TSR The Sedimentary Record
SEPM | Society for Sedimentary Geology

Identifying elusive piercing points along the North American transform margin using mixture modeling of detrital zircon data from sedimentary units and their crystalline sources

J. Clark Gilbert[1,*], **Zane R. Jobe**[1], **Samuel A. Johnstone**[2] **and Glenn R. Sharman**[3]
[1]Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401 USA
[2]U.S. Geological Survey, Geosciences and Environmental Change Science Center, Denver, CO 80225 USA
[3]Department of Geosciences, University of Arkansas, Fayetteville, AR 72701 USA

ABSTRACT The San Gabriel and Canton faults represent early stages in the development of the San Andreas fault system. However, questions of timing of initiation and magnitude of slip on these structures remain unresolved, with published estimates ranging from 42–75 km and likely starting in the Miocene. This uncertainty in slip history reflects an absence of appropriate piercing points. We attempt to better constrain the slip history on these faults by quantifying the changing proportions of source terranes contributing sediment to the Ventura Basin, California, through the Cenozoic, including refining data for a key piercing point.

Ventura Basin sediments show an increase in detrital zircon U-Pb dates and mineral abundances associated with crystalline sources in the northern San Gabriel Mountains through time, which we interpret to record the basin's northwest translation by dextral strike-slip faulting. In particular, an Oligocene unit mapped as part of the extra-regional Sespe Formation instead has greater affinity to the Vasquez Formation. Specifically, the presence of a unimodal population of ∼1180 Ma zircon, high (57%) plagioclase content, and proximal alluvial fan facies indicate that the basin was adjacent to the San Gabriel anorthosite during deposition of the Vasquez Formation, requiring 35–60 km of slip on the San Gabriel-Canton fault system. Mixture modeling of detrital zircon data supported by automated mineralogy highlights the importance of this piercing point along the San Gabriel-Canton fault system and suggests that fault slip began during the late Oligocene to early Miocene, which is earlier than published models. These two lines of evidence disagree with recent models that estimate >60 km of offset, requiring a reappraisal of the slip history of an early strand of the San Andreas transform zone.

KEYWORDS detrital zircon geochronology, strike-slip tectonics, tectonic reconstruction, tectonostratigraphy

INTRODUCTION AND TECTONIC HISTORY

The San Andreas Fault is currently the primary geologic boundary between the Pacific and North American plates. This plate boundary is the most studied in the world due to its complex change from a convergent to transform margin beginning at ∼28 Ma (Atwater, 1989) and its inherent seismicity and proximity to large population centers. The San Gabriel and Canton faults are older strands of the San Andreas fault system and despite decades of debate, existing reconstructions of slip are still in conflict. The two faults are herein considered the San Gabriel-Canton fault system (SGCF) due to their similar trend and offsetting basement features (Fig. 1).

Along transform margins, piercing points are interpreted where similar basement features or contacts between sedimentary units intersect the fault trace (Crowell, 1962). Piercing points are useful references for structural restorations because many of these points were originally adjacent before later offset by lateral fault movement. However, slip offset and fault timing estimates often have high degrees of uncertainty. This is especially true when using sedimentary rocks because sediment routing is complex and dynamic near transform faults, and the paleogeography was likely different than it is today. Previous studies have utilized detrital zircon geochronology to restore piercing points along the North American transform margin (Sharman et al., 2013; Gooley et al., 2020). Past reconstructions of the SGCF recognized similarities between crystalline units in the San Gabriel Mountains (SGM) and at Frazier Mountain (Fig. 1), but disagreed on the magnitude of slip required to restore these piercing points to their pre-offset locations (∼42–46 km, Powell, 1993; 60–75 km, Crowell, 2003). These models agreed that movement along the SGCF ended ∼5

doi: 10.2110/sedred.2021.2.3
Manuscript submitted: 02/19/2021
Received in revised format: 05/26/2021
Manuscript accepted: 06/03/2021
*Corresponding author: jclarkgilbert@gmail.com

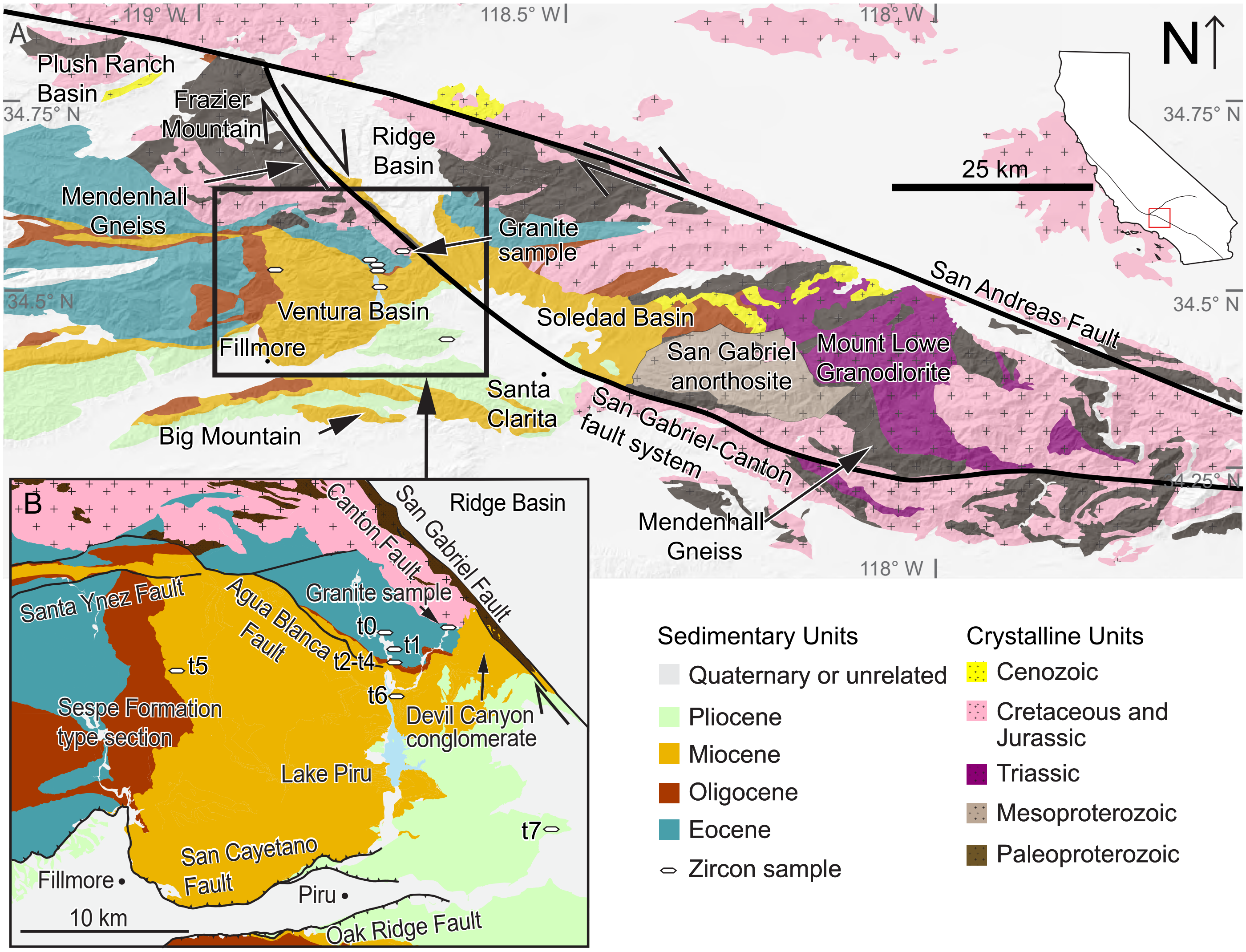

Figure 1: A) Geologic map of the eastern Ventura Basin (after Dibblee, 2010; Jennings, 2010; Jacobson et al., 2011). B) Inset map of the eastern Ventura Basin, showing sample locations t0-t7.

Ma when slip was transferred to the modern trace of the San Andreas Fault (Crowell, 1982; Powell, 1993). However, the early history of the SGCF remains unclear, and two models use the offset of the Mint Canyon Formation in the Soledad Basin to estimate a different timing of fault initiation (15–13 Ma, Powell, 1993; ~18 Ma, Hoyt et al., 2018).

Sedimentary units within the Ventura Basin record deposition adjacent to the SGCF before, during, and after SGCF slip (Fig. 1A; Yeats et al., 1994). Prior to SGCF initiation, Eocene marine sediments of the Juncal and Matilija Formations were deposited in a large, integrated catchment within the forearc basin created by the subduction of the Farallon Plate (Jacobson et al., 2011; Sharman et al., 2015). By Oligocene time, the forearc basin was filling with fluvial deposits of the Sespe Formation south of the study area (Ingersoll et al., 2018). In the study area, the clast size and mineralogy of Oligocene conglomerates suggests local sources in the emergent SGM and subsequent right-lateral translation ~60 km (Bohannon, 1975) during the Miocene. Miocene deep-marine deposits of the Modelo Formation continued to record proximal sedimentation from the SGM (Rumelhart and Ingersoll, 1997). This pattern continued until Pliocene time, when the SGCF became inactive (Crowell, 2003).

Past reconstructions of slip along the SGCF used conglomerate clasts and multiple crystalline sources as piercing points, and provenance changes were interpreted as evidence of basin translation along the fault (Crowell, 1954; Bohannon, 1975). However, the heterogeneous mineralogy of these large clasts creates high uncertainty in previous total slip offset estimates; a more detailed and complete record of the provenance of the sand-sized fraction has not been completed. This study highlights an Oligocene sample with a unimodal age fraction that is a more appropriate indicator of provenance than sedimentary units used in previous reconstructions and documents continual changes in detrital zircon (DZ) age spectra and SEM-based automated mineralogy (SAM) data in the Eocene-Pliocene Ventura Basin. We interpret this progression as a change in provenance as the basin translated northward along the SGCF. We demonstrate 35–60 km of slip on the SGCF likely initiating in Oligocene time and discuss the possible pre-Miocene slip history and the implications for the tectonic reconstruction of southern California.

METHODS

Eight samples were collected from the following units near Lake Piru, California, and numbered according to age (Fig 1B; Fig. 2): Eocene Juncal Formation (t0) and Matilija Formation (t1), Oligocene Vasquez Formation (t2, t3), Miocene Vaqueros Formation (t4) and Modelo Formation (t5, t6), and Pliocene Pico Formation (t7). Thin sections were made for seven samples and analyzed with a Tescan Integrated Mineral Analyzer for SAM (Sylvester, 2012); sample t7 was not sufficiently lithified. Each sample was analyzed for the U-Pb dates of 120–150 zircon grains via LA-ICP-MS (Hart et al., 2016) at the University of Arkansas Trace Element and Radiogenic Isotope Laboratory.

Although we recognize that Eocene sediments are unlikely to be locally sourced (Jacobson et al., 2011; Sharman et al., 2015) and that some of these age components are not unique to the SGM, we assume that DZ of Oligocene-Pliocene samples were derived from four crystalline parent source components located in the modern SGM: Cretaceous-Jurassic granitoids (CJ) (200–26 Ma), the Triassic Mount Lowe Granodiorite (LG) (280–200 Ma), the Mesoproterozoic San Gabriel anorthosite (SGA) (1300–1000

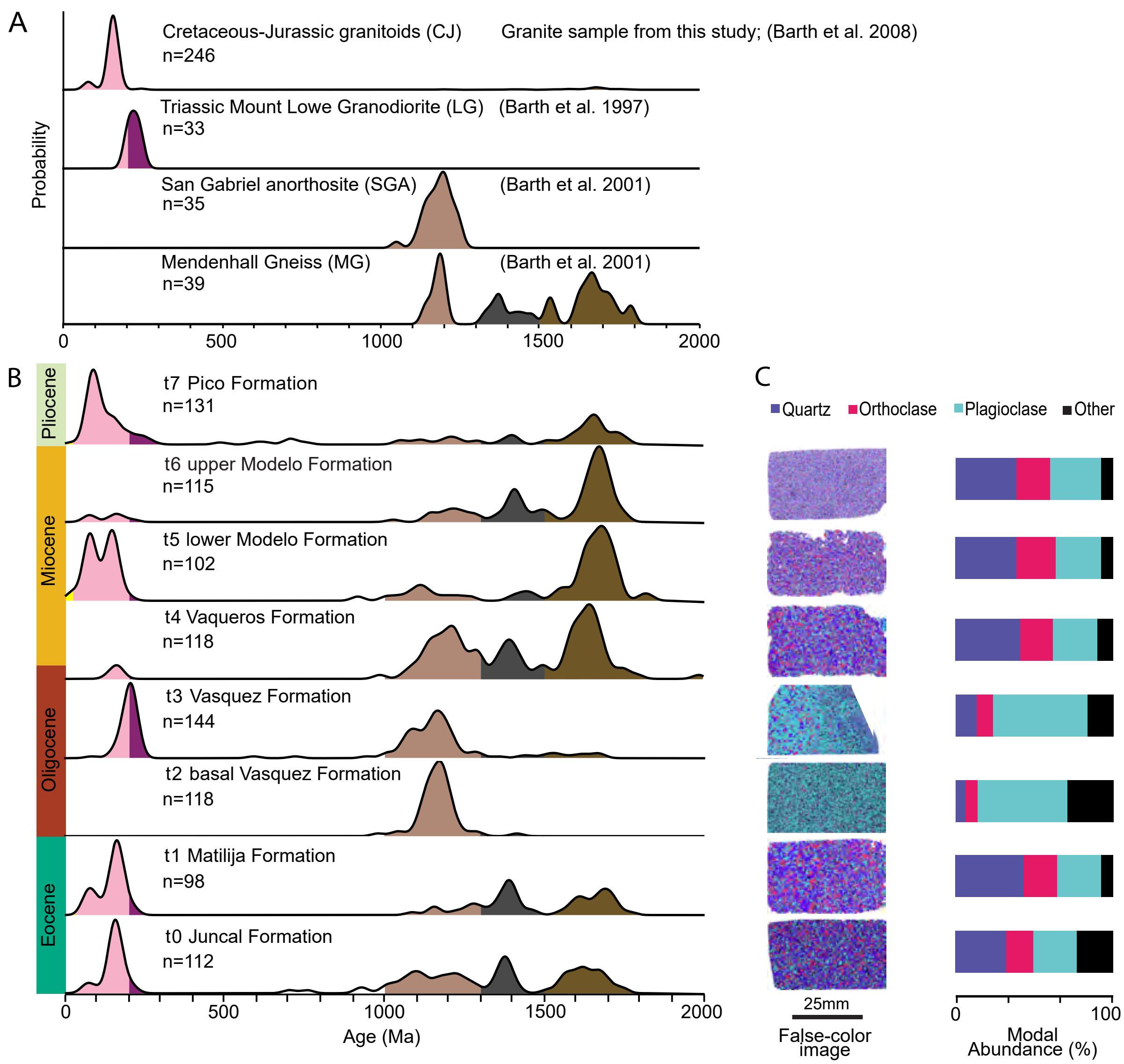

Figure 2: A) KDEs of zircon U-Pb dates from crystalline sources (parents). B) KDEs of DZ from eight Eocene-Pliocene samples (children). KDEs are not normalized and are constructed using a Gaussian kernel with a bandwidth of 20 Ma. C) Thin section false-color images of SAM data with abundant minerals labeled and bars plotting their modal abundances. The SAM and DZ data were analyzed from the same set of samples, but sample t7 was too disaggregated to make a thin section.

Ma), and the Paleoproterozoic Mendenhall Gneiss (MG) (multiple age peaks between 2000–1300 Ma). A granite sample (Fig. 1) was analyzed (n=30) and combined with published dates as the CJ parent, and the three other parents were compiled from published data (Fig. 2, Table S2). Although some formations may contain zircon recycled from older sedimentary units, we assume that recycled contributions were minor because each sample has a relatively unique age spectrum.

The contribution of each parent (crystalline source) was modeled for each child (detrital sample) following the 'top-down' approach of Sharman and Johnstone (2017). We characterized uncertainty in the mixture models using a bootstrapping approach (Malkowski et al., 2019). For each of 10,000 iterations, we resample with replacement the zircon dates from both the parent and child, calculate new kernel density estimates (KDEs), and determine the proportions of parents that mix to produce a distribution most similar to the resampled child distribution that is quantified with the Vmax metric (e.g., Saylor and Sundell, 2016). Detailed methods and data sources are included (Supplemental Material, Tables S1–S5).

RESULTS

Samples t0, t1, t4, t5, t6 and t7 contain 32–43% quartz, 17–29% orthoclase, and 25–33% plagioclase (Fig. 2B, Table S4). In contrast, the two Vasquez Formation samples (t2, t3) contain abundant plagioclase (t2, 57%; t3, 60%) and sparse quartz (t2, 6%; t3, 13%; Fig. 2B).

Eocene samples (t0–t1) contain abundant 200–26 Ma DZ and minor Permian-Triassic (280–200 Ma) and Proterozoic DZ (Fig. 2). Oligocene sample t2 contains a unimodal age fraction (1300–1000 Ma) while sample t3 has an approximately bimodal distribution consisting of older grains between 1300–1000 Ma and Phanerozoic grains between 250–140 Ma (upper Paleozoic and Mesozoic). Miocene sample t4 contains abundant 1300–1000 Ma and 2000–1500 Ma grains, samples (t5, t6) have variable Mesozoic and Proterozoic dates, and t5 has two Oligocene DZ dates. Pliocene sample t7 has DZ age modes between 200–26 Ma and 2000–1500 Ma.

Detrital zircon mixture modeling

Mixture models from Eocene samples (t0, t1) show consistent contributions from the MG (Fig. 3, Table S3; P50=55–63%, P2.5=26–45%, P97.5=76–79%, where P50 is the median value and P2.5 and P97.5 are bounds on the 95% confidence interval); CJ forms a secondary source (Fig. 3). Mixture models for the Vasquez Formation samples (t2, t3) indicate strong contributions from the SGA (P50=94–49%, P2.5=81–29%, P97.5=100–58%), with LG as a secondary source for t3 (P50=37%, P2.5=28%, P97.5=47%). Models for samples from the Vaqueros (t4), Modelo (t5, t6), and Pico (t7) Formations all indicate MG to be the dominant source (P50=55–100%, P2.5=55–89%, P97.5=87–100%), with SGA as a secondary source for t4 and CJ as a secondary source for t5, t6, and t7 (Fig. 3). SGA is not modeled to contribute appreciable sediment to t5, t6, and t7.

DISCUSSION

Pre-Miocene deposition

The two lower Eocene samples (t0, t1) have similar DZ age spectra, with modeled contributions from MG and CJ sources currently exposed in the western SGM 60–80 km to the southeast (Figs. 1, 3). However, sources of this age are common in California and not spatially distinct (Fig. 1), and we interpret this mixture to represent deposition in the forearc basin from multiple, extra-regional sources.

Units containing samples t2 and t3 are mapped as the Sespe Formation (Dibblee, 2010), but these units are texturally immature, consisting of poorly sorted sandstones and conglomerates containing angular clasts up to 7 m (Crowell, 1954; Bohannon, 1975), while the Sespe Formation is typically fine-grained, quartz-rich fluvial-deltaic deposits (Ingersoll et al., 2018). Instead, units t2 and t3 are more similar to the Miocene-Oligocene Vasquez Formation in the nearby Soledad Basin (Fig. 1A) (Hendrix and Ingersoll, 1987), and we suggest that units t2 and t3 represent locally sourced alluvial-fan deposits of the Vasquez Formation. This distinction is critical because while the age of the Sespe Formation is late Eocene–early Miocene (Ingersoll et al., 2018), the age of the Vasquez Formation is more tightly constrained between 25 and 21 Ma (Hendrix and Ingersoll, 1987; Frizzell Jr and Weigand, 1993), which narrows the age uncertainty for a unit commonly used in tectonic reconstructions.

Previous models associated large clasts of anorthosite, granite, and gneiss in Eocene–Oligocene alluvial units to sources 60–75 km away in the SGA, LG, and MG, respectively (Crowell, 1954; Bohannon, 1975). However, our DZ data sampled 4 km to the west of those outcrops favor a more spatially limited sediment source, because zircon dates that make up the ca. 1.2 Ga component in samples t2 and t3 are similar to the estimated age (1194 $\pm$ 35 Ma) of the SGA (Barth et al., 2001) (Fig. 1A). Furthermore, the abundant plagioclase (57–60%) and minor quartz (6–13%) in samples t2 and t3 (Fig. 2C) suggest a source rich in plagioclase, typical of anorthosites. These two lines of evidence suggest that, during Oligocene time, the Ventura Basin was 35–60 km to the southeast, where the SGA is nearest to the San Gabriel fault (Fig. 1). This location only requires an alluvial fan with a radius of 10–20 km to source the Vasquez Formation (t2 and t3), which is within the typical range (10–15 km) of alluvial fan radii (Hartley et al., 2010).

It is unclear why the sand-sized fraction is sourced only from the SGA (Fig. 2), while the boulder-sized fraction nearby is recording contributions from multiple sources (Powell, 1993; Crowell, 2003). Several possible combinations of fault initiation timing, local paleogeography and grain size fractionation could contribute to this difference. Our preferred interpretation is that an alluvial fan emanating from the SGA carried the sand fraction to the south or west and into the study area, while another alluvial fan emanating from south of the SGA transported the boulders to the north.

Miocene and Pliocene strike-slip associated sedimentation

DZ dates between 1300–1000 Ma diminish throughout Miocene time (Fig. 2); for example, a SGA contribution of 23% for t4 decreases to 0% for all younger samples (Fig. 3).

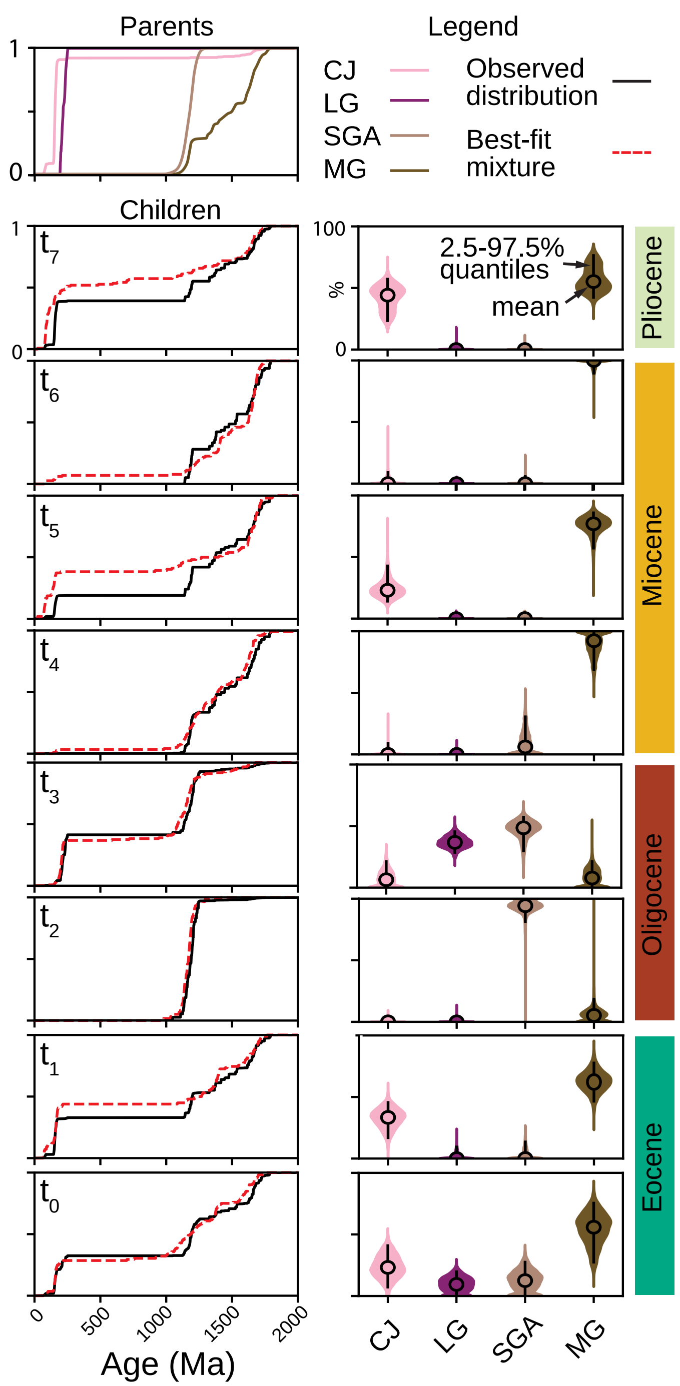

Figure 3: Left) Plots showing best-fit mixture-model results for each child sample using the Vmax comparison metric and the observed distribution. Right) Violin plots displaying range of uncertainty for each parent contribution from the resampling results.

We interpret this decrease to record the translation of the basin away from the SGA (Fig. 4). All of the best-fit mixtures from Miocene-Pliocene samples include significant but temporally variable input from MG, LG, and CJ (Fig. 2). We interpret these DZ components to represent deposition from the various sources exposed around the margins of the Soledad Basin (Fig. 1). MG and CJ rocks exist on the west side of the SGCF and technically could have provided sediment to the Ventura Basin during the Neogene. However, the occurrence of two Oligocene DZ dates analyzed in t5, likely sourced from volcanic units in the eastern Soledad Basin (Fig. 1), supports this provenance interpretation. We interpret the low proportions of >1 Ga zircon and strong CJ contribution in sample t7 as evidence of recycling of older sediments during Pliocene transpression and uplift (Ingersoll and Rumelhart, 1999; Crowell, 2003).

Explanation of piercing points and their uncertainties in the Ventura Basin

Figure 4B is a fault slip offset diagram of the relevant published reconstructions in which the boxes represent the uncertainty in the piercing points used to support the interpretations. The horizontal length of a given box represents the spatial uncertainty attributed to that piercing point, and the vertical length represents the temporal uncertainty. The lines represent the preferred interpretation of the slip offset history of the fault while respecting the constraints from the uncertainties.

Boxes 2a, 2b, t2, t3 - Offset of Oligocene conglomerates in Canton Canyon and Piru Creek

Crowell (2003) estimated that the “Sespe conglomerates” in Canton Canyon were offset ∼75 km from their interpreted source area in the western SGM. Crowell (2003) interprets that the Sespe conglomerates were deposited before 28 Ma along the scarp of a normal fault before the basin was translated (Fig. 4B, box 2a). In contrast, Powell (1993) interpreted that the Sespe conglomerates in Canton Canyon are Oligocene in age and deposited prior to strike-slip movement on the SGCF and subsequently offset 42–46 km (Fig. 4B, box 2b).

This study also uses the offset the Sespe conglomerates, here interpreted as the Vasquez Formation and represented by samples t2 and t3, and their source areas (Fig. 4B, box t2) to restore the Ventura Basin. The Vasquez Formation was deposited between 25–21 Ma in its type section in the Soledad Basin based on biostratigraphy and K-Ar dates on plagioclase (Hendrix and Ingersoll, 1987), and we assume the same age range for t2 and t3. However, we recognize the uncertainty in correlating between basins, so the outline of box t2 is dashed due to poor age constraints. Detailed information about the interpreted age of the Vasquez Formation is provided (Supplemental Material). We interpret the change from SGA-only sediment in t2 to the addition of a significant contribution of LG in t3 as evidence that the basin had moved along the SGCF between t2 and t3 deposition. The blue solid line (Fig. 4B) shows our preferred interpretation that the basin was moving prior to deposition of t3, and box t3 (Fig. 4B) displays the uncertainty in both the depositional age of sample t3 and the location of the basin during deposition. Also, box t3 is dashed due to the possibility that the contribution of LG to sample t3 is caused by changes in sediment routing rather than fault movement.

Box t4 – Offset of Vaqueros Formation (t4) and crystalline sources surrounding the Soledad Basin

We interpret the change from the SGA-only sourced Vasquez Formation (t2) to contributions from multiple crystalline sources in the Vaqueros Formation (t4) to signal that the Ventura Basin had been translated to the north and was receiving sediment from sources surrounding the Soledad Basin. Although the exact location of the Ventura Basin at the time is uncertain, this change suggests that the basin was north of the SGA during deposition of t4. The diminishing contribution of SGA from t4–t6 suggests that the Ventura Basin was likely proximal to the SGA during deposition of t4 and moving farther away from the SGA during deposition of t5 and t6. This is intuitive but speculative, and thus the spatial uncertainty brackets the basin location between where the SGA is closest to the SGCF and a location parallel to the Soledad Basin but still proximal to the SGA (Fig. 4B, box t4).

The reported age range of the Vaqueros Formation (t4) is between 27.5 Ma (Prothero, 2001) and 17 Ma (Prothero and Donohoo, 2001); its base is interpreted as Oligocene based on biostratigraphy (Blake, 1983) at Big Mountain, California, 20 km south of the study area (Fig. 1). The age of the overlying Rincon Shale is interpreted as >20 Ma near Santa Barbara, California (Prothero, 2001). We assume that the Vaqueros Formation at Lake Piru is between 25–20 Ma based on regional correlations of the base of the Rincon Shale and the top of the underlying Vasquez Formation; the blue line represents our preferred slip-history model (Fig. 4B). However, we recognize the uncertainty in these correlations, and we place a conservative age range of 27.5–18 Ma (Fig. 4B, box t4), which honors the oldest reported age of the Vaqueros Formation at Big Mountain. The 18 Ma minimum age uncertainty bound assumes that the Vaqueros Formation is older than the 17.4 Ma base of the Modelo Formation and that the 600 m of Rincon Shale represents at least 0.6 Myr of deposition. Detailed information about the interpreted age of the Vaqueros Formation is provided (Supplemental Material).

Box t5 – Presence of Oligocene zircon within the Miocene lower Modelo Formation

Zircon analyzed from sample t5 from the lower Modelo Formation yielded two Oligocene dates of 23 ± 1 Ma and 22 ± 1 Ma. No known igneous intrusive or metamorphic units of that age exist near the SGCF, but late Oligocene volcanic units are within the Vasquez Formation in the Soledad Basin (Hendrix and Ingersoll, 1987; Frizzell Jr and Weigand, 1993). This suggests that during deposition of t5, a fluvial system within the Soledad Basin was supplying sediment across the SGCF to the eastern Ventura Basin and this is supported by the occurrence of Oligocene zircon in Soledad Basin sediments (Hoyt et al., 2018). Therefore, the spatial uncertainty is conservatively placed as the current north and south boundaries of the Soledad Basin (Fig. 4B, box t5) which results in a slip estimate of 12–30 km. The age uncertainty is interpreted as 13.9–17.4 Ma, which is the depositional age of the lower Modelo Formation (Yeats et al., 1994).

Boxes 6a, 6b, 6c, t6 – Offset of Devil Canyon conglomerate of the Miocene upper Modelo Formation

Boulders of gabbro, anorthosite, gneiss, and the Triassic Mount Lowe Granodiorite in the Devil Canyon conglomerate of the Miocene Modelo Formation have been used by several studies to infer that the Ventura Basin was right laterally offset from interpreted source regions in the SGM (Powell, 1993; Yeats et al., 1994; Crowell, 2003). However, each model interprets a different total offset and age. Crowell (2003) estimates the age of the Devil Canyon conglomerate between ca. 9 and 6.5 Ma and estimates ∼45 km of offset (Fig. 4B, box 6a). Powell (1993) interprets these conglomerates to be 13–10 Ma and suggests an offset of 13 km along the Canton fault (Fig. 4B, box 6b) and the spatial uncertainty is calculated simply by subtracting 13 km from the 42–46 km range of total offset given by Powell (1993). Yeats et al. (1994) interprets a 10–5 Ma age range for the Devil Canyon conglomerate and an offset of 35–56 km (Fig. 4B, box 6c).

The Devil Canyon conglomerate is not present at the location where sample t6 was collected, and correlation between the upper Miocene Modelo Formation in these two locations is difficult due to local structural complexities. At Lake Piru, the upper Modelo Formation is interpreted as 13.9–6.5 Ma in age (Blake, 1991; Yeats et al., 1994) (Fig. 4B, box t6). This conservative age uncertainty overlaps with the age interpretations of all three of the previously published models, because we do not have high resolution age control on sample t6. Similarly, while the modeled mixture of parent contributions to samples t4–t6 is variable (Fig. 3), all are interpreted to have been sourced from crystalline units surrounding the Soledad Basin. Although we interpret this variability is caused by right-lateral offset, changes in sediment routing cannot be ruled out as a cause for changes in source-terrane abundance. For this reason, we conservatively use the boundaries of the Soledad Basin as the spatial uncertainty (Fig. 4B, box t6), which results in an offset of 12–30 km.

Boxes 8a, 8b – Offset of Hasley conglomerate of the Towsley Formation in the Ventura Basin

Both Crowell (2003) and Yeats et al. (1994) used pebbles and boulders found in the Hasley conglomerate (part of the lower Towsley Formation) as evidence that sediment was sourced from the SGM. Crowell (2003) reported these clasts as similar to those from the underlying Devil Canyon conglomerate and interpreted right-lateral offset of ∼25 km for these ∼6.4 Ma beds (Fig. 4B, box 8a). Yeats et al. (1994) estimated the age of the Hasley conglomerate to be 10–5 Ma but estimated ≥30 km of slip to restore the same unit to the interpreted source region at the northern edge of the SGM (Fig. 4B, box 8b).

Box 9 – No offset of Fernando Formation across San Gabriel Fault

Yeats et al. (1994) observed no offset in the upper Fernando Formation, which is considered equivalent to the Pico Formation (t7) in this study (*sensu* Dibblee, 2010). Yeats et al. (1994) interpreted the top of the Fernando Formation to be <2 Ma and this age is used as the last possible fault movement of the SGCF (Fig. 4B, box 9).

Explanation of piercing points from other basins

Boxes 10a, 10b - Offset of Frazier Mountain and western SGM

Two studies use Frazier Mountain and similar igneous and metamorphic rocks in the western SGM to estimate total offset on the SGCF, but faulting and multiple igneous intrusions within these basement blocks have created various interpretations of how to restore them. For example, Powell (1993) restored Frazier Mountain 42–46 km southward along the San Gabriel fault (Fig. 4B, box 10a). Yeats et al. (1994) estimated 60 km of offset between the Mendenhall Gneiss of Frazier Mountain and the SGM, but does not provide an uncertainty for this slip estimate, so it is kept consistent with the 4 km estimate of Powell (1993) (Fig. 4B, box 10b). The youngest rocks in these basement blocks are Cretaceous, and therefore do not provide helpful age control for fault movement but are included as brackets (Fig. 4B, box 10a, 10b) because of their use in these models.

Boxes 11a, 11b – Offset of the Caliente and Mint Canyon Formations and their textural similarities

Both Crowell (2003) and Hoyt et al. (2018) interpret the Caliente Formation in the Plush Ranch Basin and the Mint Canyon Formation in the Soledad Basin as correlative due to similarities in texture, mineralogy, and petrology (Ehlert, 2003). These units were interpreted to have been deposited prior to initiation of fault movement and used to estimate offset along the San Gabriel fault (Crowell, 2003; Hoyt et al., 2018). Crowell (2003) estimates the age of the Mint Canyon and Caliente Formations as 16–11 Ma and restores them ∼75 km (Fig. 4B, Box 11a), adding ∼15 km of offset from previous estimates of 60 km (Crowell, 1954, 2003).

Hoyt et al. (2018) suggested that the Caliente Formation was deposited between 18–8 Ma based on biostratigraphy and magnetic stratigraphy (Prothero et al., 2008) and that the Mint Canyon Formation was deposited between ca. 14–10 Ma citing biostratigraphy data (Stirton, 1933) and zircon fission track dates of 11.6 ± 1.2 Ma and 10.1 ± 0.8 Ma (Terres and Luyendyk, 1985). Hoyt et al. (2018) interpret the age uncertainty in the model as the range between oldest age of the Caliente Formation (18 Ma) and the youngest age of the Mint Canyon Formation (10 Ma) and a preferred offset estimate of 60–70 km (Fig. 4B, box 11b). However, Hoyt et al. (2018) recognized that total slip estimates of ∼42–60 km cannot be ruled out based on petrography and detrital zircon geochronology data.

Boxes 12a, 12b – Offset of the Miocene Violin Breccia in Ridge Basin

The Miocene Violin Breccia in Ridge Basin interfingers with the Castaic, Peace Valley, and Hungry Valley Formations and is interpreted to be sourced from the Frazier Mountain area (Powell, 1993; Crowell, 2003). Crowell (2003) interpreted the age of the Violin Breccia as 10–5 Ma and that the oldest beds are offset ∼45 km from their source (Fig. 4B, box 12a).

Both Crowell (2003) and Powell (1993) interpreted the Violin Breccia to record the entire fault history. Powell (1993) interpreted the formations that interfinger with the Violin Breccia to be 10–6 Ma (Fig. 4B, box 12b) and that the oldest beds of the Violin Breccia are offset 42–45 km from their source area in the Frazier Mountain block, assigning 21–23 km of slip to the San Gabriel fault between 10–6 Ma, ∼13 km to the Canton fault between 13–10 Ma (Fig. 4B, box 12b), and <13 km to offset occurring after 6 Ma.

Box 13 – No offset of the Hungry Valley Formation in Ridge Basin

Beds of the Hungry Valley Formation are not offset across the San Gabriel fault (Crowell, 2003). Deposition of these beds is assumed to postdate movement on the San Gabriel fault, but no age uncertainty is given (Fig. 4B, box 13).

Implications for southern California tectonic reconstructions

Our preferred model suggests that the progression from t2 to t3 represents the Ventura Basin moving northward along the SGCF (Fig. 4B). This preferred timing of fault initiation between 25 and 21 Ma would predate all previous estimates of initiation of the SGCF by at least 3 Ma (Supplemental Material, Table S5) and is dependent on the depositional ages of the Vasquez and Vaqueros Formations (t2–t4) at Lake Piru but is in agreement with previous models that suggest the San Andreas transform began after 28 Ma (Atwater, 1989; Gooley et al., 2020). Two previous models (Powell, 1993; Crowell, 2003) were used to interpret a later SGCF initiation, but use the mineralogical similarities between this unit and the SGM to interpret offset. Our total slip estimate of 35-60 km (Fig. 4B) is in agreement with the 42–46 km estimate of Powell (1993), but the >60 km of offset interpreted by Crowell (2003) is not required to source the t2 and t3 sediment mixtures. Similarly, our model only partially overlaps with the 60–70 km preferred estimate of Hoyt et al. (2018) using offset of the Mint Canyon and Caliente Formations. Even if the change in DZ dates from t2 to t3 is caused by changes in sediment routing prior to translation, the consistent contribution of MG within samples t4–t7 suggests that the Ventura Basin was receiving

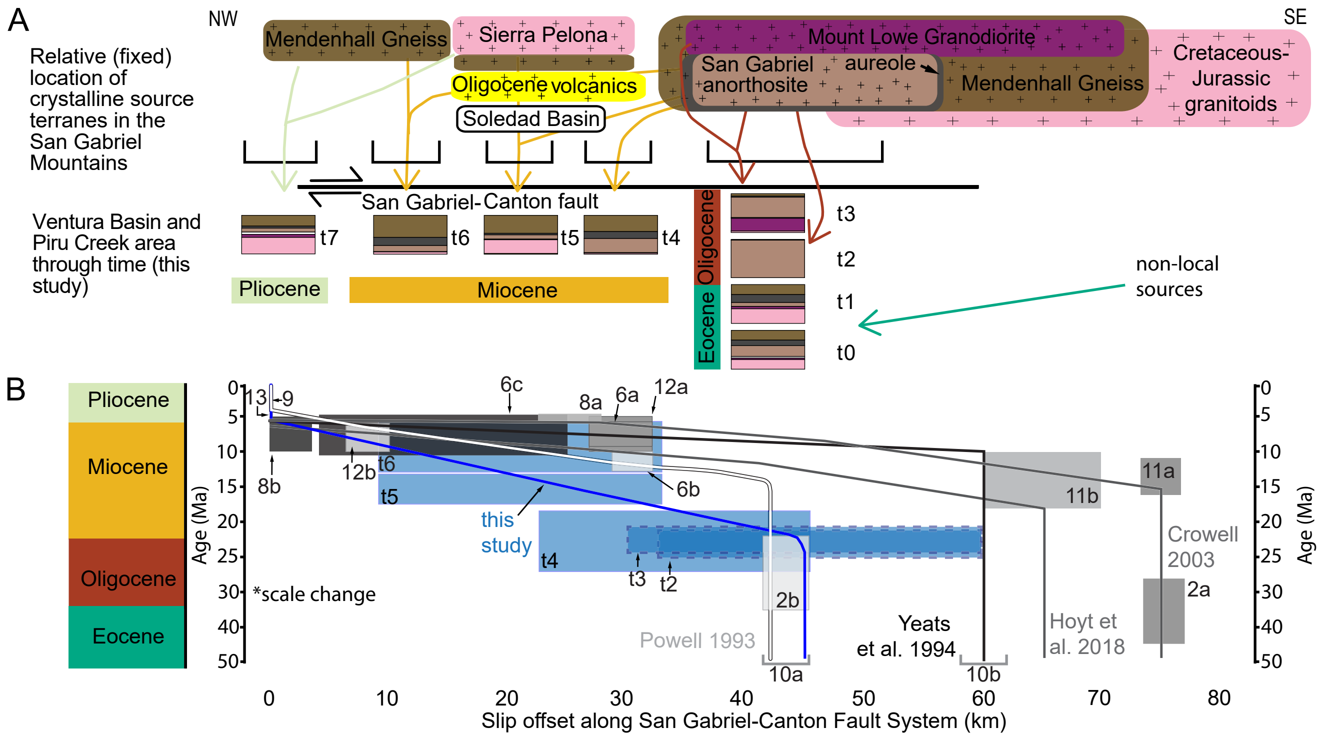

Figure 4: Compilation of the translational history of the Ventura Basin. A) Interpreted patterns of sediment routing and basin translation through time. Stacked bar charts show child sample DZ dates colored by parent age bins. B) Fault slip-offset diagram comparing our model that suggests 35–60 km of total slip to four published Ventura Basin reconstructions. Boxes represent fault slip uncertainty when reported and those with the same number in the label represent a different interpretation of the same piercing point (e.g. 2a, 2b, t2). Boxes constraining our model are colored blue and are labeled t2–t6 for consistency with the sample names. Boxes t2 and t3 are dashed because they represent interpretations with poor constraints.

sediment from the Soledad Basin rather than from MG-age rocks south of the SGA by time t4 (Fig. 4B). We conservatively interpret the range of uncertainty of fault timing as 27.5–18 Ma (Fig. 4B, box t4). Therefore, our latest SGCF initiation estimate of 18 Ma is equal to the earliest published estimate (Hoyt et al., 2018). The discrepancy between our model using the Ventura Basin and estimates using the Plush Ranch and Soledad basins (Hoyt et al., 2018) is currently unresolved. However, Hoyt et al. (2018) recognized that slip estimates between 42–60 km cannot be ruled out due to ambiguity in the sediment provenance data. This discrepancy could exist if each basin underwent different amounts of off-fault deformation during Pliocene transpression (Powell, 1993; Yeats et al., 1994) or because sediments with multiple parent components likely have higher spatial uncertainty compared to those with only one component. However, a more comprehensive regional study is required to resolve this issue.

Offset of the Devil Canyon conglomerate of the upper Miocene upper Modelo Formation (Fig. 1B) is used by three previous models to infer that the Ventura Basin was adjacent to its interpreted source area in the SGM by the time of deposition. However, we interpret the occurrence of Oligocene zircon in sample t5 to suggest that by the time of deposition of the middle Miocene lower Modelo Formation between 17.4–13.9 Ma (Yeats et al., 1994), the Ventura Basin had already translated 12–30 km along the SGCF and was receiving sediments from Oligocene volcanic sources in the Soledad Basin (Fig. 4B, box t5). Although our interpretation of the model results indicates that the fault initiated before 18 Ma, our slip estimate using the offset of the lower Modelo Formation is in agreement with the 13 km estimate of (Powell, 1993) but is not in agreement with the 35–56 km estimate of Yeats et al. (1994) or the ≥45 km estimate of Crowell (2003). The wide range of interpretations in previous models suggest that the location of the Ventura Basin during the middle–late Miocene cannot be determined with high confidence, and our conservative approach better honors these uncertainties. Dense spatial and temporal sampling of the Oligocene and Miocene units in the Ventura Basin paired with studies investigating fault kinematics and off-fault deformation may provide higher resolution fault slip estimates.

CONCLUSIONS

Automated mineralogy data and mixture modeling of DZ age distributions reveal a previously unrecognized, singular sediment source of an Oligocene unit in the Ventura Basin, southern California. Drastic differences in sedimentology, sandstone mineral abundance, and zircon age spectra between the Oligocene sediments at Lake Piru and the

Sespe Formation in its type section nearby suggest that this unit was not part of the Sespe fluvial system but more similar to the alluvial Vasquez Formation of the Soledad Basin. Most significantly, two samples from this unit have distributions of DZ dates and abundant plagioclase that strongly suggest local sourcing primarily from the SGA. Our reassessment of these sedimentary deposits and their sources redefines the placement of a more appropriate piercing point prior to initiation of the SGCF. The reemergence of multiple DZ components following deposition of the Vasquez Formation is consistent with continued northward translation of the Ventura Basin and the sourcing of sediments from crystalline units exposed north of the SGA. These results support a reconstruction with 35–60 km of slip along the San Gabriel-Canton fault with fault slip occurring as early as Oligocene time, which is earlier than previous estimates.

ACKNOWLEDGMENTS

We thank the Chevron Center of Research Excellence at Colorado School of Mines (core.mines.edu) for funding support, Jacob Covault and Elisa Medri for field assistance, and Katharina Pfaff, Greg Gordon, Barry Shaulis, Ray Ingersoll, and Carl Jacobson for insightful discussions. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Copyright notice

Literature Cited

Atwater, T. (1989). Plate tectonic history of the northeast Pacific and western North America. In Winterer, E. L., Hussong, D. M., and Decker, R. W., editors, *The Eastern Pacific Ocean and Hawaii*, pages 21–72. The Geology of North America Volume N.

Barth, A. P., Tosdal, R. M., Wooden, J. L., and Howard, K. A. (1997). Triassic plutonism in southern California: Southward younging of arc initiation along a truncated continental margin. *Tectonics*, 16(2):290–304.

Barth, A. P., Wooden, J. L., and Coleman, D. S. (2001). SHRIMP-RG U-Pb zircon geochronology of Mesoproterozoic metamorphism and plutonism in the southwesternmost United States. *The Journal of Geology*, 109(3):319–327.

Barth, A. P., Wooden, J. L., Howard, K. A., Richards, J. L., Wright, J., and Shervais, J. (2008). Late Jurassic plutonism in the southwest US Cordillera. In Wright, J. E. and Shervais, J. W., editors, *Ophiolites, Arcs, and Batholiths: A Tribute to Cliff Hopson*, volume 438, pages 379–396. Geological Society of America Special Papers 438.

Blake, G. H. (1983). Benthic foraminiferal paleoecology and biostratigraphy of the Vaqueros Formation, Big Mountain area, Ventura County, California. In Squires, R. R. and Filewicz, M. V., editors, *Cenozoic Geology of the Simi Valley Area, Southern California*. Pacific Section, SEPM Society for Sedimentary Geology.

Blake, G. H. (1991). Review of the Neogene biostratigraphy and stratigraphy of the Los Angeles Basin and implications for basin evolution. In Biddle, K. T., editor, *Active Margin Basins*, pages 135–184. American Association of Petroleum Geologists Memoir 52.

Bohannon, R. G. (1975). Mid-Tertiary conglomerates and their bearing on transverse range tectonics, Southern California. *California Division of Mines and Geology Special Report Number 118*, pages 75–82.

Crowell, J. C. (1954). Strike-slip displacement of the San Gabriel fault, southern California. *Geology of Southern California*, 170:49–52.

Crowell, J. C. (1962). *Displacement along the San Andreas fault, California*, volume 71. Geological Society of America.

Crowell, J. C. (1982). The Tectonics of Ridge Basin, Southern California. In Crowell, J. C. and Link, M. H., editors, *The Tectonics of Ridge Basin, Southern California*, pages 25–42. Pacific Section, SEPM Society for Sedimentary Geology.

Crowell, J. C. (2003). Tectonics of Ridge Basin region, southern California. In Crowell, J. C., editor, *Evolution of Ridge Basin, Southern California: An Interplay Of Sedimentation And Tectonics*, pages 157–204. Geological Society of America Special Papers 367.

Dibblee, T. W. (2010). *Geologic map of the Cobblestone Mountain Quadrangle, Ventura and Los Angeles counties, California: Dibblee Geology Center Map #DF-62: First Printing, 1996: Second Printing, 2010*. Santa Barbara Museum of Natural History, http://www.sbnature.org/.

Ehlert, K. W. (2003). Tectonic significance of the middle Miocene Mint Canyon and Caliente formations, southern California. pages 113–130.

Frizzell Jr, V. A. and Weigand, P. W. (1993). Whole-rock K-Ar ages and geochemical data from middle Cenozoic rocks, southern California: A test of correlations across the San Andreas fault. In Powell, R. D., Weldon II, R. J., and Matti, J. C., editors, *The San Andreas Fault System: Displacement, Palinspastic Reconstruction, And Geologic Evolution*, pages 273–288. Geological Society of America Memoir 178.

Gooley, J. T., Sharman, G. R., and Graham, S. A. (2020). Reconciling along-strike disparity in slip displacement of the San Andreas fault, central California, USA. *GSA Bulletin*.

Hart, N. R., Stockli, D. F., and Hayman, N. W. (2016). Provenance evolution during progressive rifting and hyperextension using bedrock and detrital zircon U-Pb geochronology, Mauléon Basin, western Pyrenees. *Geosphere*, 12(4):1166–1186.

Hartley, A. J., Weissmann, G. S., Nichols, G. J., and Warwick, G. L. (2010). Large distributive fluvial systems: characteristics, distribution, and controls on development. *Journal of Sedimentary Research*, 80(2):167–183.

Hendrix, E. D. and Ingersoll, R. V. (1987). Tectonics and alluvial sedimentation of the upper Oligocene/lower Miocene Vasquez Formation, Soledad basin, southern California. *GSA Bulletin*, 98(6):647–663.

Hoyt, J. F., Coffey, K. T., Ingersoll, R. V., and Jacobson, C. E. (2018). Paleogeographic and paleotectonic setting of the middle Miocene Mint Canyon and Caliente formations, southern California: An integrated provenance study. In Ingersoll, R. V., Lawton, T. F., and Graham, S. A., editors, *Tectonics, Sedimentary Basins, and Provenance: A Celebration of the Career of William R. Dickinson*, pages 463–480. Geological Society of America Special Paper 540.

Ingersoll, R. V. and Rumelhart, P. E. (1999). Three-stage evolution of the Los Angeles basin, southern California. *Geology*, 27(7):593–596.

Ingersoll, R. V., Spafford, C. D., Jacobson, C. E., Grove, M., Howard, J. L., Hourigan, J., and Pedrick, J. (2018). Provenance, paleogeography and paleotectonic implications of the mid-Cenozoic Sespe Formation, coastal southern California, USA. In Ingersoll, R. V., Lawton, T. F., and Graham, S. A., editors, *Tectonics, Sedimentary Basins, and Provenance: A Celebration of the Career of William R. Dickinson*, pages 441–462. Geological Society of America Special Paper 540.

Jacobson, C. E., Grove, M., Pedrick, J. N., Barth, A. P., Marsaglia, K. M., Gehrels, G. E., and Nourse, J. A. (2011). Late Cretaceous–early Cenozoic tectonic evolution of the southern California margin inferred from provenance of trench and forearc sediments. *GSA Bulletin*, 123(3–4):485–506.

Jennings, C. W. (2010). *Geologic map of California, with modifications by Carlos Gutierrez, William Bryant, George Saucedo and Chris Wills*. Department of Conservation, California Geological Survey.

Malkowski, M. A., Sharman, G. R., Johnstone, S. A., Grove, M. J., Kimbrough, D. L., and Graham, S. A. (2019). Dilution and propagation of provenance trends in sand and mud: Geochemistry and detrital zircon geochronology of modern sediment from central California (USA). *American Journal of Science*, 319(10):846–902.

Powell, R. E. (1993). Balanced palinspastic reconstruction of pre-late Cenozoic paleogeology, southern California: Geologic and kinematic constraints on evolution of the San Andreas fault system. In Powell, R. D., Weldon II, R. J., and Matti, J. C., editors, *The San Andreas Fault System: Displacement, Palinspastic Reconstruction, and Geologic Evolution*, pages 1–106. Geological Society of America Memoir 178.

Prothero, D. R. (2001). Chronostratigraphic calibration of the Pacific Coast Cenozoic: A summary. In Prothero, D. R., editor, *Magnetic Stratigraphy of the Pacific Coast Cenozoic*, pages 377–394. Pacific Section, SEPM Society for Sedimentary Geology, Book 91.

Prothero, D. R. and Donohoo, L. L. (2001). Magnetic stratigraphy of the lower Miocene (early Hemingfordian) Sespe-Vaqueros Formations, Orange County, California. In Prothero, D. R., editor, *Magnetic Stratigraphy of the Pacific Coast Cenozoic*, pages 242–253. Pacific Section, SEPM Society for Sedimentary Geology, Book 91.

Prothero, D. R., Kelly, T. S., McCardel, K. J., and Wilson, E. L. (2008). Magnetostratigraphy, biostratigraphy, and tectonic rotation of the Miocene Caliente Formation, Ventura County, California. *New Mexico Museum of Natural History and Science Bulletin*, 44:255–272.

Rumelhart, P. E. and Ingersoll, R. V. (1997). Provenance of the upper Miocene Modelo Formation and subsidence analysis of the Los Angeles basin, southern California: Implications for paleotectonic and paleogeographic reconstructions. *GSA Bulletin*, 109(7):885–899.

Saylor, J. E. and Sundell, K. E. (2016). Quantifying comparison of large detrital geochronology data sets. *Geosphere*, 12(1):203–220.

Sharman, G. R., Graham, S. A., Grove, M., and Hourigan, J. K. (2013). A reappraisal of the early slip history of the San Andreas fault, central California, USA. *Geology*, 41(7):727–730.

Sharman, G. R., Graham, S. A., Grove, M., Kimbrough, D. L., and Wright, J. E. (2015). Detrital zircon provenance of the Late Cretaceous–Eocene California forearc: Influence of Laramide low-angle subduction on sediment dispersal and paleogeography. *GSA Bulletin*, 127(1–2):38–60.

Sharman, G. R. and Johnstone, S. A. (2017). Sediment unmixing using detrital geochronology. *Earth and Planetary Science Letters*, 477:183–194.

Stirton, R. A. (1933). Critical review of the Mint Canyon mammalian fauna and its correlative significance. *American Journal of Science*, 5(156):569–576.

Sylvester, P. J. (2012). Use of the mineral liberation analyzer (MLA) for mineralogical studies of sediments and sedimentary rocks. *Mineralogical Association of Canada*, 1:1–16.

Terres, R. R. and Luyendyk, B. P. (1985). Neogene tectonic rotation of the San Gabriel region, California, suggested by paleomagnetic vectors. *Journal of Geophysical Research: Solid Earth*, 90(B14):12467–12484.

Yeats, R. S., Huftile, G. J., and Stitt, L. T. (1994). Late Cenozoic tectonics of the east Ventura basin, Transverse Ranges, California. *AAPG Bulletin*, 78(7):1040–1074.