Sediment provenance and dispersal of Neogene–Quaternary strata of the southeastern San Joaquin Basin and its transition into the southern Sierra Nevada, California

Jason Saleeby1, Zorka Saleeby1, Jason Robbins2, and Jan Gillespie3

1Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA
2Chevron North America Exploration and Production, McKintrick, California 93251, USA
3Department of Geologic Sciences, California State University, Bakersfield, California 93311, USA

ABSTRACT

We have studied detrital-zircon U-Pb age spectra and conglomerate clast populations from Neogene–Quaternary siliciclastic and volcaniclastic strata of the southeastern San Joaquin Basin, as well as a fault-controlled Neogene basin that formed across the southernmost Sierra Nevada; we call this basin the Walker graben. The age spectra of the detrital-zircon populations are compared to a large basement zircon age data set that is organized into populations from Neogene–Quaternary siliciclastic and volcaniclastic strata across the eastern Basin margin from the Cache Peak volcanic center that was nested within the Walker graben. This link was accentuated by the delivery of volcaniclastic materials into the southeastern San Joaquin Basin. In early to middle Miocene time, this linkage was maintained by a major fluvial system that we call the Caliente River, whose lower trunk was structurally controlled by growth faults along the Edison graben, which breached the western wall of the Walker graben. The Caliente River redistributed into the southeastern San Joaquin Basin much of the ~2 km of volcaniclastic and siliciclastic strata that filled the Walker graben. This sediment redistribution was forced by a topographic gradient that developed in response to uplift along the eastern Sierra escarpment system. The Caliente River built a fluvial-deltaic fan system that prograded northward across the lower trunk of the Kern River and thereby deflected the Kern drainage flux of sediment into the Basin edge northward. In mainly late Miocene time, turbidites generated primarily off the Caliente River delta front built the Stevens submarine fan system of the southeastern and central areas of the San Joaquin Basin. In late Quaternary time, 1–1.8 km of Caliente River–built strata were eroded as an epeirogenic uplift that we call the Kern arch emerged along the southeastern Basin margin, in response to underlying mantle lithosphere removal. The sediment that was eroded off the arch was redistributed mainly into the Maricopa and Tulare sub-basins that are located to the southeast and northwest, respectively, of the arch.

INTRODUCTION

The Sierra Nevada and Great Valley of California are structurally coupled and move semi-independently within the San Andreas–Walker Lane dextral transform system as a microplate (Argus and Gordon, 1991; Unruh et al., 2003). Regional relief generation and erosion of the Sierra Nevada are linked to subsidence and sedimentation in the Great Valley by regional west tilt about an axis that runs along the western Sierra Foothills (Fig. 1 inset). Subsurface studies in the southern Great Valley have shown this region to be unique by the hosting of a Neogene deep marine basin named the San Joaquin Basin (Hoets et al., 1954; Bandy and Arnal, 1969; Bartow, 1984; Bartow and McDougall, 1984). This marine basin is unique to the entire Great Valley province with a number of its principal facies boundaries trending obliquely across the southern Great Valley and intersecting the southwestern Sierra Foothills at high angle.

The southern Sierra Nevada is widely recognized for its extensive exposure of Cretaceous batholithic rocks. This region has gained recent attention for its surface expressions of the progressive loss of its underlying mantle lithosphere (Saleeby, 2003; Saleeby et al., 2013a, 2013b), leaving distinct structural, geomorphic, and thermal imprints (Wood and Saleeby, 1998; Saleeby, 2003; Saleeby et al., 2007, 2013a, 2013b; Chapman et al., 2010, 2012). Many of the unique features of the San Joaquin Basin owe their origin to these lithospheric-scale dynamic processes. Cretaceous batholithic rocks extend for a considerable distance westward from the Sierra Foothills as the Great Valley crystalline basement (Saleeby, 2007, 2014), which is particularly well documented for the basement of the San Joaquin Basin (May and Hewitt, 1948). Thus the exhumation history of the southern Sierra Nevada batholith is a critical aspect of San Joaquin Basin geologic history.

Tertiary strata of the southeastern San Joaquin Basin are currently undergoing active erosion between ~35.2°N and ~36°N (Fig. 1), along an active epeirogenic uplift named the Kern arch (Saleeby et al., 2013a, 2013b). These Tertiary strata and their facies equivalents once extended for an unknown distance nonconformably across the current southwestern Sierra basement uplift, as shown by erosional truncation and up-dip projection patterns and the mapping of the partially exhumed basement nonconformity (Fig. 1).
Figure 1. Map of the southern Sierra Nevada–eastern San Joaquin Basin region showing generalized stratigraphic units exposed along Kern arch, regional geomorphic features, major structural blocks, selected members of late Cenozoic southern Sierra Nevada fault system, and the subsurface distribution of Stevens submarine fan system (sources: Fox, 1929; Nugent, 1942; MacPherson, 1978; Davis, 1983; Bartow, 1984; Dibblee and Warne, 1986; Hirn, 1986; Maheo et al., 2009; Saleeby et al., 2009a, 2013a, 2013b; Saleeby and Saleeby, 2013, 2016). Also shown are our detrital-zircon sample sites as sample numbers (Table 2) and sample sites of Lechler and Niemi (2011) abbreviated in yellow as: N—North Fork Kern channel sand; S—South Fork Kern channel sand; L—Tejon Formation; W—Witnet Formation; G (G1 and G2)—Golar Formation 1 and 2; and from Sharman et al. (2013, 2014): S—Uvas member of Tejon Formation; and SE—San Emigdio Formation. Inset map of California shows principal features of Sierra Nevada microplate after Argus and Gordon (1991) and Unruh et al. (2003). Inset map of Kern River oil field shows well core and surface sample locations in more detail. flt.—fault.
The west-tilt axis between Sierra Nevada uplift and erosion and Great Valley subsidence and sedimentation has long been treated as a regional structural-stratigraphic datum for the tectonic and geomorphic development of the region (Huber, 1981; Unruh, 1991). Unlike the axis north of ~37°N, much of the axis south of ~37°N has been affected by late Cenozoic faulting and broad flexure (Le Pourhiet and Saleebey, 2013; Saleebey et al., 2013a, 2013b; Fig. 1 inset map). This further distinguishes the San Joaquin Basin from the rest of the Great Valley to the north.

In this paper, we pursue the complexity of the transition between the southern San Joaquin Basin and the adjacent western Sierra basement uplift by the study of sediment provenance and dispersal patterns of Neogene and Quaternary strata of the southeastern Basin. We employ surface and subsurface structural and stratigraphic mapping, conglomeratic clast analysis, and U-Pb geochronological studies of detrital and erupted zircon from key siliciclastic and volcaniclastic units of Neogene–Quaternary age. Fingerprinting of Sierran basement provenance domains is pursued by a synthesis of regional basement U-Pb zircon geochronological data and the application of these data in the light of basement exhumation and geomorphic relations. We show that specific domains of the Neogene–Quaternary strata of the southeastern Basin can be linked to modern drainage basin patterns by detrital-zircon and conglomerate clast provenances, although the magnitude of sediment input and the mutual interaction of distinct sediment dispersal domains exiting the Sierra Nevada along trunk river channels varied significantly through time. We relate these complexities to a sequence of tectonic forcing mechanisms stemming first from profound tectonic disruption and differential exhumation of the southern Sierra basement in the Late Cretaceous (Saleebey et al., 2007; Chapman et al., 2010, 2012) and a rapidly evolving series of late Cenozoic events entailing the opening of an underlying slab window (Atwater and Stock, 1998), eastern Sierra escarpment formation and derivative regional west tilt of the microplate (Unruh et al., 2003), and then the foundering of the regions underlying mantle lithosphere (Saleebey et al., 2013b). We further show that the southeastern San Joaquin Basin–southern Sierra transition has been uniquely mobile as compared to the western Sierra Nevada–Great Valley transition to the north, and is also a sensitive indicator of tectonic and geodynamic processes that were either restricted to, or more intense than along the southern 100–200 km of the microplate.

## STRUCTURAL FRAMEWORK OF THE SOUTHERN SIERRA NEVADA–SOUTHEASTERN SAN JOAQUIN BASIN TRANSITION

In Figure 1, we show a map of the southern Sierra Nevada and adjacent San Joaquin Basin region denoting a number of late Cenozoic structural and geomorphic features (references in caption). The main features that we will focus on below include the Kern arch, the Tulare and Maricopa sub-basins, the Breckenridge-Greenhorn horst, and the Walker and Edison grabens. The development of these features strongly influenced sediment provenance, dispersal, and deposition of Neogene–Quaternary strata of the southeastern San Joaquin Basin. Structural control on the development of these features was provided by a system of Neogene–Quaternary normal and related high-angle oblique slip faults that we call the southern Sierra Nevada fault system (Mahéo et al., 2009; Saleebey et al., 2009a, 2013a, 2013b; Saleebey and Saleebey, 2016).

We recognize the southeastern margin of the San Joaquin Basin as recently emergent over a broad region. This is clearly marked by significant erosional truncations of SW-dipping Neogene strata that are exposed across the Kern arch (Mahéo et al., 2009; Saleebey et al., 2009a, 2013b). Up-dip stratigraphic projections of the eroded strata are in agreement with subsurface thermochronometric data indicating 1000–1850 m of Quaternary exhumation of Neogene to lower Pleistocene strata off of the arch (Cecil et al., 2014). These same data further indicate that strata of the arch have been exhumed off of the adjacent western Sierra basement where deeply weathered low-relief areas represent the exhumed nonconformity (Mahéo et al., 2009; Cecil et al., 2014). The exhumed Tertiary nonconformity projects farther upslope as a low-relief upland surface that is preserved along major Sierran interfluves (Fig. 1). The low-relief interfluves and adjacent drainage basins have been slowly eroded together through much of Cenozoic time at an average rate of ~0.05 mm/yr (Clark et al., 2005; Mahéo et al., 2009; Sousa et al., 2016). The low-relief surface lies parallel to apatite (U-Th)/He age isochronal surfaces over large expanses of the Sierra Nevada (Clark et al., 2005; Cecil et al., 2006; Mahéo et al., 2009). The coupling of the low-relief surface to apatite isochronal surfaces provides planar structural markers for the approximation of structural relief arising from late Cenozoic vertical components of faulting and tilting related to the southern Sierra Nevada fault system (Mahéo et al., 2009).

Rock and surface uplift of the Kern arch has partitioned the eastern San Joaquin Basin into the Tulare and Maricopa sub-basins (Fig. 1). The broad uplift of the arch continues upslope as a fault-controlled, wedge-shaped basement uplift that we call the Breckenridge-Greenhorn horst (Fig. 1). The exhumed Tertiary nonconformity and adjacent low-relief upland surface across the horst exhibit the same west dip as that of the erosional truncated strata of the Kern arch. The Breckenridge-Greenhorn horst formed by E-down normal faulting along the Breckenridge-Greenhorn–Kern Canyon fault system, and SW-down normal faulting along the West Breckenridge, Kern gorge, and related faults. Principal growth on these and other important normal faults of the region was early to middle, and locally, late Miocene in age (Dibblee and Warne, 1986; Mahéo et al., 2009; Reid, 2009; Blythe and Longinotti, 2013; Chapman et al., 2017; Saleebey and Saleebey, 2016). In late Quaternary time, the horst and arch together rose epeirogenically, forcing the erosion of Tertiary strata down to basement along the western margin of the Breckenridge-Greenhorn horst, diminishing westward from lower Tertiary to lower Pleistocene stratigraphic levels across the Kern arch. Cover strata–basement contacts along the current southern Sierra range front in general consist of NW-striking, SW-down normal faults and NE-striking nonconformity segments along relay ramps in the range-front fault system (Fig. 1).
Research Paper

The southern Sierra Nevada and adjacent area of the Kern arch hosted a series of grabens that served as localized accommodation spaces during the Miocene. These grabens are resolved by structural, stratigraphic, and geomorphic relations and by low-temperature thermochronometry. The graben fills and their bounding structures have been differentially exhumed over the past ~10 m.y. with the regional rise of the southern Sierra Nevada and Kern arch. NE-down normal faults such as the Edison fault zone, in conjunction with the SW-down west Breakenridge, Kern gorge, and related fault sets, form a complex range-front graben system acting along the eastern Kern arch. The southeast segment of the range-front system is called the Edison graben, delineated on Figure 1 by the Edison fault. The Edison graben formed an important Miocene sediment channeling and accommodation space. The eastern end of this graben projects into the transition zone between the E-down Breakenridge fault and the NW-down (Neogene phase) White Wolf fault (Fig. 1). This relationship helped intensify sediment channeling through the Edison graben area (see below).

In early and middle Miocene time, a complex graben that we call the Walker graben formed across southern Sierra basement. Principal bounding structures are the E-down Breakenridge fault, the SW-down Walker Basin fault, the NE-down Bear Mountain fault, and the north-titled footwall block of the SE-down proto–Garlock fault (Fig. 1; Michael, 1960; Dibblee and Louke, 1970; Quinn, 1987; Coles et al., 1997; Mahéo et al., 2009; Saleeby et al., 2009a, 2013b; Blythe and Longinotti, 2013; Chapman et al., 2017; Saleeby and Saleeby, 2016). The Walker graben hosted the ca. 20–15 Ma Cache Peak volcanic center, which consists of silicic ignimbrites, domes and plugs, basaltic flows, and andesitic stratoclines. Volcanic strata of the Cache Peak center are interbedded with and both conformably and unconformably overlain by locally derived siliciclastic strata that accumulated into late Miocene time. This Neogene graben fill is internally faulted, tilted, and partially exhumed off its Sierran basement. The plausible extent of the fill (Fig. 1), beyond its current erosional remnants, is broadly constrained by stratigraphic, geomorphic, and low-temperature thermochronometry (Mahéo et al., 2009; Saleeby and Saleeby, 2016). We show below that Neogene strata of the Walker graben fill were in continuity with strata of the southeastern San Joaquin Basin principally through the area of the transition between the White Wolf and Breakenridge faults (Fig. 1).

Facies relations indicate that the San Joaquin Basin deepened southward during the Neogene across the area of the Kern arch and Maricopa sub-basin (Bandy and Arnal, 1969; Olson, 1988; Saleeby et al., 2013b). Surface and subsurface mapping farther south indicates that Neogene units of the Basin thin southward across the White Wolf fault, where they lie above deeply exhumed Sierran basement of the Tejon embayment, and farther south along the emergent forelimb of the Tehachapi–San Emigdio fold-thrust belt (Davis, 1983; Hirst, 1986, 1988; Goodman and Malin, 1992; Gordon and Gerke, 2009; Chapman and Saleeby, 2012). Subsurface mapping in the Tejon embayment indicates that Miocene normal faults of the southern Sierra system also influenced sedimentation of that region, and mapping along the basement-cover strata contact of the emergent forelimb of the Tehachapi–San Emigdio fold-thrust belt reveals that Miocene normal faults penetrates into the currently emergent basement of the thrust belt.

In summary, a broad spectrum of data indicates that the southeastern San Joaquin Basin and adjacent Sierra Nevada–Tehachapi basin uplifts were cut by a complex and regionally distinct mainly normal fault system in the late Cenozoic and that, particularly in early and middle Miocene time, numerous structures of the system served as growth structures during prolific sedimentation.

### LATE CENOZOIC SEDIMENT PROVENANCE DOMAINS OF THE SOUTHERN SIERRA NEVADA REGION

**Overview**

The southern Sierra Nevada and San Joaquin Basin are well suited for basin provenance and sediment-dispersal studies owing to the existence of a large and aerially extensive database for U-Pb zircon ages of the Sierra Nevada batholith, in conjunction with surface exposures and subsurface core samples for the eastern part of the Basin that can be characterized by their detrital-zircon age spectra. In this section, we characterize distinct basin provenance domains based on U-Pb zircon age patterns (Table 1; Supplemental File 1). With distinct basin age domains defined, our detrital-zircon data can be more readily presented in the context of regional sediment dispersal patterns that link basement provenance domains to depositional domains in the Basin. We also factor in the potential complexities of the relative survivability and dilution of detrital-zircon populations along the length of large Sierran drainage basins, as well as periods of prolonged Tertiary sediment burial in some areas of the currently exposed basement. For Mesozoic time, basement ages are sufficiently abundant and show enough spatial variation that grouping of ages into 10 m.y. bins based on 206Pb/238U ages that are within 10% concordant of 207Pb/235U ages is both warranted and useful for comparison to detrital-zircon age spectra from the Basin samples.

Relative to the southeastern San Joaquin Basin margin, we recognize six distinct Sierran basin provenance domains (Fig. 2), which from north to south are: (1) the Kings, Kaweah, and Tule rivers domain; (2) White River–Poso Creek range-front domain; (3) the Kern River domain; (4) the southernmost Sierra–eastern Tehachapi domain; (5) the western Tehachapi–San Emigdio domain; and (6) the southern Owens and Indian Wells valleys domain (Fig. 2). Domains 1 through 3 may be treated for the most part as simple drainage basins that delivered first-cycle detritus into the San Joaquin Basin during Cenozoic time. Domains 4, 5, and 6 require special treatment, having been extensively covered by Tertiary strata and having undergone significant structural and topographic changes in late Neogene–Quaternary time. We start our analysis with an assessment of the age patterns derived from basement age and map patterns from each domain and then progress to the superposed complexities of Tertiary sediment burial and derivative reworking, late Cenozoic topographic changes, and potential cryptic provenance elements.
data on relative zircon fertility across the Figure 2 age bin units are sparse and may be considered a significant issue for our analysis, considering the transverse gradients in bulk and isotopic compositions that characterize the southern Sierra Nevada batholith (Nadin and Saleeby, 2008). However, batholithic gabbros, diorites, and mafic tonalites along the western Sierra Foothills and Tehachapi Range are shown to be comparably fertile to that of typical Sierran granitoids that constitute the axial to eastern zones of the batholith (Saleeby and Sharp, 1980; Saleeby et al., 1987).

**Southern Sierra Nevada Basement Age Domains**

Regionally mapped and dated plutons, or pluton clusters, of the southern Sierra Nevada batholith are color coded on Figure 2 by 10 m.y. age bins and, for domains 1 through 3, are clipped at bounding drainage divides. Areas of poor age or map control are not color coded and are deleted from our analysis. We also include in Figure 2 the thicker silicic metavolcanic units from metamorphic pendants that have yielded zircons that are dated. These data do little to alter the main age patterns of each domain, but as discussed below, small early Mesozoic peaks in the age spectra are potentially significant. Domain 1 groups the Kings, Kaweah, and Tule drainages because relative to the southeastern San Joaquin Basin, these drainages are considered to have coalesced southward as one major distributary system that debouched southward into the northern Basin margin off the southward-prograding Kings River fan (see Atwater et al., 1986). Domain 4 includes batholithic rocks that lie south of the Garlock fault, proximal to its south-facing scarp, because these rocks constitute part of the upper-plate complex of the southern Sierra detachment system, which was in part derived from, and in part lay above, autochthonous rocks of domain 4 (Wood and Saleeby, 1998; Chapman et al., 2012, 2017). Domain 5 consists of western Tehachapi–San Emigdio ranges rocks north of the San Andreas and westernmost Garlock faults.

On Figure 3, we present basement age spectra plots as histograms for each of the domains shown on Figure 2. This is done for each domain by dividing the area of each age bin by the total area for which age and map data exist (Table 1). Our comparative analysis with detrital-zircon age spectra below leads us to construct additional basement age spectra plots. For the Kern River domain, we break out a South Fork subdomain (Fig. 3F) considering the plausible early Tertiary southerly course for the Kern South Fork that debouched southward into the Walker graben and possibly the southern Indian Wells Valley region (after Kleck, 2010). On Figure 3H, we show a southeastern Sierra regional composite domain that combines data from Figures 3D, 3F, and 3G.

### Table 1. Approximate Areas (km²) of 10-M.Y. Age Bins Between 80 Ma and 280 Ma for Southern Sierra Nevada Batholith Broken into Provenance Domains as Presented in Figure 2 and Summarized in Histograms of Figure 3

<table>
<thead>
<tr>
<th>Ma</th>
<th>Domain 1</th>
<th>Domain 2</th>
<th>Domain 3</th>
<th>Domain 3'</th>
<th>Domain 4</th>
<th>Domain 5</th>
<th>Domain 6</th>
<th>Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>80–90</td>
<td>936</td>
<td>0</td>
<td>1231</td>
<td>484</td>
<td>23</td>
<td>0</td>
<td>733</td>
<td>1240</td>
</tr>
<tr>
<td>90–100</td>
<td>1140</td>
<td>184</td>
<td>1514</td>
<td>801</td>
<td>916</td>
<td>114</td>
<td>316</td>
<td>2033</td>
</tr>
<tr>
<td>100–110</td>
<td>1996</td>
<td>935</td>
<td>734</td>
<td>0</td>
<td>462</td>
<td>350</td>
<td>30</td>
<td>492</td>
</tr>
<tr>
<td>110–120</td>
<td>948</td>
<td>113</td>
<td>5</td>
<td>0</td>
<td>11</td>
<td>257</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>120–130</td>
<td>510</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>130–140</td>
<td>48</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>29</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>140–150</td>
<td>2</td>
<td>0</td>
<td>116</td>
<td>75</td>
<td>4</td>
<td>0</td>
<td>184</td>
<td>263</td>
</tr>
<tr>
<td>150–160</td>
<td>49</td>
<td>0</td>
<td>111</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>126</td>
<td>126</td>
</tr>
<tr>
<td>160–170</td>
<td>71</td>
<td>0</td>
<td>369</td>
<td>176</td>
<td>0</td>
<td>0</td>
<td>1003</td>
<td>1179</td>
</tr>
<tr>
<td>170–180</td>
<td>0</td>
<td>0</td>
<td>83</td>
<td>83</td>
<td>0</td>
<td>0</td>
<td>251</td>
<td>334</td>
</tr>
<tr>
<td>180–190</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>190–200</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200–210</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>210–220</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>220–230</td>
<td>0</td>
<td>0</td>
<td>19</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>230–240</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>240–250</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>37</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>37</td>
</tr>
<tr>
<td>250–260</td>
<td>0</td>
<td>0</td>
<td>37</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>63</td>
<td>63</td>
</tr>
<tr>
<td>260–270</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>270–280</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>5</td>
</tr>
</tbody>
</table>

Total: 5716  1232  4219  1669  1419  763  2727  5815

*Domain 1—Kings, Kaweah, and Tule rivers drainage; Domain 2—White River–Poso Creek range front; Domain 3—Kern River drainage (total); Domain 3’—south Fork Kern River; Domain 4—southernmost Sierra Nevada–eastern Tehachapi Range; Domain 5—western Tehachapi–San Emigdio ranges; Domain 6—southern Owens and Indian Wells valleys; Composite consists of domains 3’, 4, and 6.*
Figure 2. Map of southern Sierra Nevada batholith U-Pb zircon age domains grouped into 10 m.y. age bins based on age data integrated with regional map relationships. Also shown are major drainage divides, which delineate sediment provenance domains as discussed in text. Sources for map construction are in Supplemental Item 1 (see footnote 1).
Figure 3 shows clear distinctions between each plot based primarily on the relative abundances of Early versus Late Cretaceous peaks and the occurrence and intensity of Jurassic and (mainly Early) Triassic (Late Permian) peaks.

Survivability and/or dilution of detrital-zircon populations along large Sierran drainage basins are shown to be a factor for data from the Kern River and Tule Rivers (Fig. 4). This figure shows the Kern drainage basement age spectrum in comparison to modern channel sands for the medial reaches of the North and South Kern forks (Lechler and Niemi, 2011), as well as our detrital-zircon age spectrum from a terrace sand along the lower Kern trunk (sample 1, Table 2, Supplemental File 2). Figure 4A shows that the detrital-zircon signature of 80–90 Ma batholithic rocks that are abundantly exposed in the upper reaches of both Kern Forks is diluted by the signature of 90–100 Ma zircon signature of 80–90 Ma batholithic rocks that are abundantly exposed in exposures (Fig. 2). This figure also shows that Jurassic and Triassic peaks from widespread yet restricted areas of the Kern drainage (Fig. 2) are for the most part lost in lower trunk sands at the resolving power of ~100 detrital grain age data (1 sigma errors). Analyses performed at the Arizona LaserChron Center, University of Arizona, Tucson. Please visit http://dx.doi.org/10.1130/GES01359.2 or the full-text article on www.gsapubs.org to view Supplemental File 2.
analyses per sample. Figure 4B shows that the medial South Fork channel sand in general retains the principal Cretaceous spectrum of the South Fork basement exposures, while the subsidiary Jurassic and Triassic peaks of the basement are greatly amplified. The medial North Fork channel sand data show a similar relative amplification for the earlier Mesozoic peaks, although a factor of 3–4 less as compared to the medial South Fork sand. The Jurassic and Triassic peaks for the medial North and South Fork channel sands are interpreted to be only partially derived from the upper reaches of these drainages (Fig. 2). Both of these channel sand sample locations are adjacent to metamorphic pendants that contain Jurassic siliciclastic units that are enriched in early Mesozoic detrital zircon (Saleeby and Busby, 1993; J. Saleeby and A.D. Chapman, personal commun., 2012). Proximally derived detrital zircon from these virtual point sources very likely enriched early Mesozoic zircon species relative to the principal Cretaceous peaks in these sands. Dilution of North and South Fork detrital-zircon signatures relative to the lower trunk signature is also probably accentuated by sediment damming along the late Cenozoic scarp of the Kern Canyon fault system that crosses the North and South Fork confluence into the lower Kern trunk channel (Amos et al., 2010; Nadin and Saleeby, 2010; Fig. 1). This scarp currently places western footwall basement under incision and eastern hanging wall under sedimentation, thus driving the alluviation of Isabella basin. Inasmuch as the Kern Canyon system experienced similar normal displacement episodes reaching back into Miocene time (Mahéo et al., 2009; Saleeby et al., 2009a; Saleeby and Saleeby, 2016), such sediment damming is considered a potentially recurring transient in the overall sediment flux through the lower Kern trunk. In sections that follow, we pursue additional complexities in the fractionation of detrital-zircon age spectral elements by geomorphic processes.

**Cryptic Components of Basement Provenance Domains**

Widespread burial of the southern Sierra Nevada batholith by Tertiary strata is a significant factor in our analysis. These strata were derived from basement domains that extended beyond the depositional limits currently mapped for these strata, and such strata are more tractable than most basement exposures and thus liable for reworking into the San Joaquin Basin during superposed late Cenozoic uplift. Furthermore, poorly constrained, yet potentially widespread burial of deeply exhumed southern Sierra basement by higher-level
batholithic detachment sheets that were transported along low-angle normal faults during the Late Cretaceous from areas as far north as ~35.7°N presents another potential cryptic sediment provenance component. The upper-crustal detachment sheets are pervasively brecciated and retrograded in many localities to clay grade and thus also highly tractable and liable for erosion. The current distribution of such detachment sheets (Fig. 2) probably only accounts for a small proportion of their original distribution (Wood and Saleeby, 1998; Chapman et al., 2012, 2017), and thus some non-trivial component of the region's Cenozoic sediment load was likely derived from such materials. Below, we pursue the potential impact of these cryptic sediment sources on southern Sierra region provenance patterns for Neogene–Quaternary time.

**Lower Paleogene Overlap Strata and Basement Detachment Sheets**

The southernmost Sierra Nevada batholith, including the area of the Tehachapi–San Emigdio ranges, underwent subsidence to marine conditions at the end of Cretaceous time as a result of regional extension (Wood and Saleeby, 1998; Chapman et al., 2012, 2017). As a result, lower Paleogene coarse, mainly marine siliciclastic units of the Uvas (lower member Tejon Formation), Witnet and Golar formations (Nilsen et al., 1973; Cox, 1987) were deposited across deeply exhumed basement as well as tectonic veneers of upper-crustal detachment sheets of the Tehachapi–San Emigdio ranges, southeasternmost Sierra and El Paso Mountains region (Wood and Saleeby, 1998; Chapman and Saleeby, 2012; Chapman et al., 2012, 2016). Figure 5 shows detrital-zircon age-probability distribution plots for two Uvas samples (sample 2, Fig. 1 and Table 2, and sample “S” from Sharman et al., 2013) and for the Tejon (“L”), Witnet (“W”), and Golar (“G1” and “G2”) formations from Lechler and Niemi (2011). These plots are shown in comparison to the basement provenance age spectra of Figures 3E and 3H. We first note that the Cretaceous peaks of the Uvas and Tejon are Early Cretaceous dominant, whereas the Witnet and Golar are Late Cretaceous dominant. This reflects the east-west age gradient in high-volume batholithic rocks (Fig. 2) and the local proximity of the siliciclastic units to the respective batholithic age zones.

The relative intensities of the principal age peaks for the lower Paleogene overlap strata (Fig. 5) are poor matches to the age spectra of the autochthonous basement. As such, the Cenozoic overlap strata are likely to have contributed only a minor component of the southern Sierra provenance, as indicated by the low contributions of these units to the age spectra of the autochthonous basement (Fig. 2, Table 2). However, the presence of Paleogene overlap strata in the southern Sierra region suggests that these units may have played a more significant role in the sedimentary budget of the region.

### Table 2. Location Data and Sample Information for U-Pb Zircon Samples

<table>
<thead>
<tr>
<th>Sample number and sample(s)</th>
<th>Latitude (“N”)</th>
<th>Longitude (“W”)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lower Kern trunk terrace sand</td>
<td>35.49350</td>
<td>118.69808</td>
</tr>
<tr>
<td>2. Uvis member sandstone, Tejon Formation</td>
<td>34.89603</td>
<td>119.10041</td>
</tr>
<tr>
<td>3. Cache Peak ash-flow tuff (basal Kinnick Formation)</td>
<td>35.18637</td>
<td>118.34263</td>
</tr>
<tr>
<td>4. Ash-flow tuff (Kinnick Formation outlier)</td>
<td>35.17139</td>
<td>118.47639</td>
</tr>
<tr>
<td>5. Walker Formation fluvial reworked tuff</td>
<td>35.33849</td>
<td>118.71859</td>
</tr>
<tr>
<td>6. Basal Walker Formation outlier, air-fall tuff</td>
<td>35.37001</td>
<td>118.67561</td>
</tr>
<tr>
<td>7. Lower Walker Formation fluvial reworked tuff</td>
<td>35.41344</td>
<td>118.75229</td>
</tr>
<tr>
<td>8. Olcese Formation, marine reworked tuff</td>
<td>35.51287</td>
<td>118.90165</td>
</tr>
<tr>
<td>9. Caliente River channel wall sand</td>
<td>35.33834</td>
<td>118.71879</td>
</tr>
<tr>
<td>10. Kern River Formation conglomerate</td>
<td>35.44274</td>
<td>118.91480</td>
</tr>
<tr>
<td>11. Oil well KER0009TO, Kern River Formation</td>
<td>35.44457</td>
<td>118.98703</td>
</tr>
<tr>
<td>12. Kern River Formation deltaic sandstone</td>
<td>35.42649</td>
<td>118.93643</td>
</tr>
<tr>
<td>13. Upper Bena Formation fluvial sandstone</td>
<td>35.39588</td>
<td>118.78157</td>
</tr>
<tr>
<td>14. Chanac Formation fluvial sandstone</td>
<td>35.41444</td>
<td>118.83795</td>
</tr>
<tr>
<td>15. Oil well 33_14TO, Kern River and Chanac formations</td>
<td>35.44969</td>
<td>118.96746</td>
</tr>
<tr>
<td>16. Lower Bena Formation shallow marine sandstone</td>
<td>35.36415</td>
<td>118.76300</td>
</tr>
<tr>
<td>17. Kern River Formation northern facies sandstone</td>
<td>35.53076</td>
<td>118.95386</td>
</tr>
<tr>
<td>18. Kern River Formation northern facies sandstone</td>
<td>35.57330</td>
<td>118.95885</td>
</tr>
<tr>
<td>19. Kern River Formation northern facies sandstone</td>
<td>35.60378</td>
<td>118.95088</td>
</tr>
<tr>
<td>20. Water well, Etchegoin Formation sandstone</td>
<td>35.81082</td>
<td>118.98829</td>
</tr>
<tr>
<td>21. Oil well ROD0116, Kern River Formation</td>
<td>35.41586</td>
<td>118.96362</td>
</tr>
<tr>
<td>22. Oil well TEJ0002TO, Kern River Formation</td>
<td>35.45503</td>
<td>119.01285</td>
</tr>
<tr>
<td>23. Oil well 19_0012TO, Kern River Formation</td>
<td>35.48312</td>
<td>119.00428</td>
</tr>
<tr>
<td>24. Oil well Houchin #1, Stevens Sandstone</td>
<td>35.20765</td>
<td>118.84326</td>
</tr>
<tr>
<td>25. Oil well K&amp;M #27-5, Stevens Sandstone</td>
<td>35.25551</td>
<td>118.89290</td>
</tr>
<tr>
<td>26. Oil well Fee #2, Stevens Sandstone</td>
<td>35.39449</td>
<td>119.05038</td>
</tr>
<tr>
<td>27. Oil well Friant Prospect #21-36, Stevens Sandstone</td>
<td>35.45563</td>
<td>119.13371</td>
</tr>
</tbody>
</table>
thonous rocks from the underlying basement domains. The Uvas samples from domain 5 show inordinately strong Jurassic peaks as compared to those of domain 5. We interpret this as a virtual point-source enrichment of Jurassic zircon derived from the western San Emigdio mafic complex (Fig. 2), which lies nonconformably beneath the Uvas. The lower levels of the Uvas also include submarine landslide deposits that contain clasts and blocks derived from the mafic complex (Chapman et al., 2012, Fig. 4). This is consistent with the enrichment of Jurassic detrital zircon in the Uvas. The western San Emigdio mafic complex is an upper-crustal detachment sheet that is interpreted to have been derived from the southern end of the western Sierra Foothills belt in the region currently occupied by the eastern reaches of the Maricopa sub-basin (Saleeby et al., 2009b; Chapman et al., 2012). The lateral extent of this allochthonous sheet above the domain 5 autochthon during early Paleogene time is poorly constrained. The Uvas basal nonconformity
overlaps both this upper-crustal detachment sheet as well as deep crustal-lower-plate batholithic rocks of the principal San Emigdio basement complex (Chapman and Saleeby, 2012), furtherposing the possibility of an expansive ephemeral Jurassic provenance terrane in the area, which has been largely lost to Cenozoic erosion. The Permo-Triassic peaks in sample S from the Uvas (Fig. 5A) do not have an exposed proximal source. Zircon-bearing rocks of this age are absent along the western reaches of the Sierra Nevada batholith (Fig. 2) but are present in the southeastern provenance domains (3′ and 6). The Pastoria detachment sheet also lies tectonically on the principal basement complex (Fig. 2) and is hypothesized to have originated above the deeply exhumed batholithic autochthon of the southeastern Sierra Nevada (Chapman et al., 2012). Batholithic rocks of 90–100 Ma age are widespread subsequently lost to erosion. The Uvas sample with the Permo-Triassic peaks in the region as part of the Pastoria sheet and that such fragments have been deeply exhumed batholithic autochthon of the southeastern Sierra Nevada (Chapman et al., 2012). Batholithic rocks of 90–100 Ma age are widespread in the Pastoria sheet, as they are in the southeastern batholithic autochthon (Fig. 2). The most plausible explanation for the Permo-Triassic peaks in the Uvas is that such zircon-bearing pluton fragments were transported into this region as part of the Pastoria sheet and that such fragments have been subsequently lost to erosion. The Uvas sample with the Permo-Triassic peaks is also enriched in 90–100 Ma zircon, relative to both the other Uvas sample and the overlying Tejon sample (sample L), further suggesting a Pastoria sheet detrital component.

The Witnet and Golar samples are compared to the southeastern Sierra regional provenance domain in Figure 5B, in recognition of the southerly paleo-topographic gradient of the southern Sierra Nevada (Saleeby et al., 2013b), the likelihood of a latest Cretaceous structurally controlled topographic lineament having developed along the trace of southern Owens and Indian Wells Valleys (Bartley et al., 2007), and based on the hypothesis of southerly flowing river drainages having fed the Golar-Witnet basin (Kleck, 2010; Lechler and Niemi, 2011). The intensities of the principal age peaks for these samples are divergent from one another and from those of the adjacent basement. Cretaceous, Jurassic, and Triassic batholithic rocks are irregularly distributed across the southeastern Sierra regional provenance domain, both in the autochthon and in detachment sheets (Fig. 2). Taking into account the likelihood of erosional loss of substantial areas of the detachment sheet complex, both during deposition of the lower Paleogene overlap strata and during extensive pre-Neogene erosion of these strata, virtual point sources for Jurassic and Triassic zircon, dispersed amongst the more extensive Cretaceous sources, are likely to have been rendered largely cryptic and recorded primarily as the divergent zircon age spectra of the Witnet and Golar samples.

Exposures of the lower Paleogene overlap strata are quite limited and dispersed along the southermost Sierra region (Fig. 1). These strata were extensively eroded in late Eocene to Oligocene time prior to localized sedimentary overlap in the Neogene. Such erosion cut into batholithic basement as well and undoubtedly contributed to the progressive loss of upper-level basement detachment sheets that were dispersed across the region (Chapman et al., 2017). In this regard, the lower Paleogene overlap strata constitute an important proxy for basement detrital-zircon provenance components lost to early Tertiary erosion.

**Neogene Overlap Basins**

Between late Eocene and Oligocene time, substantial areas of the lower Paleogene overlap strata of the southernmost Sierra and Tehachapi ranges region were erosionally stripped, thereby re-exposing basement (Michael, 1960; Dibblee and Louke, 1970; Nilsen et al., 1973; Reid and Cox, 1989; Mahéo et al., 2009; Saleeby et al., 2013b). Subsequently, in the early Miocene, the normal-fault–controlled Walker graben formed an important accommodation space within southern Sierra basement (Mahéo et al., 2009; Blythe and Longinotti, 2013; Saleeby et al., 2013b; Chapman et al., 2017; Saleeby and Saleeby, 2016). Similar age normal faulting spread across the southeastern San Joaquin Basin, extending southward across the area of the western Tehachapi–San Emigdio ranges and Tejon embayment (Nilsen et al., 1973; Hirst, 1986, 1988; Davis and Lagoie, 1988; Goodman and Malin, 1992; Reid, 2009; Chapman and Saleeby, 2012). We focus here on the Walker graben, which had an important influence on southeastern San Joaquin Basin stratigraphy and paleogeography.

The Walker graben accommodated the deposition of up to ~2 km of the middle and lower Miocene Kinnick and Bopesta formations (Michael, 1960; Dibblee and Louke, 1970; Quinn, 1987), which hosted the ca. 20–15 Ma Cache Peak volcanic center (Michael, 1960; Coles et al., 1997; Saleeby and Saleeby, 2013, 2016). Our preliminary sediment provenance and dispersal studies of the southeastern San Joaquin Basin suggested a direct stratigraphic linkage between Miocene strata of the Walker graben and the southeastern San Joaquin Basin (Saleeby et al., 2013a; Saleeby and Saleeby, 2013, 2016). Most telling is the widespread occurrence of boulders, cobbles, and pebbles of distinct andesitic and dacitic volcanic rocks of the Cache Peak center within upper Neogene–lower Pleistocene mainly fluvial strata of the southeastern Basin margin, as first recognized by Bent (1985). Compounded on this is the presence of: (1) clasts containing distinct plant remnants that occur in Kinnick lacustrine sequences; and (2) clasts of leucogranite and granodiorite that occur as voluminous internal composite dike swarms within large southeastern Sierra batholithic plutons, both in situ and in detachment sheets (Saleeby et al., 1987, 2008; Ross, 1989; Wood and Saleeby, 1998; Chapman et al., 2012, 2017). Figure 6A is a field photograph from the sample 10 “Kern River Formation” conglomerate bed, with a clast population that is representative of populations dispersed throughout the Kern River, Chanac, and Bena formations (Fig. 7 stratigraphic column). The clast association of Neogene volcanics, plant fossils, and leucogranites and granodiorites is unique to the southeastern Sierra region, as compared to all other areas of the southern Sierra Nevada. Below, we refer to this distinctive clast association as “Caliente River type." Recognition of this clast association stimulated further investigation into provenance relations by detrital-zircon U-Pb studies and the additional application of these techniques to pyroclastic deposits that extend from the Walker graben into the southeastern San Joaquin Basin.

Silicic ignimbrite beds derived from the Cache Peak volcanic center occur within the alluvial and lacustrine strata of the Kinnick and Bopesta formations (Michael, 1960; Dibblee and Louke, 1970; Saleeby and Saleeby, 2013; Chapman et al., 2017). The intensities of the principal age peaks for these samples are divergent from one another and from those of the adjacent basement. Cretaceous, Jurassic, and Triassic batholithic rocks are irregularly distributed across the southeastern Sierra regional provenance domain, both in the autochthon and in detachment sheets (Fig. 2). Taking into account the likelihood of erosional loss of substantial areas of the detachment sheet complex, both during deposition of the lower Paleogene overlap strata and during extensive pre-Neogene erosion of these strata, virtual point sources for Jurassic and Triassic zircon, dispersed amongst the more extensive Cretaceous sources, are likely to have been rendered largely cryptic and recorded primarily as the divergent zircon age spectra of the Witnet and Golar samples.

Exposures of the lower Paleogene overlap strata are quite limited and dispersed along the southermost Sierra region (Fig. 1). These strata were extensively eroded in late Eocene to Oligocene time prior to localized sedimentary overlap in the Neogene. Such erosion cut into batholithic basement as well and undoubtedly contributed to the progressive loss of upper-level basement detachment sheets that were dispersed across the region (Chapman et al., 2017). In this regard, the lower Paleogene overlap strata constitute an important proxy for basement detrital-zircon provenance components lost to early Tertiary erosion.
et al., 2017). Initial topography that was at least locally controlled by synsedimentary faulting appears to have strongly influenced deposition and preservation of the more proximal ignimbrites, but more distal deposits preserved as lacustrine water-laid deposits exposed along the westernmost outlier of Kinnick exposures indicate dozens of distinct explosive events (Dibblee and Louke, 1970; Chapman et al., 2017). More distal equivalents of the Kinnick ignimbrites occur in strata of the southeastern San Joaquin Basin as air-fall, water-laid and fluvial reworked tuffs. U-Pb age data on zircon microphenocrysts from the Kinnick ignimbrites and derivative felsic tuffs of the Basin (Fig. 1) indicate numerous explosive eruptions between 19.5 and 17.5 Ma (Saleeby and Saleeby, 2013, and data presented below).

Figure 8 shows U-Pb zircon age-probability distribution plots for ash-flow tuffs proximal to the Cache Peak center and from the westernmost Kinnick exposure and for four tuff layers that lie in lower Miocene strata of the southeastern San Joaquin Basin. Sample 3 is from the thickest recognized Kinnick ash-flow tuff taken proximal to the Cache Peak center. In addition to its microphenocrystic zircon, it entrained zircon grains with ages that are typical of the underlying basement of domain 4 (Figs. 3D and 8). These data show that entrainment of basement zircon occurred at the eruption site. All other tuff samples include similar Late Cretaceous exotic zircon with various admixtures of older Mesozoic grains with ages that match peaks from the southeastern Sierra regional provenance domain (Fig. 3H). The Tehachapi Creek sample (sample 4, Fig. 8) is from one of a series of ash-flow tuffs that lie below (lacustrine) water-laid tuffs of the westernmost Kinnick outlier (Fig. 1). Its overall age spectrum is similar to that of sample 3 but with its microphenocryst age ~0.6 m.y. older than sample 3. Accessibility restrictions in the areas of samples 3 and 4 allowed the sampling of only the medial stratigraphic levels of both ignimbrite sequences. The ca. 17.7 and 18.3 Ma ages on these samples (Fig. 8) lie in the medial range of the 16–20 Ma age bounds placed on the Cache Peak center by magnetostratigraphy (Coles et al., 1997).

Three silicic tuff beds were sampled from the lower Miocene Walker Formation along the southeastern margin of the Kern arch (samples 5 through 7, Fig. 1). Sample 5 is from one of several fluvial reworked ash beds from Walker Basin Creek (Fig. 6B). The bed sampled was the thickest observed and had the lowest content of exotic clasts observed. It yields a zircon microphenocryst age that is within error and carries similar exotic age peaks as the sample 3 ash-flow tuff (Fig. 8). This poses the possibility that the sample 5 tuff bed is the direct distal equivalent of the sample 3 ash flow. Sample 6 is a fine ash bed sitting directly on Sierran basement at the base of an erosional outlier of the Walker Formation. Sample 7 is a discontinuous tuff layer near the base of the Walker Formation, adjacent to where it interfingers with the lower part of the shallow-marine Olcese Formation (Bartow, 1984). Samples 6 and 7 yield the same zircon microphenocryst ages within error (ca. 19.65 Ma) and share similar exotic peaks (Fig. 8). This, in conjunction with stratigraphic position, suggests that they record the same eruptive event. This event may also be expressed by one of two fluvial reworked tuffs that lie in fluvial Walker strata stratigraphically below the sample 5 tuff bed. Continuing northwestward to the Poso Creek area (Fig. 1), sample 8 is from a shallow-marine reworked tuff bed lying within the lower Olcese Formation. It yields a ca. 19.5 Ma zircon microphenocryst age that is within error of the basal Walker tuff bed ages (samples 6 and 7, Fig. 8). The zircon yield of sample 8 is the lowest of the group of tuffs studied, and its Cretaceous exotic age peak is the largest amongst the group. We interpret this to be a result of its more distal position from the Cache Peak center, relative to the other samples, and to its reworking under shallow-marine conditions.

The lower Miocene tuff horizons provide important time-stratigraphic constraints for the southeastern San Joaquin Basin, as well as additional information on detrital components contributed to the Basin from the Walker graben. The microphenocryst ages that we report span 17.4–20 Ma, including errors (Fig. 8). We show below that detrital zircon within Neogene–Pleistocene strata of the southeastern San Joaquin Basin that were most plausibly derived from the Cache Peak volcanic center range down to ca. 15 Ma. We thus interpret the eruptive history of the Cache Peak center to have spanned ca. 20 Ma to ca. 15 Ma.
Figure 7 (on this and following page). Stratigraphic cross sections that show generalized stratigraphic relations of the Kern arch area as well as positions for a key subset of our U-Pb zircon samples. Note that widespread faults are omitted and are primary control on unit thickness variations. Generalized geologic map and stratigraphic column for Kern arch area shown below section AA’. Dated volcanic horizon sources are shown for our data (sample numbers) and for A (U-Pb zircon), and B (plagioclase Ar/Ar) from Saleeby and Saleeby (2015, personal observation), and for C (plagioclase Ar/Ar) from Baron et al. (2007). Sources for sections and map: Addicott (1956, 1965, 1970); Klausing and Lohman (1964); Dibblee et al. (1965); Richardson (1966); Lofgren and Klausing (1969); Bandy and Arnal (1969); San Joaquin Nuclear Project (1975); MacPherson (1978); Bartow (1984, 1991); Bartow and McDougall (1984); Department of Conservation’s Division of Oil, Gas, and Geothermal Resources (1984); Dibblee and Warne (1986); Olson et al. (1986); Olson (1988, 1990); Miller et al. (1998); Scheirer and Magoon (2007); Mahéo et al. (2009); Saleeby et al. (2013b); and Robbins (2014). MSL—mean sea level.
Figure 7 (continued).
Stratigraphic Framework and Sampling Strategy

In Figure 7, we present diagrammatic stratigraphic cross sections for three traverses across the Kern arch and adjacent areas of the southeastern San Joaquin Basin. Subsurface stratigraphy is based on oil-well logging and discontinuous intervals of coring. Well names are listed for each section. The profound lateral changes in the unit thicknesses in the area of the Edison graben are a result of (mainly early) Neogene growth faulting. The faults are not shown on Figure 7, which focuses on first-order stratigraphic relations. The stratigraphic positions of a subset of our zircon samples are shown diagrammatically as projected relatively short distances onto the respective section traces. Also shown on the sections are the stratigraphic positions and ages of dated volcanic horizons, as well as positions of paleontological age control.

The stratigraphy of the Edison graben area is important because it contains distinct boulder beds that signal high-energy delivery of coarse detritus into the southeastern San Joaquin Basin from distinct sources at several time intervals through the Neogene. First is the lower Miocene Bealville Fanglomerate, which reflects rapid structural and topographic relief generation along the west Breckenridge, Breckenridge, and eastern White Wolf faults; next is the middle Miocene shallow-marine lower Bena Formation, for which its lower stratigraphic levels consist of mudflows containing Cache Peak-type boulders (modified after Dibblee and Warne [1986] and Bartow [1984, 1991]; Saleeby and Saleeby [2013]). With small angular discordance above the Bena Formation lies the fluvial Kern River Formation, which contains Cache Peak-type clasts at least in part reworked out of the underlying Bena Formation. With small angular discordance above the Kern River Formation lie Pleistocene fluvial sands, which include the terminal channel walls of the demised lower trunk of what we call the Caliente River (Fig. 1). As discussed below, the structural setting of the Edison graben is critical for sediment dispersal patterns during the middle Miocene through early Pleistocene because it provided a structurally controlled basement channel that linked the Walker graben and the southeastern San Joaquin Basin (Saleeby et al., 2013a, 2013b; Saleeby and Saleeby, 2016).
The Figure 7 sections show that the base of the Walker Formation is time transgressive from early Miocene in the south, progressing to Oligocene and late Eocene northward (after Olson et al., 1986). This is shown by the ages and stratigraphic positions above basement of the samples 5, 7, and 8 tuff beds, and farther north by the positions of 26.9 Ma and 40.1 Ma tuff beds within the lower Walker Formation. This relationship is interpreted as an expression of the late Eocene to Oligocene erosional event that removed most of the Witnet and Tejon formations off of southernmost Sierra and Tehachapi–San Emigdio ranges basin prior to Neogene nonconformable overlap (Michael, 1960; Dibblee and Louke, 1970; Nilsen et al., 1973; Cox, 1982; Reid, 1988; Maheo et al., 2009; Chapman et al., 2017). This relationship leads us to break out the informal “Neo”–Walker Formation for distinct strata sitting nonconformably on Sierran basement south of the lower Kern River gorge. The south end of section AA′ shows a series of northwestern facies changes from mainly fluvial Neo–Walker Formation to shallow-marine Olcese Formation (lower Miocene), and shallow-marine lower Bena Formation to bathyal marine Round Mountain Formation (middle Miocene). Section AA′ also shows an important lithofacies boundary within exposures of the uppermost Miocene to lower Pleistocene “Kern River Formation” (as mapped by Bartow, 1984). We detail this boundary below, and it is also expressed in the subsurface relations shown in sections BB′ and CC′.

A major focus of our study is on the Kern River Formation (Bartow and Pittman, 1983; Baron et al., 2007; Robbins, 2014), which is well exposed over a large sector of the Kern arch and is well studied and cored in oil fields within and adjacent to the arch. Detailed study of the Kern River Formation is warranted because virtually all exposures of strata mapped as Kern River Formation, south of 35.7°N, possess abundant clast populations of the Caliente River type, calling into question the commonly assumed Kern River drainage provenance for the Formation. We studied the type exposures of the lower Kern River Formation that are deeply dissected along the trunk channel of the Kern River and a dense cluster of subsurface samples from the nearby Kern River oil field (Figs. 1 and 7, section BB′). The Kern River oil field samples cover a significant three-dimensional mass of the Kern River Formation. These subsurface samples help clarify two critical spatial problems presented by the Kern River Formation. In the vertical dimension, these samples encompass part of the −1–1.8 km of section eroded off the eastern margin of the Kern arch and which projects stratigraphically above the exposed type lower section (Saleebay et al., 2013a, 2013b; Cecil et al., 2014). The Kern River oil field is also strategically located in the area where mesoscopically observable Caliente River clasts begin to diminish rapidly northward, giving way to coarse detrital components more typical of the lower Kern River drainage and western Sierra range front to the north.

From the dense cluster of what we consider to be “ideal” Kern River Formation samples within and adjacent to the Kern River oil field, we extended our sampling horizontally across the Kern arch, in order to test for provenance distinctions between outcrops and shallow cores and/or cuttings that possess the Caliente River–type clast and those that do not. Finally, we studied individual core samples from each of the four principal lobes of the mainly late Miocene Stevens submarine fan system (MacPherson, 1978; Harrison and Graham, 1999; Hewlett and Jordon 1993; Lamb et al., 2003). Sections BB′ and CC′ (Fig. 7) show that Stevens submarine fan strata are basal equivalents to shallow-marine and fluvial-deltaic strata of the Santa Margarita, Chanac, and Bena formations. Our Stevens submarine fan samples encompass a north-south transect that tests the extent to which the Caliente River system was capable of delivering detritus into the deeper parts of the Basin during the late Miocene.

**Middle Miocene to Pleistocene Provenance Patterns of Kern Arch Sandstone Exposures**

Middle Miocene to lower Pleistocene sand-rich units of the Kern arch that are named the Bena, Chanac, and Kern River Formations are variably sorted, commonly immature plutonoclastic sandstones and sandy conglomerates with roughly subequa quartz, K-feldspar, and plagioclase modes. They typically contain pebbles, cobbles, and locally boulders of the Caliente River–type clast (Fig. 6A). From the area of Poso Creek northward, generally time-equivalent strata change markedly in composition, most notably losing Caliente River–type clasts. Local stratigraphic nomenclature in the Poso Creek area recognizes the Santa Margarita shallow-marine sandstone, age equivalent to upper Bena and Chanac to the south, and the Kern River Formation (Addicott, 1965, 1970; Bartow, 1984; Fig. 7, sections AA′ and BB′). The Santa Margarita Formation of this area lacks the Caliente River–type clast, in contrast to Chanac and upper Bena exposures to the south. Furthermore, strata mapped in this area as Kern River Formation are in stark contrast to Kern River Formation to the south of the Poso Creek area, being characterized in the north by plagioclase-dominant girty green siltstones and fine sandstones. These strata more closely resemble the uppermost Miocene to upper Pliocene Etchegoin Formation and sandy intervals of the upper Pliocene San Joaquin Formation. Our northernmost detrital-zircon sample (20) is from cuttings from a water well and consists of a green gritty siltstone that contains diatoms that resemble those present in the Etchegoin Formation, which may be in situ or possibly re-worked (W.W. Wornack, Micro-Strat, Inc., 2013, written commun.). Well-dated Etchegoin and San Joaquin strata have been cored and studied paleontologically in wells located ~5 km down dip from the sample 20 site (Klausing and Lohman, 1986; Lofgren and Klausing, 1989).

We provisionally correlate green girty siltstone and sandstone that were mapped as Kern River Formation from the Poso Creek area northward on the Kern arch as transitional into shallow-marine to estuary strata of the Etchegoin and San Joaquin formations (samples 17–20, Fig. 7, section AA′). The compositional changes that occur in strata mapped as “Kern River Formation” across the Poso Creek area lead us to define two lithosomes for the “Formation” based on conglomerate clast compositions and detrital-zircon age facies (Fig. 7 stratigraphic column): (1) Caliente River lithosome to the south, characterized by the Cache Peak-type clast a microphenocristic detrital zircon, and by detrital-zircon age spectra dominated by Late Cretaceous ages with
widely dispersed Early Cretaceous and earlier Mesozoic ages; and (2) western range-front lithosome to the north (including lower Kern trunk), which lacks Cache Peak volcanic detritus, and which exhibits detrital-zircon age spectra dominated by Early Cretaceous ages with rare earlier Mesozoic ages.

In Figure 9, we present detrital-zircon U-Pb age-probability distribution plots for middle Miocene to Pleistocene sand-rich strata exposed across the Kern arch, as well as a pertinent subset of samples studied from the Kern River oil field subsurface (Figs. 1 and 7; Table 2). The plots for the Mio-Pliocene samples are arranged from north to south, with a break in the plot at the approximate position of Poso Creek. The samples from Poso Creek northward have mesoscopic features of the western range-front lithosome, while those to the south have features of the Caliente River lithosome. Samples 17–19 have detrital-zircon age spectra dominated by the western range-front signal (domain 2, Fig. 3B). The sample 20 spectrum more closely resembles the Kings, Kaweah, and Tule rivers basement signal (domain 1, Fig. 3A). This comparison is stronger by factoring in the likely downstream dilution of the Late Cretaceous basement zircon, which for domain 1 is derived in total from the headwaters of the Kings drainage (Fig. 2). The small Jurassic peaks of samples 17–19 also have sources in domain 1.

The Caliente River lithosome zircon age facies is clearly expressed in the age-probability distribution plots of samples 12 and 13 from the “type”–Kern River and upper Bena formations (Fig. 9). Defining spectral features include significant Late Cretaceous peaks that dominate over Early Cretaceous peaks, dispersed modest Jurassic peaks, subordinate Early Triassic peaks, and for some samples, small Cache Peak ignimbrite peaks. These defining features are also well expressed in data presented below for a dense cluster of subsurface samples from the Kern River oil field (Fig. 10). For comparison with our outcrop sample data, we show on Figure 9 a subset of the Figure 10 data. The major producing sand packets of this oil field are identified by letters ranging from the uppermost G-sand to lowermost R-sand(s) (after Nicholson, 1980). The type–Kern River Formation exposure (sample 12) is correlative to the subsurface R-sand. On Figure 9, we also present plots for R-sands from well sites 15 and 21, which are the well sites most proximal to the sample 12 outcrop (Fig. 1). We also present a G-sand zircon age-probability plot for the nearby well site 11. Figure 9 shows that all of these subsurface samples are composed of Caliente River lithosome sands.

Modest admixtures of range-front zircon added to the Caliente River detritus is recorded in samples 14 and 16 (Fig. 9). The lower Bena sample (16) is from well-sorted shallow-marine sandstone that clearly has the Caliente River lithosome signature with its Cache Peak ignimbrite peak, but with Jurassic peaks muted, and a broad Cretaceous peak displaced toward Early Cretaceous relative to typical Caliente River lithosome spectral patterns. Cache Peak–type clasts are not present in the sample 16 sequence of sandstone and siltstone-shale but are abundant in mudflows deeper in the lower Bena section. The sample 16 field site is within the Edison graben (Fig. 7 section AA’), which in middle Miocene time was bounded by proximal fault-controlled basement exposures of mainly Early Cretaceous age (Figs. 1 and 2), the interpreted source of the mixed detrital-zircon signal. Sample 14 (Chanac sandstone exposure) has a distinct mid-Cretaceous peak that resembles part of the composite peak of sample 16, and it also has a large Cache Peak ignimbrite peak at ca. 18 Ma. Jurassic peaks are apparently diluted out at the resolving power of ~100 zircon analyses per sample. The intensity of the ca. 18 Ma peak is of interest, in the context of the enrichment of Early Cretaceous over Late Cretaceous detrital zircon. The sample 6 air-fall tuff in the Walker Formation outlier (Fig. 1) lies directly on 100–110 Ma range-front basement. Erosion of such an ash-on-basement sequence from the footwall block(s) of the Kern gorge and/or west Breckenridge fault(s) mixed into subcaliente Caliente River detritus would produce the sample 14 spectrum. In contrast, the 15.7 Chanac core sample exhibits an age spectrum more typical of the Caliente River lithosome but nevertheless somewhat enriched in Early versus Late Cretaceous zircon (Fig. 9). This sample site is ~15 km NNW of the sample 14 Chanac site, which was evidently ample distance for the Caliente detrital flux to dilute locally derived range-front detritus producing the observed age spectrum.

The importance of locally derived range-front zircon added to Caliente River detritus is also expressed in zircon age spectra from the youngest strata studied (Fig. 9). Sample 9 was taken from the wall of the Caliente River terminal channel. This sample has a Caliente River lithosome-like spectrum but with enrichment of Early Cretaceous relative to Late Cretaceous ages. The Early Cretaceous zircon signal is interpreted as a local admixture of western range-front detritus (Figs. 3B and 4A). The walls of the Caliente River terminal channel were deposited during significant uplift and erosion of the Kern arch and the adjacent Breckenridge-Greenhorn horst (Maheio et al., 2009; Cecil et al., 2014). This included erosion of the western range-front area that is primarily Early Cretaceous in age (Fig. 2). Sample 10 is from the sand matrix of a conglomerate lens (Fig. 6A) mapped as part of the “lower Pleistocene” interval of the Kern River Formation (Bartow, 1984). We alternatively interpret this, and other similar surface level clast-rich conglomerate lenses, as Pleistocene erosional lags that were concentrated into low-gradient channels as ~1400 m of Kern River Formation strata were eroded off of the Kern River oil field area during the Pleistocene uplift of the Kern arch (Maheio et al., 2009; Cecil et al., 2014). The footwalls of both the Kern gorge and west Breckenridge faults were undergoing exhumation at this time as well, exposing abundant 100–110 Ma basement (Fig. 2) to be eroded and mixed into Caliente River detritus as it was eroded and locally reworked.

Comparative viewing of the Figure 9 detrital-zircon age spectra, with the basement age distributions of Figures 2 and 3, and the Figure 1 sample locations, indicates that together a northerly derived flux of detritus from the Kings to Tule drainages, and a more locally east-derived range front plus lower Kern trunk sediment flux bounded the southerly derived detrital flux from the Caliente River during the late Neogene. This produced the profound compositional changes observed in the area of Poso Creek. Compounded on this was a secular change in the availability of distinctive range-front, basement-derived detrital zircon adjacent to the area of the southern Kern arch, which we will return to below under “Paleogeography.”
Figure 9. Detrital-zircon U-Pb age-probability distribution plots for middle Miocene to Pleistocene strata from surface exposure and selected core samples of the Kern arch displaying differences between Caliente River and western range-front lithosome zircon age spectra, as well as apparent mixtures. Samples are arranged in general north to south progression downward, with break in plot in area of Poso Creek, south of which Caliente River detrital-zircon facies dominate. Sample locations are shown on Figure 1, location data are given in Table 2, and analytical data are shown in Supplemental Item 2 (see footnote 2).
Figure 10. Detrital-zircon U-Pb age-probability distribution plots for core sample sequences in Kern River and Chanac formations from Kern River oil field core samples. The plots are shown in stratigraphic sequence for each well with the wells arranged spatially from southwest to northeast. Upper-right plot is cumulative probability plot for all core samples shown (except for Chanac sample number 15.7) and samples 11, 12, and 17–19 (Fig. 9), for which respective sample sites are all traditionally mapped as “Kern River Formation” (Dibblee et al., 1965; Bartow, 1984). Sample locations shown on Figure 1, including inset map, location data given in Table 2, and analytical data are shown in Supplemental Item 2 (see footnote 2).
Subsurface Interface between Caliente River and Western Range-Front Lithosomes

The Kern River oil field is an ideal area to pursue the spatial relations between the Caliente River and western range-front lithosomes in the area of the type–Kern River Formation. The oil field spans the area where surface exposures express this transition in mesoscopic detrital components, and there is a wealth of subsurface log and core data and samples available (Robbins, 2014). In Figure 10, we present detrital-zircon age-probability distribution plots for vertical sequences of core samples from four locations in the Kern River oil field. The stratigraphic positions of our samples based on informal sand packet designations (Nicholson, 1980) are shown for each well, and the map distribution of the well sites is shown on the Figure 1 inset map. Distinct silt and silty shale-bounded sand units within the Kern River Formation, as identified by log and core data (Robbins, 2014), were analyzed. Up to ~200 m of Kern River Formation section are encompassed in the sample sequence with well site 15 sampling into the underlying Chanac Formation. Figure 7 section BB’ shows the approximate stratigraphic intervals studied for samples 11 and 15 well sites. In Figure 10, we also compile a detrital-zircon age–cumulative-probability plot for the suite of samples included in the figure, as well as samples 11 and 12 from the Kern River Formation and samples 17–19 from the area north of Poso Creek (Fig. 9). Chanac Formation samples are excluded because the cumulative plot focuses on uppermost Miocene–Pliocene strata that are mapped as Kern River Formation (Dibblee et al., 1965; Bartow, 1984).

Figure 10 shows that the sand units of the Kern River Formation from the Kern River oil field are primarily Caliente River lithosome, as exhibited in the detrital-zircon age spectra of 21 out of the 23 core samples (including well site 11, Fig. 9). In aggregate, the 21 spectra strongly resemble the age spectra from our surface-exposure samples from the type–Kern River and upper Bena formations (samples 12 and 13, Fig. 9). The spectra of the K-sand of well site 15 and the R1-sand of well site 23 display a significant western range-front detrital contribution, as expressed by a shift in its principal batholithic peak to Early Cretaceous dominant. On Figure 10, well sites 22 and 23, and 21 and 15 are arranged in south to north sequence relative to one another, akin to the spatial pattern plot of Figure 9. In parallel to the Figure 9 relationship, the two wells that contain the range-front signal in their K- and R-sands are located to the northeast of the wells that do not (Figs. 1 and 10). We interpret these relationships to indicate that lenses of western range-front (including lower Kern trunk) sands were transported to the southwest and west to be intercalated and partially mixed with more voluminous Caliente River sands that were transported from the southeast into the area of the oil field. The cumulative age-probability plot (Fig. 10) further contrasts the distinct detrital-zircon facies that characterize the distinctive Caliente River versus range-front lithosomes. The interfingering of these lithosomes in the Kern River oil field area is significant because the oil field is located virtually along the modern lower Kern trunk channel, where it is now vigorously eroding through Neogene strata of the Kern arch. We return to the paleogeographic significance of this finding below.

Regional Sediment Provenance Patterns of the Stevens Submarine Fan System

Upper middle (?) to upper Miocene submarine fan strata of the southern San Joaquin Basin are broadly referred to as the Stevens Sandstone (MacPherson, 1978; Webb, 1981; Hewlett and Jordon, 1993; Harrison and Graham, 1999; Lamb et al., 2003). These distinctive strata are restricted to the Basin in the region southwest and south of the Kern arch and are ponded to the south against the White Wolf fault (Fig. 1). In subsurface, the Stevens sandstone is inter-gradational with Santa Margarita Formation, updip to the northeast (Fig. 7, sections BB’ and CC’). MacPherson (1978) has divided the system into four principal lobes with the oldest to the south, termed the Valpredo fan, and decreasing in age progressing northward through the Bena, Fruitville, and Rosedale fans. The Fruitvale and Rosedale fans are relatively well studied due to their prolific hydrocarbon reserves. These two fans occur over considerably shallower depth intervals than the Valpredo and Bena fans, lying above the southwestern basement ramp of the Kern arch and partly affected by anticlinal culmination that borders the southern margin of the arch. In contrast, the Valpredo and Bena fans lie in the Maricopa sub-basin beneath thick Pliocene–Pleistocene sections that have been eroded primarily off of the emergent Kern arch and Tehachapi–San Emigdio fold-thrust belt. Each of these fans has been interpreted to have been fed by submarine canyons (MacPherson, 1978; Webb, 1981) with: (1) the Valpredo fan fed from a canyon cut across the Tejon embayment and draped northward across the White Wolf fault; (2) the Bena fan fed from the Bena channel (Edison graben) issuing from the mouth of what we call the Caliente River but interpreted by these workers as the ancient course of the Kern River; and (3) the Fruitvale and Rosedale fans, hypothetically fed from canyons issuing from the then newly established lower Kern River gorge drainage. Subsequently, Harrison and Graham (1999) have studied in considerable detail the Fruitville and Rosedale fans and have refuted the submarine canyon feeder model for these two fans. They interpret these fans to have issued directly off the front of coalesced river deltas that were built across a narrow faulted shelf. Below, we adopt this model for the Bena fan as well, but we also recognize that a canyon-fed system may be at least in part applicable for the Valpredo fan.

We have studied Stevens Sandstone cores from four well locations that in general correspond to the medial stratigraphic intervals along the eastern margin of each principal lobe (Fig. 1). On Figure 11, we present detrital-zircon age-probability distribution plots for each Stevens sample, and in order to evaluate possible detrital contributions from the south, we show the age-distribution plot for the western Tehachapi–San Emigdio basement domain (Fig. 3E, domain 6). We also show a composite detrital-zircon age-probability distribution plot for all available samples of the lower Paleogene marine overlap strata lying on domain 5 basement. These consist of the two Uvas and the Tejon Formation samples shown in Figure 5A, as well as an additional sample of the Tejon Formation and two samples from the overlying upper middle to upper Eocene San Emigdio Formation (from Sharman et al., 2013, 2014). These units were extensively eroded prior to depositional overlap by Oligocene and
mainly Miocene strata (Nilsen et al., 1973; Chapman and Saleeby, 2012), and thus detritus reworked from these units may have contributed significantly to the Valpredo lobe (MacPherson, 1978; Webb, 1981). In particular, Hirst (1988) maps, in the Tejon embayment subsurface, NW-trending sand tongues within the upper Miocene Monterey Formation that are plausibly interpreted as channel fills lying in NW-trending slope gullies. The age spectrum for basement domain 5 is dominated by Early Cretaceous peaks ranging from 100 to 120 Ma (Fig. 11). The small Upper Jurassic peak (150–160 Ma) represents the western San Emigdio mafic complex basement inlier (Fig. 2) that is nonconformable beneath the Uvas member of the Tejon Formation. As discussed above, detrital zircon derived from the mafic complex was abundantly contributed to the lower Paleogene marine overlap strata (Fig. 5A), as further shown by the composite age-probability distribution plot for these strata on Figure 11.

Samples 24–27 from the Stevens submarine fan system yield similar age-probability distribution plots to each other, at first order, and these resemble spectra of the Caliente River zircon facies (Figs. 9 and 10). Sample 24, from the Valpredo fan, has a modest relative enrichment in 100–120 Ma zircon, as well as Jurassic zircon. We interpret the enrichment of the 100–120 Ma grains as detritus derived from domain 5 basement, and the Jurassic grains as detritus reworked from the lower Paleogene overlap strata (Fig. 11). These detrital contributions were mixed into Caliente River lithosome sands that were shed from the Caliente River delta front into the basin as Stevens fan system turbidites. Comparison of the samples 25–27 age spectra to spectra from most of the Caliente zircon facies samples (Figs. 9 and 10) shows a shift in the principal Cretaceous peak from 80 to 100 Ma age bins to the 100–110 age bin. This is interpreted as a lower Kern River range-front lithosome admixture to the Caliente River lithosome. Except for areas from Poso Creek northward, such lithosome mixing appears to have been more vigorous for pre– and post–Kern River Formation samples (lower Bena and Chanac samples 14 and 16 and upper Pleistocene channel samples 9 and 10). We return to this observation below under “Paleogeography.”

In the discussions that follow, we integrate the provenance relations that we have presented for middle Miocene to Pleistocene sandstones with structural, geomorphic, and low-temperature thermochronometric data in the development of a sediment provenance, dispersal, and related paleogeographic model. We reject the notion of the lower Kern River drainage being the principal conduit for detritus of the Stevens, Santa Margarita, Chanac, Bena, and “Kern River” formation sands. We alternatively bootstrap a number of different data relations into a model whereby the Walker graben fill and progressively exhumed parts of its bounding basement fault blocks supplied most of the detritus for these sands via the structurally controlled course of the middle Miocene to early Pleistocene Caliente River. Of focus are the structural and stratigraphic settings of the Edison graben as well as late Miocene–Pliocene regional tectonic forcing of eastern Sierra Nevada rock and surface uplift, which resulted in the redistribution of most of the Walker graben fill into the southeastern San Joaquin Basin.

# PALEOGEOGRAPHY

## Nomenclature

The detrital-zircon age data along with conglomerate clast assemblages and map relations reveal a problem with the widely accepted stratigraphic nomenclature of the Kern arch (after Bartow and Pittman, 1983; Bartow and McDougall, 1984; Bartow, 1991). This is the assumption that widespread allu-
vial, fluvial, and deltaic strata termed by these workers as “Kern River Formation” were derived from the Kern River drainage through the lower Kern gorge. This is shown to be incorrect by the Caliente River detrital-zircon age facies that greatly dominate our sample suite from the Kern River Formation (Figs. 9 and 10), as well as the presence of the Caliente River-type clast that is either present in our Kern River Formation outcrop samples and/or is widely spread in beds that are in stratigraphic proximity to our sample sites. We assert that the name “Kern River Formation” should be restricted to a descriptive term based on the active incision of the modern Kern River through the type-area of the Formation (sample 12 site and Kern River oil field, Fig. 1 inset) and not as a genetic term denoting the source of the Formation.

Constraints on Sediment Provenance and Dispersal Posed by the Topographic Evolution of the Southern Sierra Nevada

The topographic evolution of the southern Sierra Nevada is directly linked to the flux of sediment into the southeastern San Joaquin Basin through generally west-flowing trunk channels of major Sierran drainage basins (Fig. 2). The origin of the trunk channels is directly related to the long-term landscape evolution of the range. An ongoing debate has persisted over the past century on this subject, polarized by the contrasting views that major trunk canyons owe their first-order morphology to ancient (Late Cretaceous) versus more recent (late Neogene–Quaternary) incision regimes (reviewed in Jones and Saleeby, 2013; Sousa et al., 2016). Recently, more quantitative constraints have been added to this debate by the development and application of cosmogenic surface dating and low-temperature thermochronometry integrated with geomorphic observations (House et al., 1998, 2000; Stock et al., 2004; Clark et al., 2005; Mahéo et al., 2009; Sousa et al., 2013, 2016). These studies are broadly applicable to the San Joaquin to Kern River drainages, although the direct quantitative constraints are greatest for the medial to lower Kings River drainage. Nevertheless, the constraints that do exist for the Kern River drainage can be bootstrapped with regional geomorphic patterns and the Kings River quantitative constraints to offer a plausible history for the incision for the Kern River drainage system.

Focusing on the area of the Kings River canyon that is below the area affected by extensive glaciation, three distinct phases of canyon incision are recognized: Late Cretaceous (500-m scale), middle to late Eocene (1000-m scale), and late Pliocene–Quaternary (~400 m) (House et al., 2001; Stock et al., 2004; Sousa et al., 2016). The Late Cretaceous and Eocene paleotopographic components are broadly incised into the low-relief upland surface shown on Figure 1 (House et al., 1998, 2001; Clark et al., 2005; Mahéo et al., 2009). The Eocene component constitutes the principal trunk channel, which characterizes the medial to lower Kings River drainage. This paleogeomorphic domain extends westward to the edge of the western Sierra Foothills, where its antiquity has been directly determined in the region between the San Joaquin and White River drainages (Fig. 1), retaining up to ~500 m of paleorelief relative to the eastern San Joaquin Basin margin (Saleeby et al., 2013a; Sousa et al., 2013). The late Pliocene–Quaternary component of incision has cut the steep inner canyon slots that are typical of many Sierran river trunks and that is so well developed in Kings Canyon (Stock et al. 2004). Based on geomorphic observations, Figueroa and Knott (2010) interpret the lower Kern River gorge, where incised across the footwall of the Kern gorge fault and a modest distance into the footwall of the west Breckenridge fault (Fig. 1), to be of similar antiquity as the inner canyon slots to the north. We agree with this interpretation and further note that the broader deep canyon form of the lower Kern River as incised across the footwall of the west Breckenridge fault resembles the older Eocene (Late Cretaceous) canyon form. This analysis cannot be extended to areas east of the Kern Canyon fault due to Neogene–Quaternary offsets and areas of sediment ponding related to the southern Sierra fault system (Fig. 1).

The recognition of substantial erosional regimes of Late Cretaceous and Eocene age in major southern Sierra drainage basins in conjunction with late Pliocene–Quaternary rock and surface uplift of the Kern arch and Breckenridge-Greenhorn horst provides a critical geomorphic framework to interpret the relative amplification patterns of Sierran basement provenance domains in the detrital-zircon age spectra of Neogene–Pleistocene strata studied here.

Structural Controls on Sediment Dispersal and Ponding

On Figure 1, we show the principal members of the late Cenozoic southern Sierra Nevada fault system, including members that cut strata of the southeastern San Joaquin Basin. A number of lines of evidence indicate significant activity on the system in early and middle and locally extending into late Miocene time (Nugent, 1942; Dibblee and Warne, 1986; Hirst, 1986, 1988; Goodman and Malin, 1992; Reid, 2009; Blythe and Longinotti, 2013; Saleeby et al., 2013b; Chapman et al., 2017; Saleeby and Saleeby, 2016). In the analysis presented below, we show that this fault system was highly instrumental in controlling sediment dispersal and ponding relationships throughout the southeastern San Joaquin Basin and across much of the southern Sierra Nevada area south of 35.5°N.

Structure sections presented in Michael (1960), Samsel (1960), Quinn (1987), Dibblee and Louke (1970), Mahéo et al. (2009), and Chapman et al. (2017) taken in aggregate show that much of the crystalline basement of the southern Sierra Nevada was covered by Miocene strata that were ponded in the Walker graben. The intra-graben Kinnick and Bopesta formations consisted of ~2 km of Miocene volcanic and siliciclastic strata (Michael, 1960; Dibblee and Louke, 1970; Quinn, 1987; Coles et al., 1997). The occurrence of the Cache Peak ignimbrites of the graben fill in the Tehachapi Creek area outlier (sample 4 site) and the occurrence of vesiculated hypabyssal intrusions and brecciated volcanic neck remnants of the Cache Peak center (Dibblee and Louke, 1970; Quinn, 1987) indicate that the Miocene section extended westward to immediate proximity to the Breckenridge fault. Disturbance patterns of apatite He/(U-Th) ages from
batholithic basement of the Tehachapi Creek area and the hanging wall of the Breckenridge fault further indicate that a similar thickness of sediment overburden as that of the principal Kinnick-Bopesta section extended westward into the area of the Breckenridge fault (Maheo et al., 2009). Structural and topographic relief on the Breckenridge fault diminishes southwestward into its transition zone with the northeast end of the White Wolf fault (Fig. 1). Adjacent to this transition zone, normal displacements along the NW-striking Bear Mountain fault to the southeast and the west Breckenridge-Kern gorge system and Edison fault to the northwest accentuated a transverse structural trough across the White Wolf–Breckenridge system (Fig. 1). The northwest segments of this trough consist of the Edison and range-front graben system.

The role of the Edison graben in controlling Neogene sediment dispersal was recognized by MacPherson (1978), who used the term “Bena channel.” This fault-controlled channel was hypothesized to have been the principal conduit for the delivery of the late Miocene Bena submarine fan deposits (Stevens sandstone) into the area of Maricopa sub-basin. Our field studies have revealed other important dispersal relations. Boulders and cobbles of Cache Peak volcanic rocks occur in mudflow deposits of the lower Bena Formation within the Edison graben (Saleeby and Saleeby, 2015). These deposits demonstrate that by middle Miocene time, there was a high topographic gradient linkage between the Walker graben and the southeastern San Joaquin Basin, via the Edison graben. This is interpreted as the principal path that coarse Cache Peak volcanic debris followed into the southeastern San Joaquin Basin. Lower Bena marine strata of the Edison graben area are in mixed gradation upward, entailing multiple internal erosional surfaces, with the fluvial-deltaic strata of the upper Bena Formation (Fig. 7, sections AA’ and CC’). Lower and upper Bena strata of the Edison graben and adjacent Kern arch area are also in modest angular unconformity beneath the Kern River Formation (Bartow and McDougall, 1984; Dibblee and Warne, 1986). This discontinuity, as well as those within the Bena Formation, represents viable reworking paths for coarse Cache Peak volcanic debris into the fluvial sediment flux of the upper Bena, Chanac, and Kern River formations along the late Miocene and Pliocene course of the Caliente River.

Constraints Posed by Paleocurrent Data

Exposures of the upper Bena, Chanac, and Kern River formations on the Kern arch and the Walker Formation in the Edison graben are well suited for paleocurrent determinations. The Walker, upper Bena, Chanac, and parts of the Kern River formations along the current eastern San Joaquin Basin margin are dominated by coarse fluvial sandstones, whose channel and foreset bedding relations indicate a dominance of northwestward transport (Miller, 1986; Saleeby et al., 2013a). Farther into the Basin, more proximal to the Kern River oil field, the Kern River Formation is deltaic lower in the section, passing upward to braided stream facies higher in the section (Saleeby et al., 2013a; Robbins, 2014). Inward-facing foresets from lateral bar deposits in the type–Kern River deltaic exposures (sample 12 site) are likewise consistent with northwest river delta transport (Saleeby et al., 2013a, Station 2-6). Serial resistivity amplitude maps for the Kern River Formation of the Kern River oil field subsurface (Fig. 12) show a strong NW-trending fabric between sand and silt-shale packets. The scale and intensity of the resistivity fabric are interpreted to have formed primarily in a braided stream environment, controlled by a NW-directed topographic gradient (Gillespie et al., 2014; Robbins, 2014).

The predominance of NW-directed paleocurrent indices for Miocene and Pliocene strata of the southeastern San Joaquin Basin is consistent with the structural channeling of the Caliente River system through the Edison graben and the northwestward progradation of the Caliente River fan system into the southeastern San Joaquin Basin.

Paleogeographic Model and Tectonic Forcing

In Figure 13, we present a generalized paleogeographic model for the southeastern San Joaquin Basin and adjacent southern Sierra Nevada for the time interval of 8–10 Ma (medial late Miocene). This time interval appears pivotal for sediment-dispersal patterns of the Sierra Nevada with widespread erosion forced by the initiation of the eastern Sierra escarpment system and attendant regional W-tilting of the Sierran microplate (Busby and Putirka, 2009; Saleeby et al., 2009a). During this time interval, the Walker graben sedimentary-volcanic fill transitioned from sediment accumulation to extensive erosion. Sediment accumulation and localization of volcanism in the Walker graben were controlled by normal offsets on the southern Sierra fault system that initiated by ca. 20 Ma in response to the underlying opening of the Pacific-Parallon slab window (Atwater and Stock, 1998). By 8–10 Ma, active slab window opening had migrated northward by hundreds of kilometers, thereby ceasing its principal impact on the region, leaving the southern Sierra fault system as mainly benign basement penetrating breaks with up to kilometer-scale structural relief (Saleeby and Saleeby, 2016). As the Walker graben fill was eroded, underlying structural relief on the basement surface emerged as local topographic relief. Initial growth along the eastern Sierra escarpment also forced rapid east-directed sedimentation into the El Paso basin and Indian Wells Valley subsurface (Loomis and Burbank, 1988; Monastero et al., 2002; Fig. 13). This time interval also entailed the transition from the normal displacement phase of the proto–Garlock fault to the inception of the widely recognized left-slip Garlock fault (Monastero et al., 1997; Blythe and Longinotti, 2013).

In Figure 13, we show (in red) select members of the southern Sierra fault system that were active in early, middle, and locally late Miocene time and had a significant influence on the late Miocene and Pliocene paleogeography. We also show (in black) significant faults that initiated in the late Miocene. The model posits that fault-controlled regional west tilt of the Sierran microplate forced the exhumation of the Walker graben fill, resulting in the redistribution of much of its fill into the southeastern San Joaquin Basin. Preexisting basement relief along a number of early to middle Miocene normal faults that in part bounded the Walker graben were instrumental in the sediment redistribution pattern.
Figure 12. Lithologic map showing orientations of sand versus silt-shale packets within four stratigraphic intervals sampled for detrital zircon in three of the core sections studied from the Kern River oil field. Maps differentiate, in two dimensions, high-resistivity sand packets from low-resistivity silt-shale packets as derived from three-dimensional resistivity amplitude mapping based on hundreds of wells within the oil field. Specific depth intervals between ~115 m and ~441 m measured depths are correlated with specific core sample levels in red (after Gillespie et al., 2014; Robbins, 2014). The strong NW-SE-trending fabric is interpreted as primary braid plane channel structure. Note NE-SW orientation of modern Kern River channel in lower right of each frame.
The transition zone between the E-down Breckenridge fault and the NW-down White Wolf fault provided a structurally controlled breach in the west wall of the Walker graben for the main trunk of the Caliente River to exit the graben and distribute its detritus into the Basin via the Edison graben (Figs. 1 and 13). Thickness variations across the Edison graben that are well expressed in lower and middle Miocene strata are also expressed in upper Miocene strata (Fig. 7, sections AA′ and CC′), suggesting that growth along the graben also contributed to northwest-directed river-trunk channeling (Bena channel of MacPherson, 1978). Late Miocene as well as Pliocene growth along significant early to middle Miocene normal faults is widely observed elsewhere along the southeastern Basin margin (Reid, 2009; Saleeby and Saleeby, 2016).

Figure 13 depicts fluvial-deltaic sands of the upper Bena Formation prograding northwestward across the shallow-marine lower Bena Formation within the Edison graben. This is paralleled farther to the northwest by the progradation of the fluvial-deltaic Chanac Formation across middle to upper bathyal Round Mountain Formation (Bandy and Arnal, 1969; Fig. 7, section AA′). Progradation of upper Bena and Chanac intervals of the Caliente River lithosome occurred while there was substantial relief on the west Breckenridge fault. Sierran basement of the emergent footwall of this fault carries the range-front and lower Kern trunk zircon age signal (Fig. 2). It follows that detrital contributions by minor streams issuing off of this scarp into the northwestward-prograding Caliente River lithosome resulted in admixtures of locally derived zircon into the more voluminous Caliente River lithosome, as recorded in samples 14 and 16 (Fig. 9). Note that the Kern gorge fault scarp is depicted as completely, or in large part, buried in the late Miocene, while in Pliocene time, it was completely buried (Mahéo et al., 2009; Cecil et al., 2014; Saleeby and Saleeby, 2015).

The 8–10 Ma time interval also entailed prolific turbidite deposition of the Stevens submarine fan system (Hewlett and Jordon, 1993; Harrison and
Graham, 1999; Lamb et al., 2003), although early fan growth may have initiated in late middle Miocene time (MacPherson, 1978). The transition from the shallow-marine to fluvial-deltaic Bena is likewise broadly constrained in time across the middle to upper Miocene boundary, and it follows that upper Bena (+Chanac) delta growth corresponds to initial Stevens submarine fan growth. Integrating our work with that of MacPherson (1978) and Harrison and Graham (1999), we envisage a voluminous fluvial-deltaic system prograding out into the San Joaquin Basin along, and ultimately burying, the Edison graben, with the issuing of delta-front turbidites first into the Valpredo and Bena fans, and then migrating northward to contribute to the Fruitvale and Rosedale fans. We favor the production of the two northern lobes from the northwestern-opening Caliente River delta front over the hypothesis of having been a pre-existing canyon fed from the northeast (MacPherson, 1978) because of the strength of the Caliente River lithosome detrital-zircon signature in samples 26 and 27 (Fig. 11). The mixed detrital-zircon age signal from the southern (Valpredo) Stevens fan is shown to have developed by Monterey Formation sand tongues and Santa Margarita shallow-marine sand sheets of the Tejon embayment area (Hirst, 1988) cascading across the White Wolf fault and into the Caliente delta front along slope gullies or small canyons. We reject a commonly held view (e.g., MacPherson, 1978) that the transition from the Bena to the Fruitvale and Rosedale fans originated from the lower Kern River gorge capturing the upper Kern drainage. We argue below and elsewhere (Saleeby and Saleeby, 2013, 2016; Saleeby et al., 2013a; Cecil et al., 2014; also Figueroa and Knott, 2010) that the lower Kern River gorge, west of the west Breckenridge fault, was incised entirely in the Pleistocene. As discussed above, the lower Kern drainage between the west Breckenridge and Kern Canyon–Breckenridge faults has a morphology that is more akin to the Late Cretaceous to Eocene paleolandscapes of the southern Sierra Nevada. As such, the Neogene sediment flux through the lower Kern trunk was probably modest as compared to its Quaternary flux.

The modest sediment flux inferred for the restricted lower Kern trunk for Neogene time is consistent with the northward progradation of the Caliente River lithosome out into the San Joaquin Basin across the path of the lower Kern trunk. Not only was the Walker graben fill more easily eroded than coherent Sierran basement of the greater Kern drainage to the north, but also large tracks of the basement adjacent to, and possibly beneath, the graben fill consisted of a veneer of highly shattered and retrograded detachment sheets (Wood and Saleeby, 1998; Chapman et al., 2012, 2017). These highly tractable materials readily supplied abundant detritus into the Caliente drainage system just as the Walker graben fill did. Coherent basin incision of the Kern drainage compounded by local base-level disruptions and sediment ponding intervals driven by normal displacements along the Kern Canyon fault (Saleeby et al., 2009a; Nadin and Saleeby, 2010) resulted in a limited sediment flux along the lower Kern trunk, as compared to the voluminous flux of the Caliente River. Sediment ponding along the Kern Canyon fault resulted in an unknown amount of alluviation in Isabella basin. It is possible that in much of Miocene time a deeply alluviated valley system extended from Isabella basin to the northern margin of the Walker graben, conceivably to be followed by the South Fork of the Kern River (Fig. 13; Kieck, 2010).

The predominance of Caliente River lithosome sands throughout our Kern River Formation sample suite (Figs. 9 and 10) shows that the Walker graben fill and its bounding basement scarps continued to serve as the principal sediment source for the southeastern San Joaquin Basin margin through Pliocene and perhaps early Pleistocene time. In the area of the Kern River oil field (Fig. 1), the northwestward progradational Caliente River fan system is observed to have preceded out from deltaic to braided stream facies over late Miocene into Pliocene time (Fig. 12; Miller, 1986; Saleeby et al., 2013a, Station 2-6; Robbins, 2014). Updip stratigraphic truncations of the Kern River Formation (Fig. 7, sections BB’ and CC’; and structure sections in Mahéo et al., 2009; Saleeby et al., 2009a, 2013b), as well as thermochronometric data (Mahéo et al., 2009; Cecil et al., 2014) indicate that up to 1850 m of Neogene strata were eroded off the eastern margin Kern arch and Kern gorge fault footwall in the late Quaternary. Much of the eroded strata consisted of the Kern River Formation. It follows that the entire Kern gorge fault scarp, as well as much of the west Breckenridge fault scarp, were buried during Kern River Formation deposition. Such burial would conceal range-front lower Kern trunk sediment sources thereby explaining the lack of this proximal provenance signal in most Kern River Formation samples south of the Poso Creek area. Exposure of these scarps prior to Kern River Formation deposition and their re-exposure by exhumation in the late Pleistocene plausibly explains the modest to strong signal from the range-front provenance in underlying Chanac sands, as well as our Pleistocene channel samples (Fig. 9).

Pleistocene time issued in profound changes in the tectonics and sediment dispersal patterns of the southeastern San Joaquin Basin–southern Sierra Nevada transition. Mantle lithosphere delamination, which promoted Sierran microplate breakoff with its attendant regional W-tilt, propagated in late Pliocene–early Pleistocene time diagonally across the San Joaquin Basin–western Sierra transition driving late Quaternary epeirogenic uplift of the Kern arch and adjacent Breckenridge-Greenhorn horst (Saleeby et al., 2013a, 2013b). This drove rapid erosion of up to ~1850 m of lower Pleistocene and Neogene strata off the Kern arch and adjacent western Sierra basement (Mahéo et al., 2009; Cecil et al., 2014; Fig. 7). As the basement was exhumed across the footwall of the Kern gorge fault, the lower Kern trunk channel was superimposed as a steep-walled basement channel with large meanders that resemble the meander pattern that is still expressed downstream where the channel continues eroding through Neogene strata of the arch. The late Quaternary Kern River fan is distributing its sediment load into the axial southern Great Valley (Fig. 1). Sediment eroded off the northern and southern flanks of the arch is redistributed northward into the Tulare sub-basin and southward into the Maricopa sub-basin (Saleeby et al., 2013b, Figs. 5 and 8). Seismic-reflection data presented in Miller (1999) suggest that significant sediment redistribution off the arch and into the Tulare sub-basin initiated between 1 and 2 Ma (middle to late Pleistocene time).
Maximum structural and topographic relief of the Kern arch and adjacent western Sierra produced by Quaternary epeirogenic uplift runs along a NE-SW-trending axis that crosses the Poso Creek area (Fig. 1). We hypothesize that the trunk channel of the now demised Caliente River was progressively deflected southward into its current orientation (Figs. 1 and 2), forced by the related southward tilting of the southern flank of the arch. The demise of this once voluminous fluvial system appears to have resulted from the exhaustion of its principal siliciclastic-volcaniclastic Walker graben fill source. Residual Neogene rocks now remaining in the eroded remnants of the graben consist mainly of highly indurated vent-proximal lava flows, dune, plug, and hypabyssal rocks that once constituted the core of the Cache Peak volcanic center.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

We have presented data on the age distribution of major plutonic units of the southern Sierra Nevada batholith and used these data to define provenance domains and major drainage systems linking the batholith source region to Neogene and Pleistocene plutoniclastic sandstones of the southeastern San Joaquin Basin. We have integrated these findings with distinct petrographic variations of the source region, regional stratigraphy of the southeastern San Joaquin Basin, and regional structural-geomorphic relations as a means of tracing erosional and depositional patterns, and in the recognition of distinct phases of tectonic forcing. We have shown that a structurally complex Miocene age volcanic graben (Walker graben) formed across the southernmost Sierra Nevada and that strata ponded within this graben had direct facies and provenance links to strata of the southeastern San Joaquin Basin. We have also shown that Neogene–Pleistocene strata of the southeastern Basin once extended a non-trivial distance nonconformably across the adjacent western Sierra basement uplift. Much of the strata ponded within the Walker graben were eroded and redistributed into the southeastern San Joaquin Basin along a newly recognized late Miocene–Pliocene fluvial system that we call the Caliente River.

Regardless of our data-intensive presentation, we consider our findings as establishing a new structural and stratigraphic “framework” that Beyond its structural setting of its prolific hydrocarbon reserves. The distribution of basement-zircon age domains and our findings of their distinct signatures in detrital-zircon populations in the strata we have studied establish a framework to study in detail provenance and dispersal patterns along the eastern margin of the Basin. Most notable is the use of additional detrital-zircon geochronological techniques in conjunction with detailed subsurface mapping in order to resolve the interface and mixing facies of voluminous sands transported into the Basin by the Caliente River and less voluminous basement-eroded sands issuing from the Kern River and other major Sierran trunk rivers to the north, as well as detritus derived from the western Tehachapi and San Emigdio ranges. This approach should be applied equally well to fluvial-deltaic strata of the Chacan, Santa Margarita, Bena, and Kern River formations, and submarine fan strata of the Stevens system. We have used the current standard technique of ~100 petrographically selected zircon grains per detrital sample analysis. We emphasize here that minor peaks in the various age spectra that we have presented potentially carry important information. We suspect that the significance of these peaks, and potentially unresolved peaks of interest could be brought into greater focus and utility by recently developed, automated 1000-grain analysis techniques (Gehrels et al., 2012).

ACKNOWLEDGMENTS

Conversations and written communications with L. Knauer, D.D. Miller, and S.A. Reid greatly enriched this research. Technical assistance from A.D. Chapman, K.A. Farley, G.E. Gehrels, and F.J. Scoula is kindly acknowledged. Acquisition of core samples from the California State University, Bakersfield Core Repository, Chevron North American Exploration and Production, and James Baxley was essential for this study. J. Saleebey and Z. Saleebey acknowledge support from the Caltech Tectonics Observatory, and J. Robbins and J. Gillespie acknowledge support from the Department of Physics and Geology, California State University, Bakersfield, and from Chevron North American Exploration and Production. We also acknowledge the use and intellectual support of the University of Arizona LaserChron Center. Critical reviews by Trevor Dumitru and S.A. Graham significantly improved this manuscript.

REFERENCES CITED


