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Taking apart the Big Pine fault: Redefining a major structural feature in southern California

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[1] New mapping along the Big Pine fault trend in southern California indicates that this structural alignment is actually three separate faults, which exhibit different geometries, slip histories, and senses of offset since Miocene time. The easternmost fault, along the north side of Lockwood Valley, exhibits left-lateral reverse Quaternary displacement but was a north dipping normal fault in late Oligocene to early Miocene time. The eastern Big Pine fault that bounds the southern edge of the Cuyama Badlands is a south dipping reverse fault that is continuous with the San Guillermo fault. The western segment of the Big Pine fault trend is a north dipping thrust fault continuous with the Pine Mountain fault and delineates the northern boundary of the rotated western Transverse Ranges terrane. This redefinition of the Big Pine fault differs greatly from the previous interpretation and significantly alters regional tectonic models and seismic risk estimates. The outcome of this study also demonstrates that basic geologic mapping is still needed to support the development of geologic models. **Citation:** Onderdonk, N. W., S. A. Minor, and K. S. Kellogg (2005), Taking apart the Big Pine fault: Redefining a major structural feature in southern California, *Tectonics*, *24*, TC6002, doi:10.1029/2005TC001817.

1. Introduction

[2] The Big Pine fault is an east-west striking fault zone that extends 70 km westward from the Big Bend of the San Andreas fault zone in southern California (Figure 1). The fault trend lies at the boundary between the west trending Transverse Ranges, dominated by north-south shortening, and the northwest trending transpressional Coast Ranges. Its location and extent make it an integral part of tectonic reconstructions because the fault trend provides the link between these two contrasting structural domains of the San Andreas plate boundary. However, recent geologic reconstructions have not been able to fully reconcile block motions with the previously reported kinematics along the fault [e.g., *Powell*, 1993; *Ingersoll and Rumelhart*, 1999], which suggests that a reevaluation of the Big Pine fault may be in order.

[3] The fault has been considered a major tectonic feature in southern California since it was first described by *Nelson* [1925] and has been attributed to various tectonic scenarios. *Hill and Dibblee* [1953] believed the fault to be a conjugate shear of the San Andreas fault and partially responsible for the Big Bend. The fault has also been postulated to be the northern boundary of the western Transverse Ranges rotational domain [e.g., *Whidden*, 1994; *Dickinson*, 1996], which has experienced approximately 90° of clockwise vertical axis rotation since 18 Ma [e.g., *Luyendyk et al.*, 1985; *Hornafius et al.*, 1986]. Other designations include the current southern limit of the anomalous Salinian terrane [*Ross*, 1984] and a Quaternary feature accommodating "tectonic escape" in the Big Bend of the San Andreas fault [*Keller et al.*, 1997]. Despite the importance that this fault zone holds for both regional and general tectonic problems, relatively few detailed studies have been conducted along the fault itself.

[4] In this paper, we present the results of recent geologic investigations and detailed mapping that provide new geologic constraints for the structural framework and kinematics of this fault trend. Our data conflict with the hypothesis of a single, continuous Big Pine fault exhibiting left-lateral strike-slip displacement [*Hill and Dibblee*, 1953] and call for a reevaluation of proposed offset features. We propose that the Big Pine fault is actually an alignment of three separate structures that have experienced primarily dip-slip displacement. This revision holds significant implications for regional models of southern California tectonics as well as general models of vertical axis rotation and the evolution of strike-slip plate boundaries. Our kinematic description of the structures that comprise the Big Pine fault trend provides new data required to develop and test these tectonic models.

2. Geologic Setting and Previous Work

[5] Mesozoic though early Tertiary rocks presently exposed along the Big Pine fault trend were deposited during subduction along the western edge of North America. A thick sequence of Jurassic through Eocene forearc sedimen-

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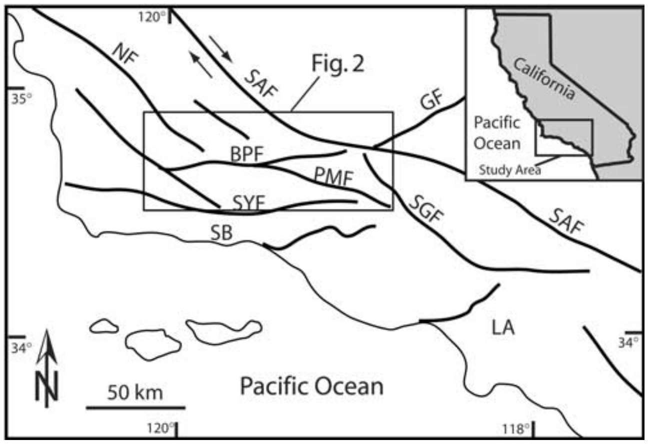


Figure 1. Simplified fault map of the western Transverse Ranges with the cities of Santa Barbara (SB) and Los Angeles (LA) for reference; BPF, Big Pine fault; GF, Garlock fault; NF, Nacimiento fault; PMF, Pine Mountain fault; SAF, San Andreas fault; SGF, San Gabriel fault; SYF, Santa Ynez fault.

tary rocks overlies continental arc basement rocks, exposed along the eastern part of the fault trend, and an accretionary wedge complex (Franciscan Formation) in the west [*Dibblee*, 1982] (Figure 2). The juncture of these two basement terranes is concealed beneath the sedimentary sequence, so its exact nature and location in the area are unknown. The cessation of subduction and development of the proto-San Andreas transform boundary in early Miocene time [*Atwater*, 1989] resulted in the deposition of a variety of Miocene sedimentary and volcanic rocks in transtension basins. Terrestrial sedimentary rocks were deposited during Pliocene and Pleistocene time and are mainly present along the eastern part of the fault trend. Structures in the area are mainly west trending to northwest trending reverse faults and folds, except for the San Andreas fault, which exhibits right-lateral strike-slip displacement.

[6] The Big Pine fault was originally described as a north dipping reverse fault by *Nelson* [1925], who mapped the fault along the south side of Big Pine Mountain. *Hill and Dibblee* [1953] interpreted the fault to extend 60 km east from Big Pine Mountain to the San Andreas fault zone, as it is currently depicted on geologic maps of California [e.g., *Jennings et al.*, 1977]. This designation, along with *Hill and Dibblee*'s [1953] interpretation of approximately 16 km of left-lateral strike-slip displacement along the fault, has been widely accepted and incorporated into numerous models of southern California tectonics over the past 50 years. Because of the lack of detailed studies on the Big Pine fault itself since the 1960s, these early interpretations have gone untested until now.

3. Structural Framework of the Big Pine Fault Trend

3.1. Western Big Pine Fault

[7] The western Big Pine fault (Figure 2) is a curvilinear, west striking fault segment that stretches 40 km through a remote, mountainous area of the Los Padres National

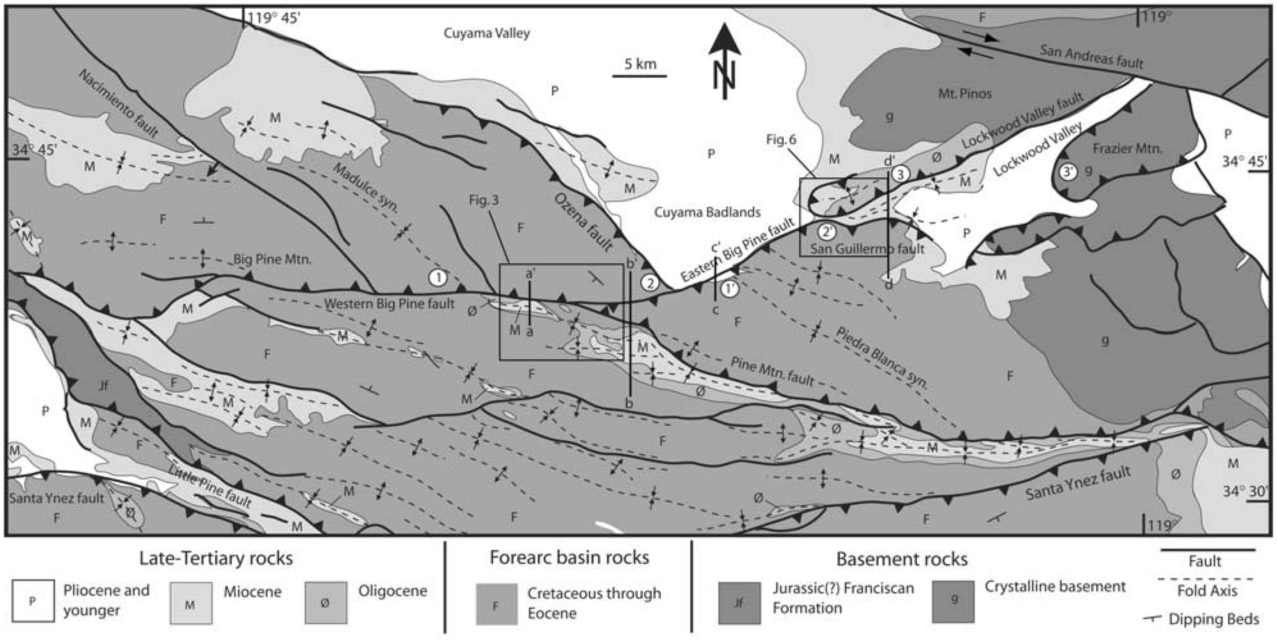


Figure 2. Geologic map of the northwestern Transverse Ranges showing major faults and folds. Circled numbers denote locations of previously hypothesized offsets (see text). Locations of cross sections and detailed maps presented in this paper are also shown. Geology is compiled from *Jennings et al.* [1977], *Dibblee* [1982], *Minor* [1999], *Kellogg* [1999], and *Onderdonk* [2003].

Forest. The fault dips north, typically between 40° and 60°, and exhibits reverse displacement. Late Cretaceous through Eocene rocks are exposed in the 2000 m high peaks of the hanging wall block along the north side of the fault. These rocks are deformed by primarily northwest striking structures, including the Nacimiento fault and the Madulce syncline, that are clearly truncated by the western Big Pine fault. In the footwall block, Late Cretaceous through Miocene rocks are folded into a series of tight, locally overturned, synclines whose axial planes parallel the fault (Figures 2 and 3). Folds that trend oblique to the fault in the footwall are more intensely folded and overturned as they approach the fault (Figure 4). The fault is delineated by a zone of intensely deformed clay gouge ranging from 1 to 5 m thick. This inner fault zone is surrounded by a gradational damage zone that includes breccias, gouge, phacoids of wall rocks, and s and z folds in wall rock strata. Kinematic indicators such as drag folding (at both map and outcrop scale) and rare slickenlines indicate primarily dip-slip displacement (Figures 3 and 5).

[8] Recent 1:12,000 geologic mapping indicates that the western Big Pine fault is continuous with the Pine Mountain fault to the east (Figure 3) [*Onderdonk*, 2003]). The Pine Mountain fault is also a north dipping thrust fault that places Eocene sedimentary rocks in the hanging wall block against tight, overturned synclines of Eocene through Miocene rocks in the footwall block [e.g., *Vedder et al.*, 1973]. It displays the same structural geometry, kinematics, geologic contrasts across the fault, geomorphic expression, and crosscutting relationships as the western Big Pine fault, and a continuous fault zone connects the two structures. The Pine Mountain fault extends 60 km eastward where it dies out near the San Gabriel fault (Figure 1). The eastern Big Pine fault is truncated by the western Big Pine–Pine Mountain fault and lies in the hanging wall of this major structure (Figure 5).

[9] A precise determination of displacement on the western Big Pine–Pine Mountain fault is not possible because of the discontinuity in structural grain and stratigraphy across the fault. Stratigraphic contrasts across the fault include thickness changes of approximately 1000 m in the Eocene formations and large lithologic differences in Oligocene through Pliocene rocks (see *Onderdonk* [2003] for a complete description). These contrasts make it impossible to confidently correlate stratigraphic horizons but suggest that a large amount of dip-slip displacement has occurred along this structure (as hypothesized by previous investigators [e.g., *Powell*, 1993; *Vedder and Stanley*, 2001]). A large amount of displacement is also implied by the abrupt changes of approximately 30° to 45° in paleomagnetic declinations across the fault [*Onderdonk*, 2005]. Timing of movement along the fault can only be constrained as post-Miocene on the basis of offset geologic units. The high topography in the hanging wall and geomorphic features such as linear mountain fronts and stream valleys suggest Quaternary movement; however, there is no evidence of active faulting.

3.2. Eastern Big Pine Fault

[10] The eastern Big Pine fault (as defined by *Kellogg and Minor* [2005]) is a south dipping reverse fault that extends eastward from the Pine Mountain fault and bounds the southern edge of the Cuyama Badlands (Figure 2). The fault typically dips about 45° south and places Eocene sedimentary rocks in the hanging wall block over Miocene through Pliocene rocks in the footwall block [*Minor*, 2004]. A major syncline that trends oblique to the fault in the hanging wall plunges to the northwest as it approaches the fault, suggesting drag folding associated with reverse displacement. The footwall Pliocene formations are commonly folded into synclines against the fault. Kinematic indicators, such as drag folding and fault straie observed along the fault, suggest minor amounts of both right-lateral and left-lateral displacement in addition to the dominant reverse sense (Figure 6) [*Minor*, 1999, 2004].

[11] Detailed mapping (Figure 6) shows that the eastern Big Pine fault is continuous to the east with the San Guillermo fault [*Minor*, 1999]. The San Guillermo fault is also a south dipping thrust fault that places Eocene sandstone and shale over Miocene and Pliocene rocks (Figure 7). Adjacent to the fault in the footwall block, the Miocene and Pliocene rocks are folded into an overturned syncline, which parallels the curvilinear trace of the fault and has an axial surface that dips to the south. Drag folding indicates reverse displacement, and kinematic indicators along this section of the fault show predominantly reverse displacement with a subordinate amount (20–30%) of strike-slip motion (Figures 6 and 7).

[12] A quantitative determination of dip-slip displacement on the eastern Big Pine–San Guillermo fault is not possible because of incomplete exposure of the older units in the footwall block and the erosion of younger units in the uplifted hanging wall block. However, cross sections (Figure 7) imply at least 3 km of reverse separation in the western Lockwood Valley area and at least 4 km of reverse separation along the southern edge of the Cuyama Badlands. Unconformities in the Miocene and younger strata suggest that displacement began in late Miocene to early Pliocene time and continued through Pleistocene time [*Minor*, 1999, 2004]. Scarps in terrace deposits of the Cuyama River [*Minor*, 2004] suggest that Quaternary vertical displacement has occurred along the fault.

3.3. Lockwood Valley Fault

[13] The Lockwood Valley fault (Figures 2 and 4) is a northeast striking fault zone that extends 20 km from the San Andreas fault to the eastern Cuyama Badlands [*Kellogg*

Figure 3. Detailed geologic map of the western Big Pine–Pine Mountain fault where it truncates the eastern Big Pine fault. Kinematic data are plotted in the lower hemisphere with arrows indicating movement of the hanging wall. See Figure 2 for location.

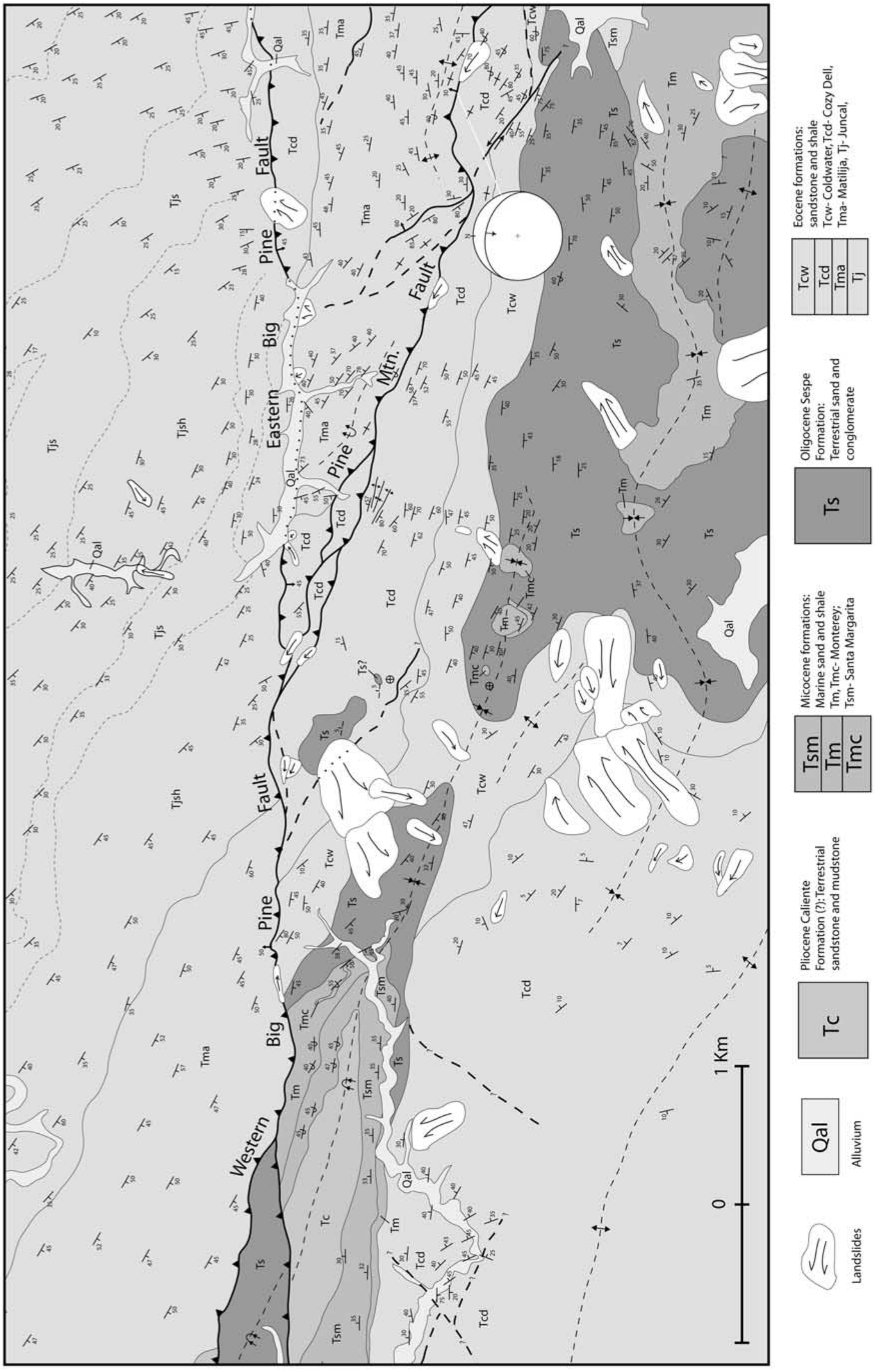

Western Big Pine Fault
Eastern Big Pine Fault
Pine Mtn. Fault
Tjs
Tjsh
Tma
Tcd
Tcw
Ts
Tm
Tmc
Tsm
Tc
Qal
Ts?
0
1 Km
Landslides
Qal
Alluvium
Tc
Pliocene Caliente Formation (?): Terrestrial sandstone and mudstone
Tsm
Tm
Tmc
Micocene formations: Marine sand and shale Tm, Tmc- Monterey; Tsm- Santa Margarita
Ts
Oligocene Sespe Formation: Terrestrial sand and conglomerate
Tcw
Tcd
Tma
Tj
Eocene formations: sandstone and shale Tcw- Coldwater, Tcd- Cozy Dell, Tma- Matilija, Tj- Juncal,

Figure 3

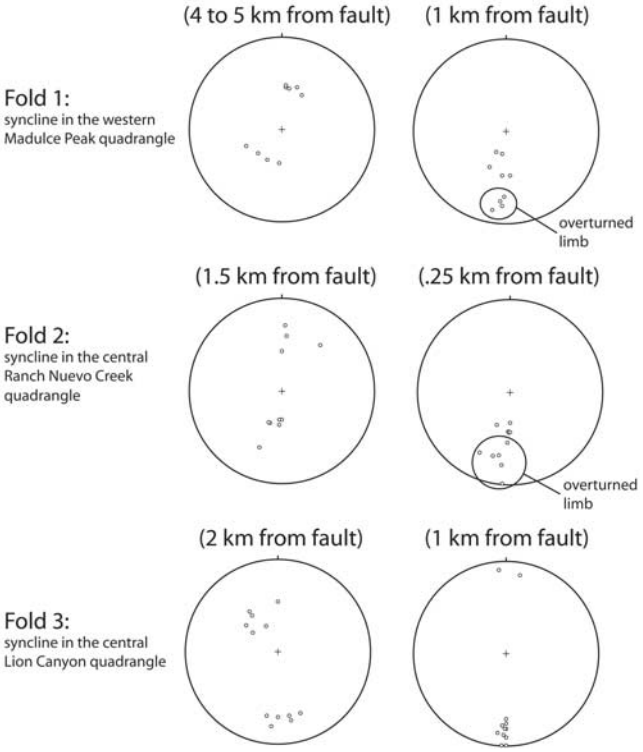


Figure 4. Stereograms of poles to fold limb measurements on three separate folds from locations away from and close to the western Big Pine–Pine Mountain fault.

and Minor, 2005]. The fault juxtaposes late Oligocene sedimentary and volcanic rocks on the northwest against younger Miocene sedimentary rocks on the southeast. Along most of its length the fault exhibits a steep dip, and kinematic indicators indicate primarily left slip (Figure 6). Near its western end, however, the fault becomes an east striking thrust fault whose trace curves northward along the eastern edge of the Cuyama Badlands. This north to east dipping thrust fault bounds the western limit of the late Oligocene Plush Ranch Formation and exhibits mainly reverse slip striae. In Lockwood Valley, Miocene and Pliocene sedimentary rocks are deformed by folds and small-displacement reverse faults that trend and strike parallel to the fault. This mode of deformation and the large coeval thrust faults along the south side of Lockwood Valley suggest that the primary mode of Plio-Pleistocene deformation in the area was north-south shortening [*Kellogg and Minor*, 2005].

[14] Several authors have proposed that a late Oligocene normal fault was present along or near the trace of the Lockwood Valley fault [e.g., *Bohannon*, 1976; *Cole and Stanley*, 1995]. Depositional relationships of the Plush Ranch Formation along the northwest side of the fault suggest that these rocks were deposited in a basin in which subsidence was controlled by a normal fault along the southeast edge of the basin. Coarse fan delta breccia, conglomerate, and sandstone dominate the southeastern part of the exposed section and were likely deposited along an active normal fault scarp that was roughly coincident with the Lockwood Valley fault zone [*Cole and Stanley*, 1995]. To the north, the Plush Ranch Formation changes lithology to lactustrine deposits with interbedded basalt flows. This northern transition in depositional facies is obliquely truncated by the present-day Lockwood Valley fault, suggesting that the older basin-bounding normal fault has been partially hidden by more recent deformation. These kinematic and geologic relations suggest that the Plush Ranch Formation was deposited along a normal fault, which was later partially reactivated or truncated by the left reverse slip Lockwood Valley fault in Pliocene time. The fault is currently marked by linear mountain fronts, uplifted on the north side, suggesting Quaternary displacement. However, Holocene and late Pleistocene alluvial deposits overlap the fault and do not appear to be offset.

4. Discussion

4.1. Reevaluation of Proposed Left-Lateral Displacement

[15] The interpretation of a single continuous Big Pine fault exhibiting left-lateral strike-slip offset [e.g., *Hill and Dibblee*, 1953] has been incorporated into numerous models and reconstructions of southern California tectonics [e.g., *Powell*, 1993; *Dickinson*, 1996]. Our observations indicate that the Big Pine fault is actually an alignment of three separate faults and therefore requires a reevaluation of the kinematics and proposed offset along the fault trend. Here we summarize reported offset features and evaluate their validity in light of recent field observations and detailed mapping.

[16] The Big Pine fault was interpreted to exhibit left-lateral offset on the basis of the followings arguments: *Hill and Dibblee* [1953] found (1) that oblique slip striations were observed in the fault zone, but the reversals in dip and throw along the fault led them to interpret primarily strike-slip displacement, (2) apparent left-lateral deflection of drainages across the fault, (3) east-west trending drag folding adjacent to the fault, (4) possible left-lateral displacement of the Piedra Blanca syncline and San Guillermo fault on the south from the Madulce syncline and Ozena fault on the north (see locations 1 and 2, Figure 2), and (5) the occurrence of Miocene sedimentary rocks farther west on the north side of the fault in the Cuyama Badlands than on the south side where they are exposed in Lockwood Valley; (6) *Poyner* [1960] noted that isolated outcrops of a felsic dike located along the west side of the Ozena fault appear to be offset 14 km to the east where similar outcrops are found on the south side of the Big Pine fault in the Wagon Creek area; and (7) *Crowell* [1962] and *Carman* [1964] also suggested left-lateral displacement on the eastern Big Pine fault on the basis of clasts in the Oligocene-Miocene Plush Ranch Formation (location 3, Figure 2), and they pointed out that distinctive augen gneiss clasts in the Plush Ranch Formation north of the fault most likely came from the closest exposed source area 15 km to the east on the south side of the fault. Proposed arguments 1–7 for left-lateral displacement are addressed as follows.

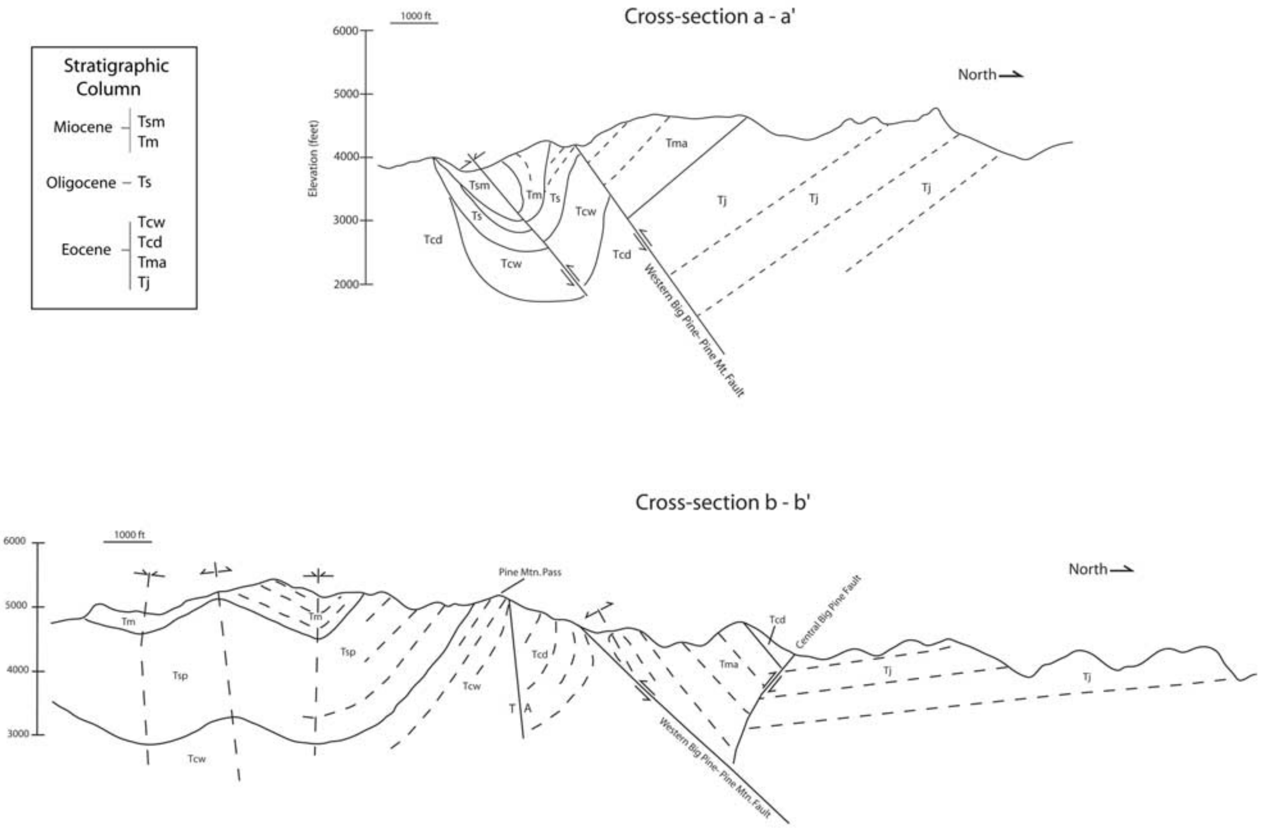


Figure 5. Cross sections a-a′ and b-b′ across the western Big Pine–Pine Mountain fault (see Figure 2 for locations). Units are Santa Margarita Formation (Tsm), Monterey Formation (Tm), Sespe Formation (Ts), Coldwater Formation (Tcw), Cozy Dell Formation (Tcd), Matilija Formation (Tma), and Juncal Formation (Tj).

[17] 1. The apparent reversals in dip and throw reported by *Hill and Dibblee* [1953] stem from their interpretation of a single continuous Big Pine fault. Our interpretation of three separate faults explain the apparent dip reversals, which occur at two locations: (1) where the north dipping western Big Pine–Pine Mountain fault intersects the south dipping eastern Big Pine fault (Figure 3) and (2) where the south dipping eastern Big Pine fault abuts the western end of the northwest dipping Lockwood Valley fault (Figure 6). Changes in the apparent throw occur at these fault intersections and where northwest striking structures, such as the Ozena fault, are truncated by the faults.

[18] 2. Geomorphic observations during the course of this study indicate that the reported deflection of stream channels cannot be used to interpret left-lateral offset along the Big Pine fault trend. The sense of deflection across the fault trend is not consistent, most drainages show no offset, Quaternary deposits in the deflected drainages show no evidence of offset, and many "deflected" streams in the area do not correspond to actual fault traces (Figure 8). The few abrupt changes in stream direction along the fault zone appear to be the result of lithologic changes across and along the fault zone.

[19] 3. East-west striking beds are present along much of the Big Pine fault trend, as mentioned by *Hill and Dibblee* [1953]. However, these attitudes are consistent with drag folding due to reverse displacement on the faults rather than left-lateral strike slip. Bedding in the footwall blocks is commonly folded up against the faults and overturned in many places. The faults are locally paralleled by anticlines in the hanging walls and overturned synclines in the footwall blocks (Figures 2, 3, 5, 6, and 7). Reverse sense drag folding is also apparent in the hanging wall of the eastern Big Pine fault where the strike of tilted Eocene sedimentary beds is deflected parallel to the fault trace as the northwest trending Piedra Blanca syncline plunges into the fault trace.

[20] 4. The hypothesis that the San Guillermo fault is the left-lateral offset of the Ozena fault (locations 2 and 2′, Figure 2) is negated by the detailed mapping of *Minor* [1999], which shows that the San Guillermo fault is continuous with the eastern Big Pine fault. The apparent offset of the Madulce syncline from the Piedra Blanca syncline (locations 1 and 1′, Figure 2), both of which fold Eocene sedimentary rocks, is based on the observations that the synclines and the rocks they fold look strikingly similar. However, these synclines are not unique. A large number of

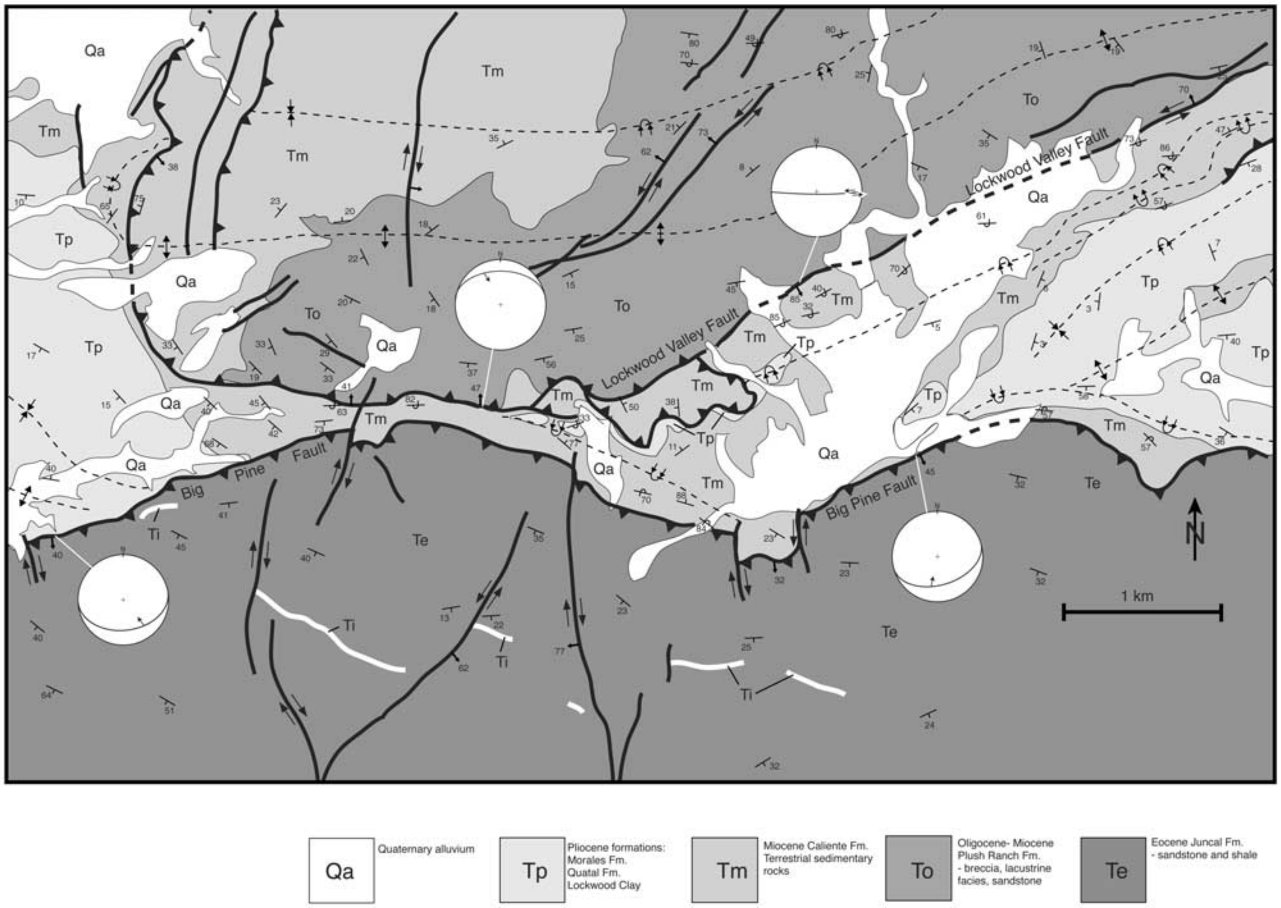


Figure 6. Detailed geologic map of the eastern Big Pine–San Guillermo fault and the western end of the Lockwood Valley fault. Kinematic data are plotted in the lower hemisphere with arrows indicating movement of the hanging wall. See Figure 2 for location.

folds in Eocene and older rocks throughout the area have the same orientation. In addition, faults and smaller folds that parallel the synclines do not match up, making it difficult to infer offset based on structural features (Figure 9). Middle Miocene sedimentary rocks lie unconformably on the Madulce syncline to the northwest [*Vedder*, 1968], constraining the time of folding between late Eocene and early Miocene. If the synclines are correlative, it is possible that they were offset by an earlier fault that has since been reactivated or overridden by later reverse faulting.

[21] 5. The present distribution of Miocene terrestrial deposits in the Cuyama Badlands and Lockwood Valley does not necessitate left-lateral displacement. These rocks are not confined to the two valleys but instead form a belt of nearly continuous exposure along the entire footwall block of the eastern Big Pine–San Guillermo fault. They are also present in the hanging wall of the San Guillermo fault and in the uplifted area of Mount Pinos north of the Lockwood Valley fault. If the previously inferred left-lateral displacement of 16 km is removed, these units do not match up. The distribution of these rocks and the orientations of the folds that deform them are better explained by reverse displacement on the faults.

[22] 6. The Oligocene felsic dikes found on the north and south sides of the eastern Big Pine (locations 2 and 2′, Figure 2) consist of a few isolated outcrops with strikes that vary between west and northwest. These outcrops roughly parallel the faults and local bedding orientation and do not extend more than about 1 km away from the eastern Big Pin–San Guillermo fault, suggesting that they may be related to the fault. It is not known whether the dikes are also present beneath the younger Pliocene and Quaternary rocks along the fault in the southern Cuyama Badlands between these two locations. However, because these two locations are the only known outcrops of felsic dikes in the immediate area, they appear to support the strike-slip interpretation.

[23] 7. Although correlation of augen gneiss clasts in the Plush Ranch Formation to a source terrain 13 km to the east (locations 3 and 3′, Figure 2) is consistent with an interpretation of left-lateral displacement, it does not necessitate strike-slip movement. The gneissic source rock may also underlie Miocene rocks located directly across the fault to the south (Figures 2 and 7). Additional subsurface or

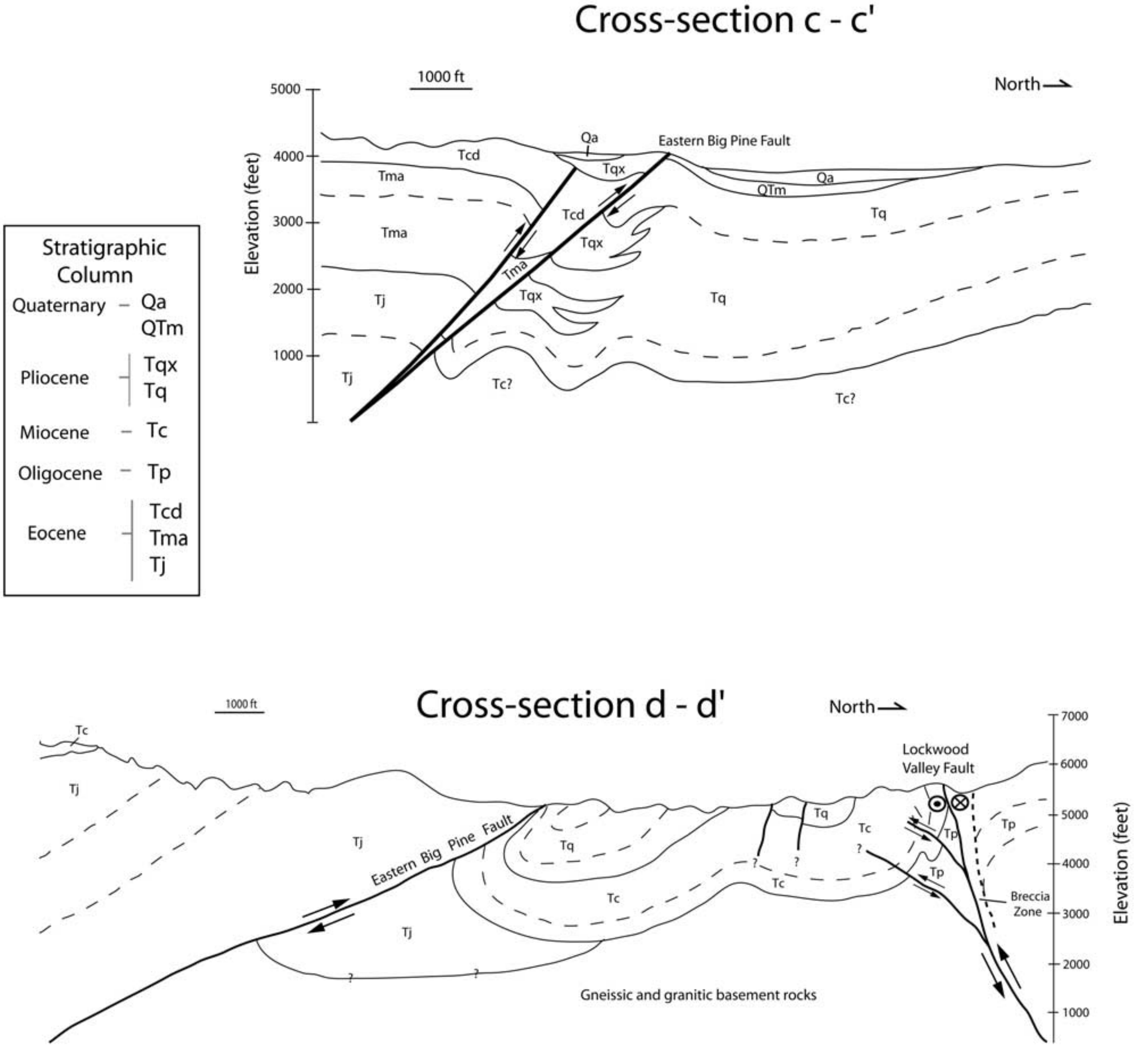


Figure 7. Cross sections c-c′ and d-d′ across the eastern Big Pine–San Guillermo fault and the Lockwood Valley fault (see Figure 2 for locations). Units are Quaternary alluvium (Qa), Morales Formation (QTm), Quatal Formation (Tq), Quatal Formation breccia (Tqx), Caliente Formation (Tc), Plush Ranch Formation (Tp), Cozy Dell Formation (Tcd), Matilija Formation (Tma), and Juncal Formation (Tj).

geophysical data are needed to test this. When the previously postulated strike-slip displacement is removed, a clockwise rotation of the southern side of the Big Pine fault is needed to prevent unreasonable overlaps due to the curvature of the fault trend. This leaves the source terrain no closer to the Plush Ranch gneiss clasts than without strike-slip restoration (Figure 9).

[24] All of the geologic features along the Big Pine fault trend previously proposed to indicate left-lateral offsets are either inconclusive or can be better explained by the structural model put forth here. In addition, reconstruction of the postulated offsets addressed above creates discrepancies in the individual ties as well as the regional tectonics. For example, matching of the Madulce and Piedra Blanca synclines results in a significant mismatch in the location and kinematics of the other faults and folds (Figure 9). Reconstruction of strike-slip motion also requires relative rotation between the two sides of the fault trend to accommodate the bend in the fault trend and to prevent unreasonable overlaps. This rotation is in an opposite sense to that recorded by paleomagnetic data in the area [e.g., *Luyendyk et al.*,

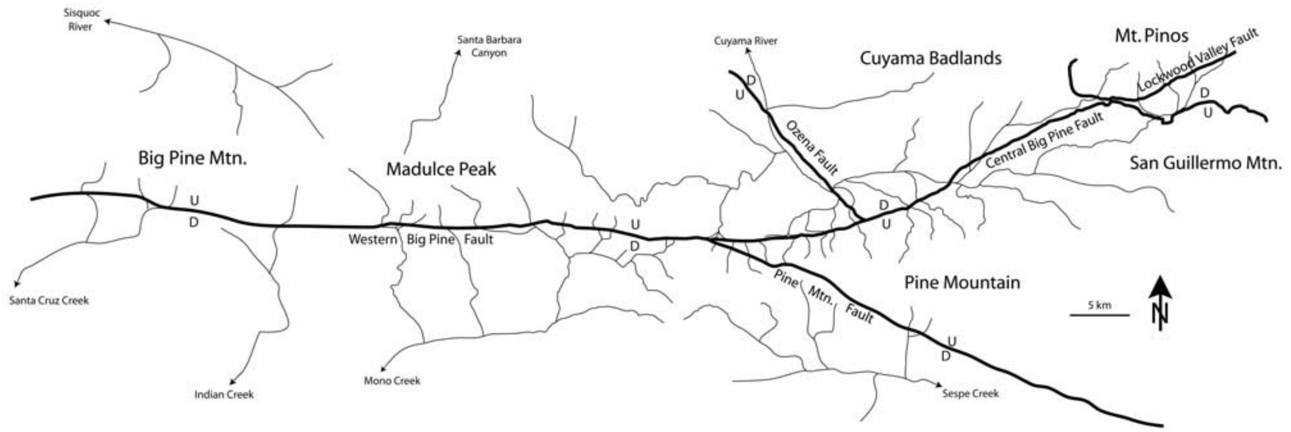


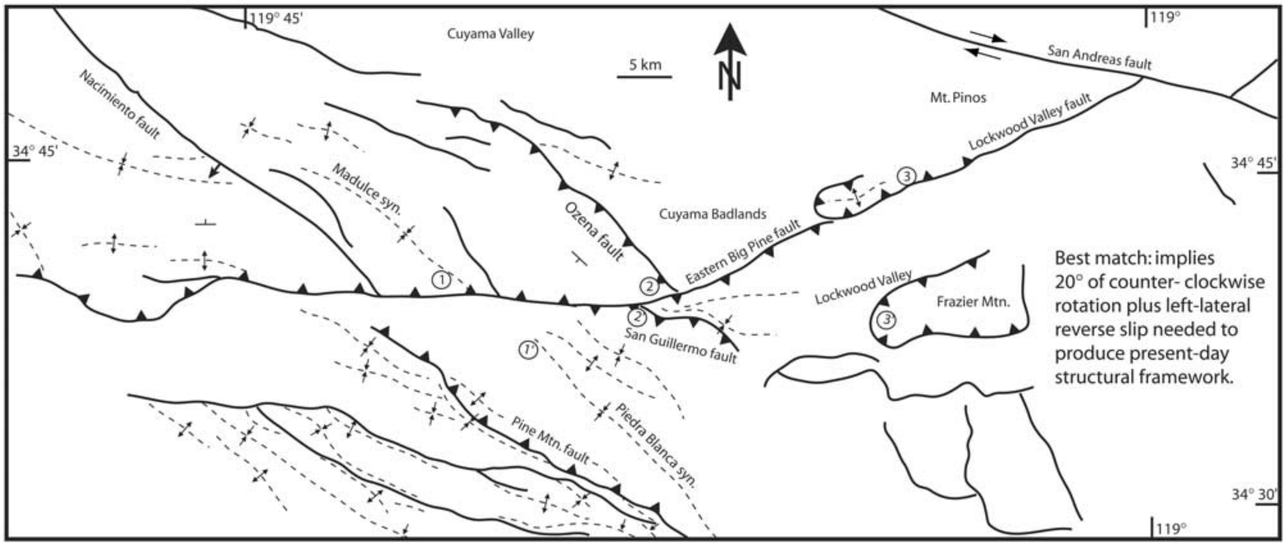
Figure 8. Major streams along the Big Pine fault trend, showing no consistent deflection across the fault.

1985; *Whidden*, 1994; *Onderdonk*, 2005] and is therefore regarded as unjustified.

4.2. Significance for Regional Tectonics

[25] The individual structures along the Big Pine fault trend played a key role in some of the major events in the tectonic evolution of southern California. One such event is the clockwise vertical axis rotation of the western Transverse Ranges terrane by about 90° since 18 Ma [e.g., *Luyendyk et al.*, 1985]. Contrasts in paleomagnetic declinations, Cenozoic stratigraphy, and structural style suggest that the western Big Pine–Pine Mountain fault defines the northern boundary of the rotated western Transverse Ranges terrane [*Onderdonk*, 2003, 2005]. Reverse displacement along this fault may have accommodated as much as 45° of rotation between the western Transverse Ranges and the Coast Ranges to the north. Our revision of the local tectonic framework and the recognition of significant reverse displacement along this structure, instead of strike-slip displacement, result in considerable changes to kinematic models of vertical axis rotation.

[26] Structures that make up the eastern Big Pine fault trend may also have been involved in transferring displacement across a restraining step over in the early San Andreas system. *Yeats et al.* [1989] suggested that an early Miocene precursor of the San Andreas fault in the southern Coast Ranges is represented by the Chimineas-Russell-Ozena fault, which is truncated at its southern end by the Big Pine fault trend. Displacement across the eastern Big Pine fault, Lockwood Valley fault, and other nearby thrust faults during this time may have transferred plate boundary slip



Best match: implies 20° of counter- clockwise rotation plus left-lateral reverse slip needed to produce present-day structural framework.

Figure 9. A best fit reconstruction showing problems with previously postulated left slip piercing points. Note the mismatch of structures across the Big Pine fault trend and the unjustified rotation required for reconstruction. Additional spatial problems related to the fault bend and overlaps at the western end of the fault trend are not depicted.

to the east where it continued into the Los Angeles basin along the Canton–San Gabriel fault [*Yeats and Stitt*, 2003].

[27] Our redefinition of the Big Pine fault trend as three separate structures solves several problems with regional tectonic reconstructions and kinematic models of southern California. In his extensive reconstruction of the San Andreas fault system, *Powell* [1993] had problems fitting restored left slip on the Big Pine fault and noted that the reconstruction necessitated shortening across this fault trend instead of strike slip. Other palinspastic reconstructions [e.g., *Ingersoll and Rumelhart*, 1999; *Nicholson et al.*, 1994] also require significant amounts of shortening across the structures that make up the Big Pine fault trend that were not previously justified. *Dickinson* [1996] presented a model for vertical axis rotation of the western Transverse Ranges that depicted the Big Pine fault as a single structure that formed the northern boundary of the rotated domain. This model assumed left slip along the fault, which required the formation of triangular basins at the intersections of the Big Pine fault with northwest striking faults of the southern Coast Ranges. These basins do not exist, and the space problems that require them are eliminated by the observed reverse faulting and revised structural framework presented in this paper. This new interpretation also provides a better fit to the overall deformation pattern of the Transverse Ranges, which are dominated by Pliocene and younger contractional features and uplift. Reverse displacement along the structures that make up the Big Pine fault trend has accommodated shortening in the Transverse Ranges due to convergence between the North American and Pacific plates in the Big Bend region of the San Andreas fault.

[28] Seismic risk estimates for the northwest Transverse Ranges need to be reevaluated in light of the new data. The lack of a major left-lateral Big Pine fault would decrease the maximum expected earthquake magnitude in Lockwood Valley and the southern Cuyama Valley. In contrast, a continuous western Big Pine–Pine Mountain fault would make this fault one of the largest reverse faults in southern California, which may pose a greater seismic risk than previously supposed. However, this fault does not show strong evidence of Holocene offset, and none of the structures that comprise the Big Pine fault trend currently exhibits seismic activity. Further neotectonic research along these faults is needed to fully evaluate the potential seismic hazard in the area.

5. Conclusion

[29] Detailed mapping along the Big Pine fault trend suggests that this feature is an alignment of three separate structures: a north dipping western Big Pine–Pine Mountain fault, a south dipping eastern Big Pine fault, and a steeply northwest dipping Lockwood Valley fault. These structures all experienced reverse separation in Pliocene and later time but exhibit different kinematic histories. This new interpretation requires changes to regional kinematic models, tectonic reconstructions, and seismic risk estimates for southern California.

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References

Atwater, T. (1989), Plate tectonic history of the northeast Pacific and western North America, in *The Geology of North America*, vol. N, *The Eastern Pacific Ocean and Hawaii*, edited by E. L. Winterer et al., pp. 21–71, Geol. Soc. of Am., Boulder, Colo.

Bohannon, G. R. (1976), Mid-Tertiary nonmarine rocks along the San Andreas fault in southern California, Ph.D. thesis, Univ. of Calif., Santa Barbara.

Carman, M. F., Jr. (1964), Geology of the Lockwood Valley area, Kern and Ventura counties, California, *Spec. Rep. Calif. Div. Mines Geol.*, *118*, 62 pp.

Cole, R. B., and R. G. Stanley (1995), Middle Tertiary extension recorded by lacustrine fan-delta deposits, Plush Ranch Basin, western Transverse Ranges, California, *J. Sediment. Res., Sect. B*, *65*(4), 455–468.

Crowell, J. C. (1962), Displacement along the San Andreas fault, California, *Spec. Pap. Geol. Soc. Am.*, *71*, 61 pp.

Dibblee, T., Jr. (1982), Regional geology of the Transverse Ranges Province of southern California, in *Geology and Mineral Wealth of the California Transverse Ranges*, edited by D. L. Fife and J. A. Minch, pp. 7–26, S. Coast Geol. Soc., Santa Ana, Calif.

Dickinson, W. R. (1996), Kinematics of transrotational tectonism in the California Transverse Ranges and its contribution to cumulative slip along the San Andreas transform fault system, *Spec. Pap. Geol. Soc. Am.*, *305*, 46 pp.

Hill, M. L., and T. W. Dibblee (1953), San Andreas, Garlock, and Big Pine faults, California, *Geol. Soc. Am. Bull.*, *64*, 443–458.

Hornafius, J., B. Luyendyk, R. Terres, and M. Kamerling (1986), Timing and extent of Neogene tectonic rotation in the western Transverse Ranges, California, *Geol. Soc. Am. Bull.*, *97*, 1476–1487.

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

Jennings, C. H., R. G. Strand, and T. H. Rogers (1977), Geologic map of California, 1 sheet, scale 1:75,0000, Calif. Dep. of Conserv., Sacramento.

Keller, E. A., K. Mueller, and L. D. Gurrola (1997), "Big Bend" of the San Andreas fault: Hypothesis of tectonic extrusion, *Geol. Soc. Am. Abstr. Programs*, *29*(6), 235.

Kellogg, K. S. (1999), Geologic map of the Lockwood Valley quadrangle, Ventura County, California, *U.S. Geol. Surv. Open File Rep., 99–130*, 1 sheet scale 1:24,000.

Kellogg, K. S., and S. A. Minor (2005), Pliocene transpressional modification of depositional basins by convergent thrusting adjacent to the "Big Bend" of the San Andreas fault: An example from Lockwood Valley, southern California, *Tectonics*, *24*, TC1004, doi:10.1029/2003TC001610.

Luyendyk, B. P., M. J. Kamerling, R. R. Terres, and J. S. Hornafius (1985), Simple shear of southern California during Neogene time suggested by paleomagnetic declinations, *J. Geophys. Res.*, *90*, 12,454–12,466.

Minor, S. A. (1999), Preliminary geologic map of the San Guillermo Mountain quadrangle, Ventura County, California, *U.S. Geol. Surv. Open File Rep., 99–032*, 1 sheet, scale 1:24,000.

Minor, S. A. (2004), Geologic map of the Reyes Peak quadrangle, Ventura County, California, *U.S. Geol. Surv. Open File Rep., 2004–1420,* 1 sheet, scale 1:24,000.

Nelson, R. N. (1925), Geology of the hydrographic basin of the Upper Santa Ynez River, *Univ. Calif. Publ. Geol.*, *15*, 327–396.

Nicholson, C., C. Sorlien, T. Atwater, C. Crowell, and B. Luyendyk (1994), Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system, *Geology*, *22*, 491–495.

Onderdonk, N. W. (2003), Geometry and kinematics of structures that accommodated large-magnitude differential vertical-axis rotation of the western Transverse Ranges, southern California, Ph.D. thesis, Univ. of Calif., Santa Barbara.

Onderdonk, N. W. (2005), Structures that accommodated differential vertical axis rotation of the western Transverse Ranges, California, *Tectonics*, *24*, TC4018, doi:10.1029/2004TC001769.

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 *The San Andreas Fault System: Displacement, Palinspastic Reconstruction, and Geologic Evolution*, edited by R. Powell, R. R. Weldon, and J. Matti, *Mem. Geol. Soc. Am.*, *178*, 1 – 106.

Poyner, W.D. (1960), Geology of the San Guillermo area and its regional correlation, Ventura County, California, M.A. thesis, Univ. of Calif., Los Angeles.

Ross, D. C. (1984), Possible correlations of basement rocks across the San Andreas, San Gregorio-Hosgri, and Rinconada-Reliz-King faults, California, *U.S. Geol. Surv. Prof. Pap.*, *1317*, 37 pp.

Vedder, J. G. (1968), Geologic map of Fox Mountain Quadrangle, Santa Barbara County, California, *U.S. Geol. Surv. Misc. Geol. Invest. Map, I–547*, 1 sheet, scale 1:24,000.

Vedder, J. G., and R. G. Stanley (2001), Geologic map and digital database of the San Rafael Mountain 7.5-minute Quadrangle, Santa Barbara County, California, *U.S. Geol. Soc. Open File*, 01 – 290.

Vedder, J. G., T. W. Dibblee, and R. D. Brown (1973), Geologic map of the upper Mono Creek-Pine Mountain area, California, showing rock units and structures offset by the Big Pine fault, *U.S. Geol. Surv. Open File Rep., 71-0309*, 1 sheet, scale 1:48,000.

Whidden, K. J. (1994), Paleogeography of the southern California forearc basin in the Late Cretaceous and early Paleogene: Evidence from paleomagnetism and carbonate facies analysis, Ph.D. thesis, Univ. of South. Calif., Los Angeles.

Yeats, R. S., and L. T. Stitt (2003), Ridge basin and San Gabriel fault in the Castaic Lowland, southern California, *Spec. Pap. Geol. Soc. Am.*, *367*, 131 – 156.

Yeats, R. S., J. A. Calhoun, B. B. Nevins, H. F. Schwing, and H. M. Spitz (1989), The Russell fault: An early strike slip fault of the California Coast Ranges, *AAPG Bull.*, *73*(9), 1089 – 1102.

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