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Structure and mechanics of the San Andreas–San Gregorio fault junction, San Francisco, California

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[1] The right-lateral San Gregorio and San Andreas faults meet west of the Golden Gate near San Francisco. Coincident seismic reflection and refraction profiling across the San Gregorio and San Andreas faults south of their junction shows the crust between them to have formed shallow extensional basins that are dissected by parallel strike-slip faults. We employ a regional finite element model to investigate the long-term consequences of the fault geometry. Over the course of 2–3 m.y. of slip on the San Andreas-San Gregorio fault system, elongated extensional basins are predicted to form between the two faults. An additional consequence of the fault geometry is that the San Andreas fault is expected to have migrated eastward relative to the San Gregorio fault. We thus propose a model of eastward stepping right-lateral fault formation to explain the observed multiple fault strands and depositional basins. The current manifestation of this process might be the observed transfer of slip from the San Andreas fault east to the Golden Gate fault.

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1. Introduction

[2] Four major strike-slip fault zones cross through the San Francisco Bay region, which accommodate most of the ~39 mm/yr of relative plate motion between the Pacific plate and the Sierra Nevada range. This study is concerned with the junction between two of those faults, the San Gregorio and the San Andreas, located west of the Golden Gate adjacent to the city of San Francisco (Figure 1). These right-lateral faults are not parallel, but instead converge, with the San Gregorio making a more northerly trend than the northwest striking San Andreas. Here we focus on the mechanical and structural consequences of this fault junction. The right step between the San Andreas fault and the offshore Golden Gate fault to its east is thought to have been the nucleation site of the 1906 earthquake [e.g., *Geist and Zoback*, 1999], making the structural evolution of this region particularly interesting.

[3] In this paper we use first arrivals observed from large air gun sources on an orthogonal transect across the San Gregorio and San Andreas faults to invert for shallow velocity structure. This velocity profile is then applied for depth migration of a coincident seismic reflection section. The two profiles are overlain, enabling an enhanced interpretation of the shallow basin structures and strike-slip faulting. In addition we develop a kinematic model from 3-D finite element modeling of the San Gregorio-San Andreas junction,

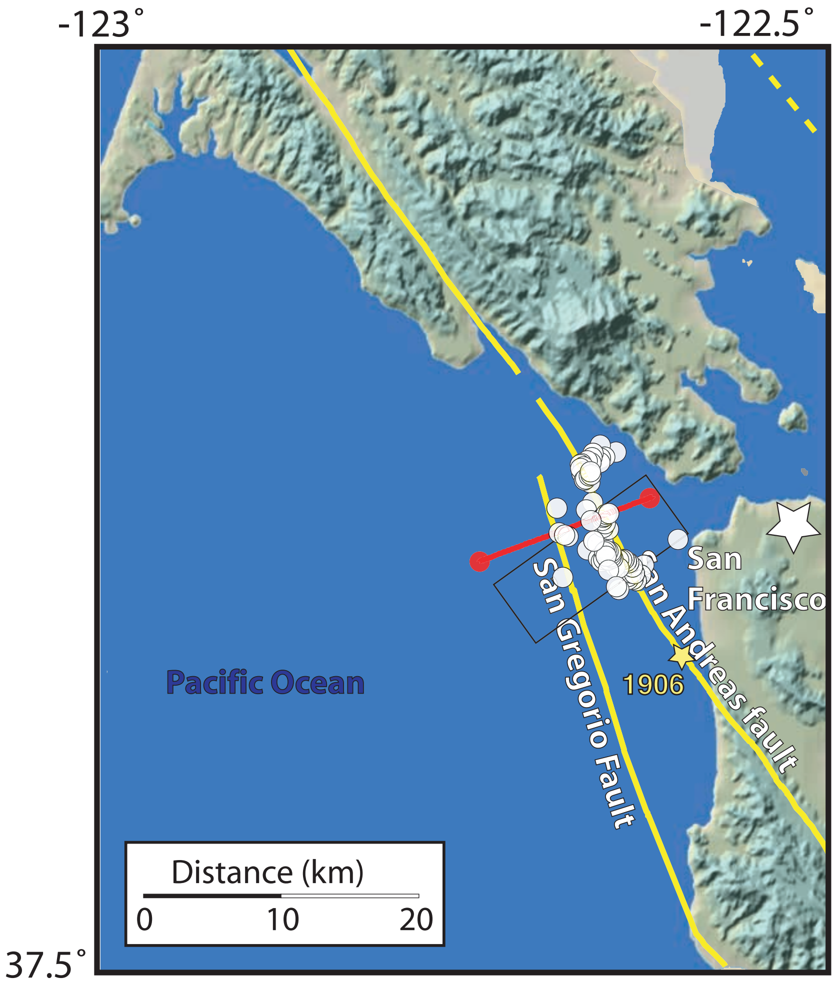

Figure 1. The San Gregorio fault approaches the more northwest trending San Andreas fault in the offshore Golden Gate region. The red line shows the location of a seismic refraction and reflection cross-section model. The white dots are a subset of relocated earthquake epicenters [*Waldhauser and Ellsworth*, 2000] that occurred near the seismic cross section. The black box around the epicenters shows the area of hypocenters collapsed onto the 2-D cross section in Figure 2. The yellow star shows the approximate epicenter of the 1906 earthquake [*Geist and Zoback*, 1999].

which lends insight to the temporal evolution of the fault zone.

2. Seismic Transect

[4] Joint seismic reflection and refraction data were gathered across the San Gregorio and San Andreas faults on the Golden Gate platform adjacent to the city of San Francisco (Figure 1). Reflection data were collected with a multichannel seismic system capable of imaging geologic structures to 1- to 2-km depth with a spatial resolution of 5 to 10 m in relatively shallow water environments [*Childs et al.*, 2000]. Resulting common midpoint data were sixfold to twelvefold, with a 3.125-m common midpoint interval. Data were recorded at a 1-ms sample interval to a 2 s record length. We developed a coincident seismic velocity cross section that was used for poststack migration of the reflection data, which in turn was superimposed on the section to enhance interpretation.

[5] A 2-D tomographic velocity model across the San Gregorio and San Andreas faults was calculated from first arrival times from large air gun sources. Individual floating hydrophones with radio telemetry units were used as receivers, which were anchored at 100- to 200-m intervals adjacent to the ship track lines to record air gun blasts. The air guns were fired at 50-m intervals along the receiver array and to off-end distances of ~20 km. First arrivals are generally of good quality, and because of the ~20-km offsets, these data can be utilized for refraction velocity analysis. We employed a 2-D tomographic inversion of first arrival

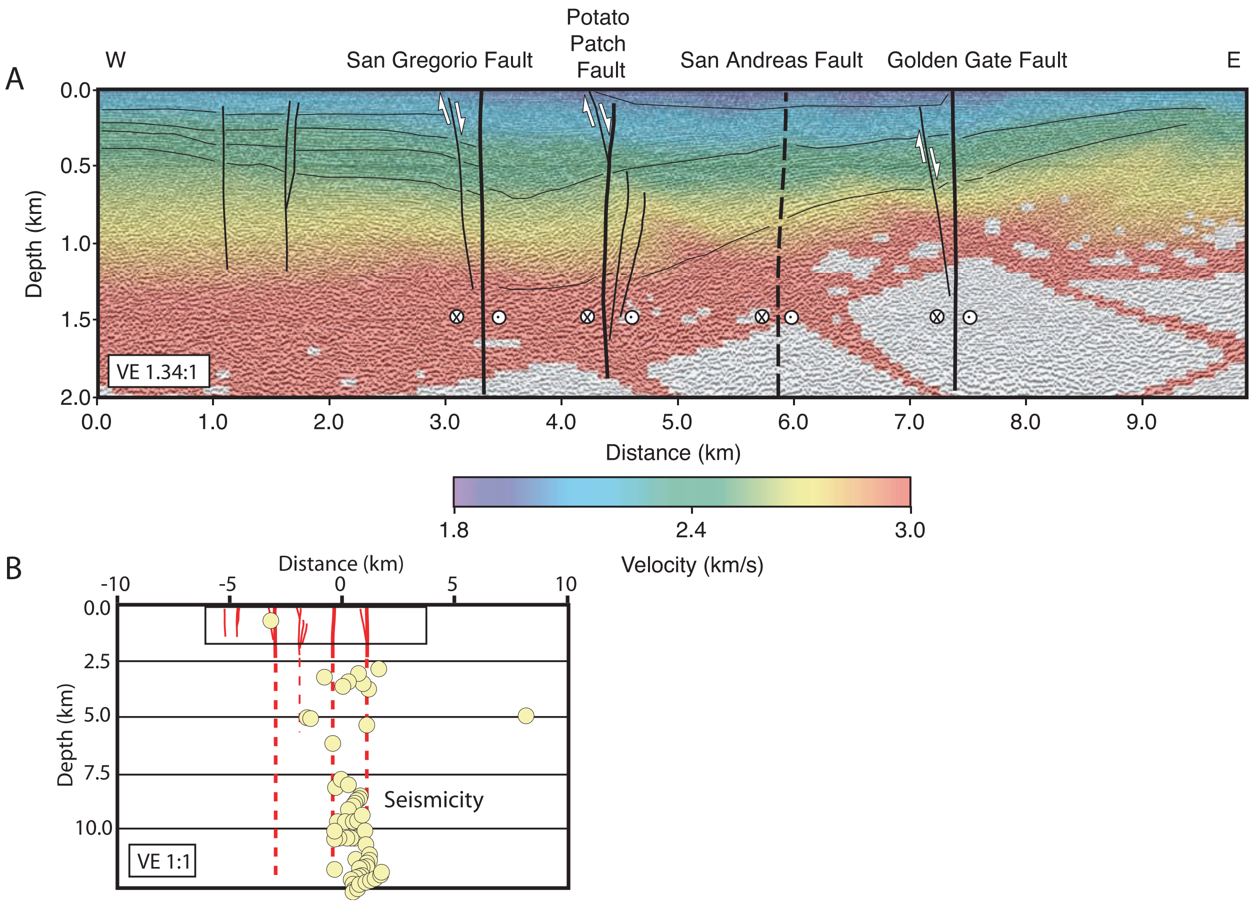

Figure 2. (a) Seismic reflection profile (location shown in Figure 1 and as black rectangle in Figure 2b) across the San Gregorio and San Andreas faults are shown. The common midpoint stack was depth migrated using the seismic velocity profile shown as shaded contours underlying it. The velocity profile was inverted from independently acquired first arrivals recorded at longer offset. Four oblique strike-slip faults are interpreted. The San Andreas fault has the smallest influence on the sedimentary structure, probably because at the latitude of this cross section most slip is transferred east to the Golden Gate fault [e.g., *Jachens et al.*, 2003]. (b) Earthquake hypocenters projected onto the cross section (map view of epicenters shown in Figure 1) are shown.

times [*Parsons et al.*, 1996] that uses a finite difference travel time technique developed by *Vidale* [1990] to perform accurately in the presence of large velocity contrasts. A total of 8640 travel times recorded on 66 receivers were hand picked from receiver gathers, and inverted for velocity structure on 25- × 25-m cells. The RMS travel time misfit was reduced to less than 0.1 s (estimated picking error) after 7 iterations.

[6] Clear evidence of strike-slip faulting can be seen on the resulting cross section (Figure 2). The San Gregorio fault marks the west edge of a ~1- to 2-km deep sedimentary basin. The basin is in turn dissected by at least three more strike-slip faults. All the strike-slip faults either break, or reach very near the surface, suggesting that they are active (or were until very recently) in accommodating relative plate motion. A clear contrast can be seen across the San Gregorio fault (Figure 2) from eastward dipping strata on the west side of the fault to a more synclinal feature to its east. That feature is in turn truncated by the Potato Patch fault [*Bruns et al.*, 2003], which is associated with subsidiary, small-offset normal faults that offset layering within the sedimentary basin, and that suggest active transtensional deformation.

[7] East of the Potato Patch fault, a slight thickening of the most recent sedimentary section is evident in the upper 0.5 km, and very young deposits are inferred near the surface from their lower seismic velocity; this feature was also noted by *Cooper* [1973], *McCulloch* [1989], and *Bruns et al.* [2003], who inferred a Holocene age. The San Andreas fault, which has by far the highest long-term slip rate of all the faults in the system shows little or no effect on sedimentary layering in the

seismic cross section (Figure 2). However, *Jachens et al.* [2003] suggested, on the basis of uncut magnetic anomalies, that San Andreas fault slip is transferred to the Golden Gate fault across a right step south of the seismic cross section. Thus the San Andreas fault may not be active on this cross section. The Golden Gate fault does have a more significant effect on the sedimentary section, and appears to truncate the youngest sedimentation. A normal fault is associated with the Golden Gate fault to its west, as inferred from dip changes in nearby strata.

[8] Most small earthquakes near the fault junction occur below ~2.5 km depth, and the relocated hypocenters [*Waldhauser and Ellsworth*, 2000] are distributed mostly beneath the San Andreas and Golden Gate faults (Figure 2). Focal mechanisms from the region tend to be extensional, and occur in broad distribution around the releasing step between the San Andreas and Golden Gate faults (up to 15–20 km away from the step), and to at least 10- to 11-km depth [*Zoback et al.*, 1999]. The width of the slip transfer zone between the San Gregorio and San Andreas faults is only 3–4 km wide, but extensional focal mechanisms are present over a substantially larger volume and therefore suggest that the releasing geometry puts a broader crustal volume into an extensional state.

3. Modeling and Interpretation

[9] We used a finite element model of the San Francisco Bay region to examine the evolution of the San Gregorio-San Andreas fault junction. The model was composed of eight-node viscoelastic elements. The proportion of viscous to elastic behavior of a given element was governed by the local crustal geotherm derived from heat flow measurements (C. Williams, personal communication, 2001). Temperature dependence of strain rate ($\dot{\varepsilon}$) in the model was controlled by the creep equation $\dot{\varepsilon} = A\exp(-Q_c/RT)\sigma^n$ [e.g., *Kirby and Kronenberg*, 1987], where A, Q_c (activation energy), and n are experimentally derived elastic constants, R is the universal gas constant, T is temperature, and σ is differential stress. In the lower-temperature upper crust, the model behaved elastically, while deformation in deeper, higher-temperature regions grew increasingly more anelastic.

[10] The model edges were oriented parallel and orthogonal to the Pacific plate-Sierra Nevada block relative motion vector of ~N34°W (Figure 3), and fault slip was induced by moving the western model edge at a 39-mm/year rate [e.g., *DeMets et al.*, 1994; *Savage et al.*, 1999]. The relative motion vector could vary by 2°–5° more northerly from the value used [e.g., *Argus and Gordon*, 2001; *Savage et al.*, 2004]. A more northerly relative motion vector does not change the releasing geometry of the San Gregorio-San Andreas junction, but might imply that more time would be required to produce observed deformation.

[11] The eastern model edge (east of the Hayward-Rodgers Creek fault system) was held fixed to the Sierra Nevada block, and was not free to move laterally. Faults were modeled by cuts through the crust [e.g., *Holbrook et al.*, 1996; *Henstock et al.*, 1997; *Parsons and Hart*, 1999] that represented the major strike-slip faults of the San Francisco Bay region. The San Gregorio-San Andreas fault junction was initiated southeast at its 3-Ma position (assuming 17 mm/yr San Andreas fault slip rate); the absolute position of the junction is relatively unimportant because the same result is recovered regardless. Slip rates on faults (including gradients along strike) were solved for in the model and were not imposed. The faults were deformable, and constructed from contact elements that obey a Coulomb failure relation. A similar model was used by *Parsons* [2002a, 2002b] to calculate tectonic stressing rates for earthquake probability calculations and to examine long-term fault interactions; in those efforts, the model reproduced long-term fault slip rates and shorter-term geodetic observations.

[12] The Bay area fault model was allowed to deform for 3 m.y. (the likely maximum age of the current San Andreas configuration of San Francisco Peninsula [*McLaughlin et al.*, 1996]), and the results illustrate some consequences of the San Gregorio-San Andreas fault geometry. The San Gregorio fault slips 5–9 mm/yr near its junction with the San Andreas fault, which in turn slips about 17–20 mm/yr [*Working Group on California Earthquake Probabilities*, 1999]. In the finite element model, variation in slip rate between the San Gregorio and San Andreas faults and the angle between them have the effect of opening a narrow basin that elongates with time (Figure 3 and Animation 1). The upper crustal blocks in the finite element model behave elastically, thus in this realization the basin appears as a hole in the model. In the real Earth, this hole would be filled by sediment and collapse of its walls. However, the time evolution and growth of the hole in the model parallels expected basin formation.

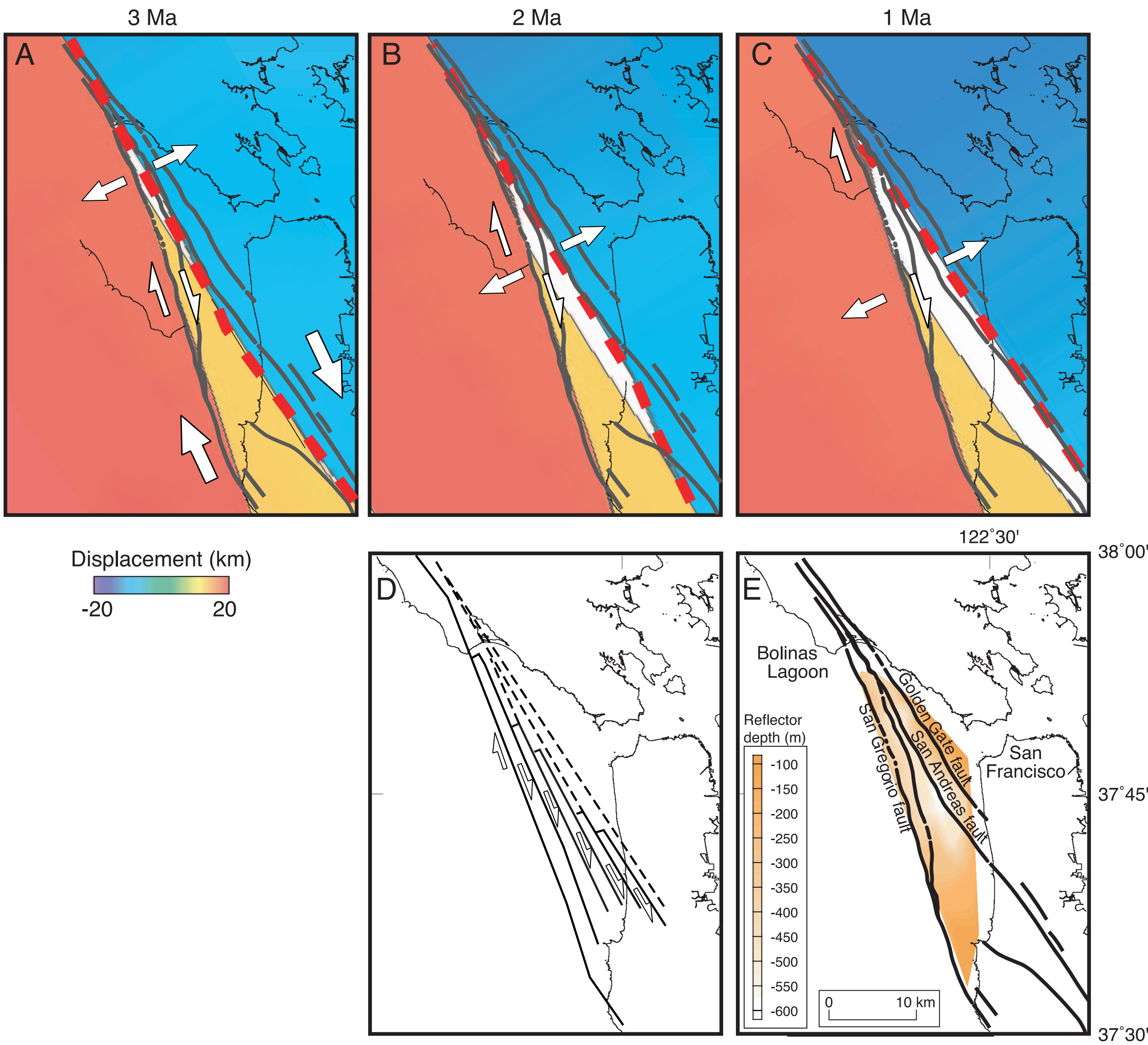

Figure 3. Kinematic models of the San Gregorio-San Andreas fault junction are shown. Shear applied to the block between the two faults causes it to rotate counterclockwise against the San Gregorio fault. (a–c) With continued strike slip in the fault system, the block opens an elongated triangular hole (white area) because of its tapered shape. This has the additional effect of an eastward migration of the San Andreas fault (thick dashed line) strike slip relative to the San Gregorio fault. (d) In the real Earth, the location of the modeled hole might be where basin formation would be expected. (e) Tracking of seismic marker beds in the sedimentary section indicates that the deepest parts of the basin are observed between the San Andreas and Golden Gate faults, in agreement with the model. We propose that eastward migration of San Andreas fault slip was accomplished by successive slivering of the crustal block east of the San Gregorio fault as shown in the conceptual diagram.

[13] An extensional basin is created between the San Gregorio and San Andreas fault because slip on the San Gregorio fault causes the crustal block between the two faults to gradually diverge from the San Andreas (Figure 3 and Animation 1). The model predicts the crustal block between the faults would likely stay in contact with the San Gregorio fault because shear applied on the block tends to rotate it counterclockwise: a rotation that is accommodated by the divergent trends of the San Gregorio and San Andreas faults. Basin formation is predicted on the San Andreas side of the block (Figure 3). As a consequence, the locus of San Andreas fault strike-slip motion is predicted to have migrated eastward relative to the San Gregorio fault (Animation 2). Thus over time, the model predicts that the crustal block between the San Gregorio and San Andreas

faults is subjected to extensional stress, and has likely been dissected by strike-slip faulting that migrates eastward. In addition, the model predicts relative uplift east of the San Andreas and subsidence to the west (Animation 3).

[14] We propose a conceptual model adapted from the finite element model and the seismic cross section that has the locus of San Andreas right-lateral slip episodically stepping eastward relative to the San Gregorio fault over time. The youngest strand is thus predicted to be the one farthest east of the San Gregorio fault. This process has the effect of abandoning offset slivers of crust that are expected to be associated with sedimentary basins along their edges (Figure 3). This model explains the observation of parallel strike-slip faults between the San Gregorio and San Andreas faults (Figure 2). In addition, the model suggests the presence of basement rocks adjacent to the San Gregorio fault increasingly to the south of the Golden Gate, and deeper sedimentary basins to the northeast. 3-D depth mapping of a prominent reflection horizon by *Bruns et al.* [2003] indicates a deepening basin in the northeast part of the crust between the San Gregorio and San Andreas faults, and shows a basement high to the southwest (Figure 3), in accord with the proposed model.

[15] The finite element model makes a number of predictions regarding long-term regional evolution. The scale of observed and predicted basins is best matched after ~1–2 m.y. of slip on the San Gregorio and San Andreas faults. The offshore region in the model undergoes mild extension and subsidence west of the San Andreas fault in accord with broadly observed extensional focal mechanisms. The process of basin opening and stepping of strike-slip accommodation tends to persistently unclamp the hypocentral region of the 1906 earthquake, perhaps favoring nucleation there.

[16] A further implication of the proposed model is that the initial pull-apart basin margin sedimentary facies associated with extensional strike slip would have been mostly limited to the region between the San Gregorio and San Andreas faults. This might explain the lack of depositional features associated with strike-slip faulting noted in the onshore Merced Formation east of the San Andreas by *Clifton and Hunter* [1987, 1991]. The 1.6- to 1.2-m.y.-old Merced units were deposited at about the same time the peninsular San Andreas fault was formed, yet the ~1750-m-thick, 19-km-long exposure east of the San Andreas is almost completely unbroken by strike-slip faulting.

4. Conclusions

[17] A block of crust caught between the merging San Gregorio and San Andreas faults is subjected to extension as a result of the releasing angle of the San Gregorio fault compared with the San Andreas trend. The block is dissected by right-lateral strike-slip faults that are associated with small-offset normal faults, suggestive of transtension. Finite element modeling of the fault system shows that slip on the lower-rate San Gregorio fault causes a counterclockwise rotation of the crustal block against the San Gregorio fault. Continued slip of the system opens an elongated basin between the rotated crustal block and an eastward stepping San Andreas fault. Calculated deformation of the San Andreas strike-slip zone leads us to propose a model in which the crustal block between the San Gregorio and San Andreas faults has been cut by a progression of east stepping strike-slip faults. The current manifestation of this is the right step between the San Andreas and Golden Gate faults, the apparent nucleation zone of the 1906 earthquake.

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