detritus southward and introduced population B (265–1250 Ma) and D (1.9–3.0 Ga) zircons into shoreface and tidal environments.

Up-section changes in detrital zircon provenance, stratigraphic architecture, and sandstone composition coincide with periods of tectonic activity in the Mogollon Highlands and the Sevier fold-and-thrust belt. Amalgamated fluvial strata of the upper Smoky Hollow (Calico bed) and lower John Henry Members were deposited during a period of increased tectonic activity in the Maria fold-and-thrust belt of central Arizona (Knapp and Heizler, 1990; Salem, 2009). Resultant shortening in the Mogollon Highlands increased the supply of Proterozoic intrusive igneous material, which was subsequently transported into the foreland basin. Activity in the Maria fold-and-thrust belt declined during early Santonian time (Barth et al., 2004), when the Paxton thrust sheet began to activate in the Sevier fold-and-thrust belt (DeCelles and Coogan, 2006). These factors may account for the increase in foreland basin subsidence and accommodation space observed at this time. During early Campanian time, duplex-style deformation of the Paxton thrust sheet uplifted proximal foreland basin strata and reduced accommodation rates adjacent to the Sevier thrust front (DeCelles and Coogan, 2006). As a result, reverse transverse fans draining the Sevier fold-and-thrust belt were able to pro-grade further into the foreland basin, thereby increasing sediment input from thrust belt strata. These interpretations are consistent with the up-section increase in Phanerozoic and Grenville zircons and well-rounded quartz grains in the upper John Henry and Drip Tank Members.

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REFERENCES CITED


Coleman, D.S., and Glazner, A.F., 1997, The Sierra Crest magmatic event: Rapid formation of juvenile crust during the Late Cretaceous in California. International
.../1365 -3091 .1996 .tb02020 .x.
.../v.1365–3091.1996.0802020.x.
.../v.1365–3091.1996.0802020.x.
.../v.1365–3091.1996.0802020.x.