The Evergreen basin and the role of the Silver Creek fault in the San Andreas fault system, San Francisco Bay region, California

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ABSTRACT

The Evergreen basin is a 40-km-long, 8-km-wide Cenozoic sedimentary basin that lies mostly concealed beneath the northeastern margin of the Santa Clara Valley near the south end of San Francisco Bay (California, USA). The basin is bounded on the northeast by the strike-slip Hayward fault and an approximately parallel subsurface fault that is structurally overlain by a set of west-verging reverse-oblique faults which form the present-day southeastward extension of the Hayward fault. It is bounded on the southwest by the Silver Creek fault, a largely dormant or abandoned fault that splays from the active southern Calaveras fault. We propose that the Evergreen basin formed as a strike-slip pull-apart basin in the right step from the Silver Creek fault to the Hayward fault during a time when the Silver Creek fault served as a segment of the main route by which slip was transferred from the central California San Andreas fault to the Hayward and other East Bay faults. The dimensions and shape of the Evergreen basin, together with palinspastic reconstructions of geologic and geophysical features surrounding it, suggest that during its lifetime, the Silver Creek fault transferred a significant portion of the ~100 km2 of total offset accommodated by the Hayward fault, and of the 175 km2 of total San Andreas system offset thought to have been accommodated by the entire East Bay fault system. As shown previously, at ca. 1.5–2.5 Ma the Hayward-Calaveras connection changed from a right-step, releasing regime to a left-step, restraining regime, with the consequent effective abandonment of the Silver Creek fault. This reorganization was, perhaps, preceded by development of the previously proposed basin-bisecting Mount Misery fault, a fault that directly linked the southern end of the Hayward fault with the southern Calaveras fault during extinction of pull-apart activity. Historic seismicity indicates that slip below a depth of 5 km is mostly transferred from the Calaveras fault to the Hayward fault across the Mission seismic trend northeast of the Evergreen basin, whereas slip above a depth of 5 km is transferred through a complex zone of oblique-reverse faults along and over the northeast basin margin. However, a prominent groundwater flow barrier and related land-subsidence discontinuity coincident with the concealed Silver Creek fault, a discontinuity in the pattern of seismicity on the Calaveras fault at the Silver Creek fault intersection, and a structural sag indicative of a negative flower structure in Quaternary sediments along the southwest basin margin indicate that the Silver Creek fault has had minor ongoing slip over the past few hundred thousand years. Two earthquakes with ~M6 occurred in A.D. 1903 in the vicinity of the Silver Creek fault, but the available information is not sufficient to reliably identify them as Silver Creek fault events.

INTRODUCTION

The San Andreas fault zone in central California (USA) south of the San Francisco Bay region (Fig. 1 inset) is a regionally simple structure (Jennings, 1994) composed of a single strand or, more likely, a set of subparallel but closely spaced strands (e.g., Sims, 1993; Simpson et al., 2006) that took turns accommodating slip following inception of movement on the system. For the past few million years, the San Andreas fault zone between the Garlock fault in the Transverse Ranges and roughly the latitude of Monterey, California, has been a zone at most a few kilometers wide (Jennings, 1994).

The morphology of the San Andreas fault system is dramatically different in the greater San Francisco Bay region and to the north (Fig. 1) compared to that in central California to the south. East of Monterey, the active Calaveras fault splays northward from the San Andreas fault, feeding slip onto the East Bay fault system, a system of 13 major faults forming six fault systems (three active and three abandoned) along with dozens of secondary faults that are currently or recently active (Graymer et al., 2006). Inclusion of the East Bay fault system widens the total San Andreas fault system to at least 80 km and adds such active members as the Hayward, Calaveras, Greenvale, and Rodgers Creek faults (Fig. 1), which together accommodate as much or more slip today than does the stretch of the San Andreas fault between San Francisco and Hollister (i.e., Evans et al., 2012).

The San Andreas fault, sensu strictu, between its intersections with the San Gregorio fault to the north and the Calaveras fault to the south, is, like its counterpart in central California, relatively simple, with most of its 125 km of total slip (Jachens et al., 1998) accommodated on a few closely spaced faults. In contrast, the ~175 km of total slip accommodated by the East Bay fault system (McLaughlin et al., 1996; Jachens et al., 1998) was partitioned onto many different strands and initiated ca. 12 Ma as required by the correlation of volcanic rocks across the East Bay system at Burdell Mountain and Quien Sabe
Jones and Curtis, 1991; Ford, 2007; Fig. 1). The details of some of this partitioning have been revealed (Graymer et al., 2002; McLaughlin et al., 1996), but the analysis is far from complete. Other models have been proposed for the partitioning of slip on the San Andreas system faults in the San Francisco Bay region (e.g., Powell, 1993; Wakabayashi, 1999). More recent work (Graymer et al., 2002; Wentworth et al., 2010) supports the model adopted in this paper, at least for the partition of central California San Andreas fault slip between the San Andreas fault, sensu strictu, and the southermmost Calaveras fault in the San Francisco Bay region. The partitioning of slip from the southern Calaveras fault onto all other faults of the East Bay fault system (e.g., Graymer et al., 2002), the details of which do not affect the results presented here, is not discussed in this paper.
In this study we address one of the lesser-known members of the East Bay fault system, the Silver Creek fault (Figs. 1, 2) — one that we will assert has played a major role in the development of the entire system, but that appears to be largely dormant today. Our analysis provides a quasi-four-dimensional picture of how fault strands evolve in a large strike-slip system and documents the transition from an extensional stepover to a contractional stepover. But the nature and role of the Silver Creek fault comes later in our analysis. This story begins with the discovery of a large, deep sedimentary basin, the Evergreen basin, concealed beneath the Santa Clara Valley at the south end of San Francisco Bay.

**EVERGREEN BASIN SETTING**

Normally, we would begin the description of the setting of the Evergreen basin with a discussion of the local geology. However, much of the area is covered by Quaternary deposits that conceal the basin, or by Cenozoic and Mesozoic rocks that variously reveal or conceal the basin. Thus we find it more useful to begin the discussion with a view of the geophysical data that suggest the presence of a concealed basin, and defer the discussion of the geology until the geophysical setting has been established.

**Gravity Surveys**

Gravity surveys of the Santa Clara Valley during the late 1950s and 1960s revealed prominent gravity lows along the southwest and the northeast sides of the valley, separated by a northwest-trending gravity ridge (Taylor, 1956; Robbins, 1971) that extends from an outcrop of Franciscan Complex basement with interleaved serpentinite at Communication Hill (CH in Fig. 2; also known as Oak Hill) to the southern tip of San Francisco Bay. Subsequent gravity observations (Roberts et al., 2004) have added detail to the image of the gravity field but show the same basic gravity features as the early surveys (Fig. 2). The Evergreen gravity low, lying along the northeast side of the valley, is a regular elongate feature ~10 km wide at its widest, nearly 40 km long, and as much as 40 mGal in anomaly amplitude.

Gravity lows in the California Coast Ranges that are similar to the Evergreen low typically reflect thick sections of low-density Cenozoic deposits (Chapman and Griscorn, 1980), but comparing the Evergreen low with the surface geology indicated that the cause of the low might be more complicated (Robbins, 1971). Although the low coincides predominantly with Cenozoic deposits at the surface (Fig. 2), denser Mesozoic Coast Range ophiolitic and forearc marine sedimentary rocks of the Great Valley sequence of Bailey et al. (1964) crop out within the low along a reach ~10 km long and extending across its full width. These geologic observations led Robbins (1971) to interpret the source of the low to be rocks in a graben that likely affected the entire crust. In this inferred graben, Great Valley sequence rocks were dropped down into denser Franciscan Complex basement, Franciscan Complex basement rocks were down-dropped into lower crustal rocks, and perhaps lower crustal rocks were dropped down into the upper mantle. The proposed graben-bounding structures were the Silver Creek fault on the southwest and the Hayward (and its structural continuation) and Calaveras faults on the northeast.

**Seismic Velocity Model**

For nearly two decades, the gravity observations were the only data that suggested the presence of a basin or other major structural feature beneath the northeastern edge of the Santa Clara Valley. In 1988, a three-dimensional (3-D) seismic velocity model (Michael, 1988) of the volume of crust surrounding part of the Calaveras fault covered the southern half of the Evergreen gravity low, including the section with outcropping Mesozoic rocks. This analysis revealed materials with low seismic velocities (relative to surrounding crust at comparable depth) to depths of at least 6 km, and perhaps deeper (Fig. 3), in the area of the gravity low. The low velocities of these materials, although mostly confined between the traces of the Silver Creek fault and the Calaveras fault including the reach with outcropping Mesozoic rocks, were not sufficiently diagnostic to permit differentiation between different types of Mesozoic rocks, or even between Mesozoic rocks and younger rocks. The place where the low velocity material penetrates the deepest is where late Cenozoic Silver Creek gravels crop out within the gravity low, south of the outcropping Mesozoic Great Valley sequence (Fig. 3).

**Geology**

Geologic mapping and compilations in the 1990s (Wagner et al., 1991; Graymer and DeVito, 1993; Jones et al., 1994; Page et al., 1999; Wentworth et al., 1998) around the Evergreen gravity low clarified the nature and importance of its surrounding faults and provided new information about the Mesozoic rocks that extend across the low. New geophysical data also contributed to a better understanding of the geology. The Silver Creek fault, the steep structure bounding the southwest side of the gravity low beneath Yerba Buena Ridge, is largely concealed beneath thin sheets of Mesozoic rock thrust northeast across the margin along the Silver Creek thrust. The Silver Creek thrust at the surface is observed to be a zone of reverse faults that places Mesozoic rocks of Yerba Buena Ridge on top of the late Cenozoic gravels (Crittenden, 1951; Jones et al., 1994). A reverse-fault interpretation is supported by the gravity data (Fig. 2), which show that the fault trace lies well down toward the bottom of the gravity low, a strong indicator that the Mesozoic rocks lie on top of less-dense late Cenozoic deposits. However, the gravity data imply a steeper southwest dip for the margin of the gravity low than for the reverse fault shown by Jones et al. (1994).
Figure 2. Gravity anomaly maps over the eastern Santa Clara Valley (California, USA). (A) Isostatic residual gravity anomaly shown as color bands with a contour interval of 2 mGal. Thick black lines are major faults from geologic maps and geophysical inference (see text). Thin black lines are other faults from Graymer et al. (2006). Yellow lines show the location of seismic reflection profiles (Williams et al., 2006; Wentworth et al., 2010); line labeled a-a’ is shown in Figure 5. White dashed line shows the minimum southwest extent of denser flaps of Mesozoic and/or Cenozoic rock. (B) Isostatic residual gravity anomaly contours (red lines) on geology after Graymer et al. (1996) and Wentworth et al. (1998). Contour interval is 2 mGal. Note the deep gravity low between the Silver Creek fault and the Hayward and Calaveras faults, variously over Quaternary alluvium, Tertiary rocks, and Mesozoic rocks at the surface. CCOC—Coyote Creek Outdoor Classroom drill hole; CH—Communication Hill; EVGR—Evergreen drill hole; GUAD—Guadalupe River drill hole; MOFT—Moffett Field drill hole (Beyer, 1980); YBR—Yerba Buena Ridge. Locations of drill holes are from Newhouse et al. (2004) unless otherwise noted.
Figure 3. Map showing depth to the 4.8 km/s isovelocity surface over the eastern Santa Clara Valley (California, USA) (after Michael, 1988). (A) Depths shown as color bands with contour interval of 0.5 km. Thick black lines are major faults from geologic maps and geophysical inference (see text). (B) Depth contours on geology (brown lines, contour interval 0.5 km). Note that velocities of 4.8 km/s extend to >4 km depth in areas with both Cenozoic rocks and Mesozoic rocks exposed at the ground surface. Velocities of 4.8 km/s at 4 km depth are typical of Cenozoic rocks in the San Francisco Bay region (Brocher, 2008). CH—Communication Hill; YBR—Yerba Buena Ridge.
Likely here the gravity data reflect the superposition of the Silver Creek thrust onto the Silver Creek fault. The northern half of the southwest basin margin is concealed by alluvium, but we have extended the Silver Creek fault into this area on the basis of InSAR satellite imaging data (Fig. 4), which delineate a discontinuity in land subsidence attributed to a sharp groundwater flow barrier interpreted to be caused by the concealed fault zone (Galloway et al., 2000; Schmidt and Bürgmann, 2003; Hanson et al., 2004; Choussard et al., 2014), and on the basis of sharp gravity and magnetic anomaly gradients (Fig. 2; Wentworth et al., 2010).

Multiple faults roughly coincide with the northeast margin of the Evergreen low (Fig. 2). The active creeping strand of the Hayward fault (Lienkaemper, 1992; thick black line in Fig. 2) ends within the northern end of the gravity low, but a system of northeast-dipping reverse-oblique faults continues toward the southeast along the northeast half of the low (Jones et al., 1994; Wentworth et al., 1998). The active Calaveras fault at the surface does not mark the northeast boundary of the low, but instead cuts across the southeast end of the low. At the southeast end of the low, the Calaveras fault likely dips east as it does both to the northwest and southeast based on historic seismicity (Jachens et al., 2002; Williams et al., 2005a; Simpson et al., 2004; Graymer et al., 2007). Thus the fault probably lies above the source of the low.

Because much of the northeastern boundary of the Evergreen gravity low is characterized by northeast-dipping reverse faults, we interpret the presence of the Great Valley sequence rocks and Coast Range ophiolite extending all the way across the low to the Silver Creek fault to reflect a thrust flap of Mesozoic rocks, rooted to the northeast and lying on top of younger Cenozoic deposits that produce the gravity low (Jones et al., 1994). Additional geologic and gravity data support this interpretation. Near the south end of the Mesozoic flap, the fault that separates Jurassic Knoxville Formation (Great Valley sequence) and underlying gabro of the Coast Range ophiolite from adjacent late Cenozoic Silver Creek gravels (the Clayton fault, not to be confused with the right-lateral fault of the same name that lies north of Mount Diablo) is recognized as a low-angle, north-dipping thrust fault that places the older rocks on top of the late Cenozoic deposits (Jones et al., 1994). Gravity profiles across this fault also indicate that the fault has a very low dip (the fault lies at the very bottom of the gravity gradient that reflects the transition from a gravity low over the low-density Silver Creek gravels to a gravity high over the higher-density Mesozoic rocks; Fig. 2).

Somewhat more speculatively, we interpret the gravity data in combination with the structural style shown by the thrust faults northeast of the gravity low to indicate that more than one flap of Mesozoic rock extends into the gravity low, but that the deeper one (or more) is mostly concealed beneath the alluvium northwest of the exposed flap. We suggest that the Evergreen gravity low is mostly unperturbed at both its northwest and southeast ends and that the decreased amplitude of the low in the central 15–20 km reflects denser flaps of Mesozoic and/or older Cenozoic rock rooted to the east. Indirect support for this interpretation is thinning and uplift of part of the Quaternary section encountered in the Evergreen drill hole (EVGR in Fig. 2; Wentworth et al., 2015). The minimum southwest extent of these inferred flaps is shown by the white dotted line in Figure 2A. This interpretation has a Cenozoic basin as the primary source of the huge Evergreen gravity low rather than a graben that dropped Mesozoic sedimentary rocks down into denser crust. Furthermore, as discussed later, this basin formed in response to a releasing stepover within the East Bay fault system.

Seismic Reflection Profiles

Two seismic reflection profiles (Williams et al., 2005b, 2006; Wentworth et al., 2010, 2015) and a well drilled along one of them (Guadalupe hole; Newhouse et al., 2004) provide strong support for the Cenozoic basin interpretation (Williams et al., 2005b). One 10-km-long profile lies west of and subparallel to the concealed Silver Creek fault, along the axis of the mid-valley gravity ridge that separates the Cupertino and Evergreen gravity lows (Fig. 2). This profile imaged 300–500 m of relatively flat-lying, prominent reflectors above a strong reflector interpreted to be the top of basement (Wentworth et al., 2015). The Guadalupe drill hole, located adjacent to this profile (GUAD in Fig. 2), penetrated ~410 m of unconsolidated material before bottoming in sandstone and argillite of the Franciscan Complex (Wentworth et al., 2015). Paleomagnetic measurements on cores from the upper 290 m of this drill hole indicate that the unconsolidated sediments all are normally polarized, implying that they were deposited during the Brunhes normal polarity chron and thus are <780,000 yr old (Mankinen and Wentworth, 2016). Similar ages based on paleomagnetic measurements have been found for the upper 250–300 m in other drill holes in the valley (Mankinen and Wentworth, 2003, 2016).

The second seismic reflection profile (Fig. 5; a-a’ in Fig. 2) starts on the axial gravity high, crosses the inferred Silver Creek fault, extends across the Evergreen gravity low, and terminates near the eastern edge of the gravity low in the vicinity of the west-verging thrust faults that place Great Valley sequence rocks on top of late Cenozoic deposits. On its west end, this profile images the same package of relatively flat-lying reflectors above the strong basement reflector that is seen in the axial profile. At the Silver Creek fault, the basement reflector terminates abruptly whereas the reflectors above it continue eastward into the area of the Evergreen gravity low (Fig. 5). East of the Silver Creek fault, the package of overlying reflectors associated with Cenozoic strata is imaged down to at least 1.5 km, the depth limit of reliable data from this seismic reflection survey (Wentworth et al., 2010). The reflection data image the Silver Creek fault in the unconsolidated deposits to within ~300 m of the surface. A structural sag lies above the concealed tip of the Silver Creek fault, suggesting to Wentworth et al. (2010) that continuing minor strike-slip movement with some cross-fault extension affected sediments as young as ca. 140 ka. No actual dip-slip displacement across the sag is discernable in the section, so the sag is attributed to transtension (Wentworth et al., 2010).
Figure 4. Map showing seasonal ground deformation detected by InSAR satellite imaging (Galloway et al., 2000). This seasonal ground deformation has been related to the seasonal pumping and recharge of groundwater (Schmidt and Bürgmann, 2003; Hanson et al., 2004). Warm colors (yellows and oranges) indicate high peak-to-peak amplitudes of seasonal ground deformation; cool colors (greens and blues) indicate low peak-to-peak amplitudes of seasonal ground deformation. Note the sharp lateral transition from high to low amplitudes of seasonal ground deformation across the northwest projection of the Silver Creek fault. Green lines show locations of seismic-reflection profiles (Williams et al., 2006; Wentworth et al., 2010). Heavy black lines are major strike-slip faults; thin black lines, other faults within the stepovers between the Silver Creek, Hayward, and Calaveras faults. Beige and yellow areas show mountainous and valley areas, respectively.
This seismic reflection profile also reveals features interpreted by Williams et al. (2006) as two west-verging thrust faults within the Cenozoic section near the east end of the reflection profile (thick red lines in Fig. 5). Their interpretation combined with the recognition of thrust flaps of Mesozoic rock discussed in the previous section and the identification of thrust faults in the mapped geology indicate that thrust faults are broadly distributed along the northeast margin of the Evergreen basin and extend concealed beneath the Quaternary deposits of the Evergreen basin. Concealed thrust flaps can explain the uplifted and thinned section encountered in the Evergreen drill hole.

Other recent seismic investigations detected materials with low seismic velocities beneath the Evergreen gravity low. A seismic refraction profile that in part followed the same path as the seismic reflection profile discussed above (Catchings et al., 2003; Boatwright et al., 2004) detected materials with low seismic velocities characteristic of Cenozoic basin fill to depths of at least 3 km below the center of the gravity low. Materials with much higher velocities were detected at considerably shallower depths both beneath the mid-valley gravity ridge southwest of the gravity low and also to the northeast of the gravity low. Thurber et al. (2007) constructed a 3-D model of seismic P-wave velocities in the greater San Francisco Bay region that reveals low-velocity materials (<5 km/s) to depths of 5 km beneath the southern part of the Evergreen gravity low, although their model does not show low velocities at depth beneath the deepest part of the gravity low near its northwest end. Hartzell et al. (2006) presented results compatible with low seismic velocities extending to depth in the vicinity of the gravity low. Finally, Dolenc and Dreger (2005) and Dolenc et al. (2005) detected seismic wave delays, amplifications, and other characteristics at stations over the Evergreen gravity low that are consistent with a thick section of low-velocity material. Given that seismic velocity and density are related properties, all of these studies provide added support for the presence and distribution of low-density materials that are the source of the gravity low.

**EVERGREEN BASIN MODEL**

**Qualitative Interpretation**

The geologic and geophysical evidence discussed in the previous sections is all compatible with an interpretation of the Evergreen gravity low as being caused by an 8-km-wide, 40-km-long basin filled mostly with late Cenozoic deposits that has had Mesozoic rocks derived from the Coast Range ophi-
lite and its overlying Great Valley sequence and Franciscan Complex (including interleaved serpentine mélange with enclosed blueschist tectonic blocks) thrust over its central reach. In addition to the gravity anomaly, the strongest evidence supporting this interpretation comes from the combination of the seismic reflection profiling, the data from the Guadalupe drill hole, and the geologic relations revealed near the southeastern end of the gravity low. The seismic reflection and well data show Quaternary deposits above the mid-valley basement ridge continuing northeastward into the area of the lowest gravity (deepest part of the basin) whereas the basement reflector terminates abruptly at the inferred location of the Silver Creek fault. Near the center of the gravity low, horizontal reflections continue at least to a depth of ~1.5 km (the depth where the seismic data lose resolution) without any noticeable interruption, but no strong reflections are seen that are similar to the basement reflection over the mid-valley ridge. The seismic reflection profile samples the basin at a place where the gravity data suggest that the thrust flaps of Mesozoic rock are present only along the northeast margin and so give a relatively clear view of the upper 1.5 km of the basin.

**Basin Shape Calculation**

We calculated the 3-D shape of the Evergreen basin by inverting the gravity data following the method of Jachens and Moring (1990) (see also Saltus and Jachens, 1995), constrained by outcrop geology, known depths to basement from seismic and drill hole data, and an assumed distribution of density versus depth for the basin-filling deposits. In this procedure, the gravity field is iteratively partitioned into a component caused by the low-density deposits that fill the basin and a regional component caused by lateral density variations within the surrounding bedrock. We then interpret the “basin” gravity component in terms of the 3-D distribution of Cenozoic deposits. We force the basin thickness to be zero in places where Mesozoic rocks (e.g., Franciscan Complex and Great Valley ophiolite) crop out and are considered to be in place (e.g., not lying on top of younger, less-dense Cenozoic deposits). We compensated for the distortion of the basin gravity anomaly caused by the overthrust flaps of older, denser rock by smoothly joining the contours from the northwestern end of the anomaly with those from the extreme southeastern end, those locations where our interpretation predicts that the anomaly is least perturbed by the overthrust flaps.

We have few direct measurements of density in the deeper parts of the Evergreen basin and so have assumed a density-depth function based on measurements in deep drill holes in other parts of the San Francisco Bay region (Beyer, 1980; Brocher et al., 1997; Tiballi and Brocher, 1998). The density of the upper 300 m, 2120 kg/m³, was based on the borehole gravity measurements of Beyer (1980) taken in the Moffett Field drill hole near the southern end of San Francisco Bay (MOFT in Fig. 2). This value is virtually identical to the average of density measurements in the Guadalupe drill hole and somewhat less than the average of density measurements (2235 ± 66 kg/m³) measured in the Evergreen drill hole (Newhouse et al., 2004). We prefer the density based on the borehole gravity measurements because that method continuously samples a greater volume of sediment around the borehole than do measurements on core. Densities for deeper parts of the basin fill section were based on the compilations of Brocher et al. (1997) and Smith (1992), and are as follows: between 0.3 and 1.3 km, 2220 kg/m³; 1.3–2.3 km, 2350 kg/m³; 2.3–3.3 km, 2470 kg/m³; >3 km, 2570 kg/m³. We assumed a density of 2670 kg/m³ for the basement rocks (Irwin, 1961), inferred to be predominantly greywacke of the Franciscan Complex. The change in density of the basement rock with depth is considered small relative to that of the overlying basin fill because basement rock in general is considerably less porous than the basin fill and its density would be less affected by compaction as a function of depth.

**Evergreen Basin Geometry**

The result of the constrained gravity inversion is shown in Figure 6. The Evergreen basin is seen to be a deep, highly elongate basin ~40 km long by 8 km wide. It is deepest near its northwest end (~5.5 km) and progressively shallows toward its southeast end. Its plan-view shape is relatively simple, although this simplicity is partly due to the simple way in which the gravity effects of the overthrust flaps were removed. As was apparent from the gravity anomaly itself, the Evergreen basin lies mostly between the Silver Creek fault (the mapped traces and their extension to the northwest based on InSAR data and gravity anomalies) and the southeastern projection of the active Hayward fault (in part coincident in map view with the oblique-reverse faults that today characterize the northeast edge of the basin).

Both Taylor (1956) and Dr. Rodger H. Chapman (California Department of Water Resources, 1967) carried the Silver Creek fault farther northwest than the northwest end of the Evergreen gravity low, and Catchings et al. (2006) suggested that it extends >35 km northwestward east of San Francisco Bay past the Coyote Hills (Fig. 4). Hanson et al. (2004) and Hanson (2015) also adopted the linear northwest extension of the Silver Creek fault by Catchings et al. (2006) as an element in their groundwater model, but the model did not test the extension of the fault because they only used wells south of San Francisco Bay. Wentworth et al. (2010) examined the possibility of the northwest fault extension in detail and concluded that no large, well-integrated late Cenozoic strike-slip fault continues northwestward from the northwest end of the Silver Creek fault bounding the Evergreen basin. They found no evidence for either lateral or vertical offset in the basement surface as defined by gravity, well, and seismic refraction control across the projection of the fault (their figure 8). Furthermore, they found no evidence of a hydrologic barrier along the projection of the fault, as saltwater intrusion in the shallowest aquifer (Newark) extends across the northwest extension of the fault north and south of the Coyote Hills (California Department of Water Resources, 1968) and pump-testing indicates hydraulic continuity in the next deeper aquifer south of the hills (California Department of Water Resources, 1967).
Figure 6. Subsurface configuration of the Evergreen basin (Santa Clara Valley, California, USA), inferred from constrained inversion of the gravity data. (A) Modeled depth to Mesozoic bedrock shown as color bands with contour interval of 1 km. Heavy black lines are major strike-slip faults; thin black lines, other faults. Major faults are from geologic maps and geophysical inference (see text). Green lines show location of seismic-reflection profiles (Williams et al., 2006; Wentworth et al., 2010). (B) Depth to Mesozoic bedrock shown as contours on geology (red lines, contour interval 1 km). CH—Communication Hill; YBR—Yerba Buena Ridge.
STRUCTURAL AND TECTONIC INTERPRETATION

Evergreen Basin

We propose, on the basis of the inferred shape of the Evergreen basin and its position relative to the active Hayward fault (with as much as 100 km of total strike-slip offset [Graymer et al., 2002]) and the subparallel, largely dormant Silver Creek fault, that the Evergreen basin formed as a pull-apart basin in the wake of a right step from the Silver Creek fault to the Hayward fault (Fig. 7). The length of the basin and its apparent along-strike simplicity suggest that at least 40 km of strike-slip offset has been accommodated on the Silver Creek fault. It would be possible to generate a pull-apart basin of 40 km length with <40 km of slip by merging nearby basins resulting from multiple right steps. However, we do not see the type of irregular plan-view geometry of the basin that we would expect from such a process.

A minimum of 40 km of offset accommodated on the Silver Creek fault is a significant portion of the total slip of ~100 km accommodated by the Hayward fault and suggests that the Silver Creek fault played an important role in the transfer of slip from the central California San Andreas fault to the Hayward fault. In contrast, recent seismicity precisely relocated using the double-difference method indicates that today almost all the slip is transferred to the Hayward fault via the central Calaveras fault and across the Mission seismic trend (yellow line in Fig. 1; Waldhauser and Ellsworth, 2002; Ponce et al., 2004; Simpson et al., 2004), all northeast of the Evergreen basin. In the rest of this paper, we will examine whether our proposed interpretation of the origin of the Evergreen basin is consistent with current knowledge of the East Bay fault system, and if it is, what the implications of the Silver Creek fault as an important element in the San Andreas fault system in the San Francisco Bay region are.

Constraints on Palinspastic Reconstruction: San Andreas Fault System

In order to evaluate the possible importance of the Silver Creek fault in the San Andreas system, a review of the San Andreas system offset and the partitioning of that offset is warranted. The San Andreas fault in central California (south of the latitude of Monterey) has accommodated ~300 km of total offset (Ross, 1970; Matthews, 1976, Jachens et al., 1998). In the San Francisco Bay region, this total offset is distributed onto a number of splays including (1) the San Andreas fault proper lying west of the bay and (2) faults of the East Bay fault system (e.g., Hayward fault, Calaveras fault, Greenville fault, and others) lying east of the bay. McLaughlin et al. (1996) identified a critical cross-fault correlation between (1) rocks of the Franciscan Permanente terrane in the southern San Francisco Bay region west of the Calaveras fault but east of the San Andreas fault and (2) equivalent rocks east of the San Andreas fault in the Parkfield area of central California (Fig. 1). This correlation indicated that between 160 km and 190 km of the central California San Andreas total offset was partitioned onto the East Bay fault system along the southernmost
Calaveras fault. Jachens et al. (1998) used prominent gravity highs produced by the Permanente terrane rocks in both locations and strong magnetic anomalies bracketing both Permanente terrane bodies to refine this offset estimate to 174 ± 3 km (Fig. 8), which is consistent with the correlation of Miocene volcanic rocks and related strata at Quien Sabe and Burdell Mountain (Jones and Curtis, 1991; Ford, 2007). Graymer et al. (2002) analyzed the distribution of this offset among the various East Bay faults and concluded that at least 100 km of offset was transferred from the southern Calaveras fault to the Hayward fault over the past 12 m.y.

The palinspastic restoration of 174 km of right-lateral offset on the central California San Andreas fault and the southernmost Calaveras fault not only brings the Permanente terrane rocks (and their gravity anomalies) and the Palo Prieto Pass (Hanna et al., 1972) and Hollister Valley (Robbins, 1982) magnetic bodies into alignment, but to the north also places two large 50–60-km-long magnetic bodies (as reflected by the magnetic anomalies they produce) adjacent to and facing each other across fault boundaries (Fig. 8). The western body is the long serpentinite body exposed on Yerba Buena Ridge that lies southwest of the Silver Creek fault, on the southwestern lip of the Evergreen basin.

Figure 8. Shaded-relief aeromagnetic map of central California, USA (modified from Roberts and Jachens, 1999) showing the magnetic anomalies associated with the Priest Valley and Palo Prieto Pass ophiolites and their cross-fault counterparts, the Yerba Buena Ridge and Hollister Valley ophiolites. Warm colors indicate magnetic highs; cool colors indicate magnetic lows. Note that the Yerba Buena Ridge and Hollister Valley anomalies are generally lower in amplitude than their cross-fault counterparts, likely the result of the post-separation uplift and erosion of the Yerba Buena Ridge and Hollister Valley ophiolites, as discussed in text.
As expressed by its associated magnetic anomaly, this serpentinite body has a roughly linear northeast edge nearly 50 km long, the southern half of which lies along a trace of the Silver Creek fault. Much of the northern half of this edge is concealed beneath alluvium, but its linearity suggests fault control even though we cannot establish this directly. The linearity of the southernmost edge of this body is affected by movement on the Silver Creek thrust. The eastern body, north of Parkfield and roughly centered over Priest Valley, is a mostly concealed, generally flat-lying tabular body cut by the San Andreas fault and inferred to be composed largely of serpentinite (Griscom and Jachens, 1990; Eberhart-Phillips and Michael, 1993). Based on the width of its magnetic gradient, this body is estimated to lie at a depth of a few kilometers, although precisely estimating the depth of flat-lying magnetic bodies based on their magnetic anomalies is difficult. The magnetic data indicate that this magnetic body has a linear southwest boundary ~50 km long, more than half (and perhaps most) of which coincides closely with the location of the San Andreas fault. At the south end of the Priest Valley magnetic anomaly, serpentinite is being extruded or thrust to the surface at Table Mountain (Dickinson, 1966), and smaller bodies of serpentinite crop out in many parts of the area enclosed by the magnetic anomaly. In this reconstruction, the Priest Valley anomaly lines up closely with the Yerba Buena Ridge magnetic anomaly (Figs. 8, 9).

Correlating magnetic bodies likely composed of serpentinite on opposite sides of the San Andreas fault to estimate fault offset is not necessarily straightforward, because serpentinite can behave diapirically and be subject to further serpentinitization while being transported within fault zones. Thus, counterpart bodies could change shape and degree of magnetization following dismemberment. Also, the counterpart bodies may experience different tectonic histories following separation.

Nevertheless, we feel that the evidence supports the identification of the Priest Valley and Yerba Buena Ridge magnetic bodies as offset counterparts of a once-continuous serpentinite body, even though the amplitudes of the magnetic anomalies produced by the two are quite different. First, both bodies extend up to their adjacent fault faces (the San Andreas fault and the Silver Creek fault). Second, the along-fault dimensions of both bodies are very similar (~40 km). Third, both bodies are likely subhorizontal and sheet-like in shape based on the mapping of Page et al. (1999) for the Yerba Buena Ridge body and the modeling of Griscom and Jachens (1990) for the Priest Valley body. Fourth, both bodies extend significant distances from their respective bounding faults, as much as 10 km or more, making it improbable that conditions within the fault zone would affect the entire bodies. Finally, both bodies are likely Coast Range ophiolite: Page et al. (1999) described the Yerba Buena Ridge body as such, and, although the Priest Valley body is concealed, the deep drill hole at the San Andreas Fault Observatory at Depth (SAFOD) penetrated rocks of the Great Valley sequence northeast of the San Andreas fault (Zoback et al., 2011) above the Priest Valley body. Thus, Coast Range ophiolite, the depositional basement of the Great Valley sequence, would likely exist at depth below the drill hole.

The higher amplitude of the magnetic anomaly over the Priest Valley body compared to that over Yerba Buena Ridge is likely the result of the Yerba Buena Ridge body being thinner than its cross-fault counterpart at Priest Valley. The Yerba Buena body is exposed and has been subject to erosion. Page et al. (1999) concluded that on Yerba Buena Ridge, uplift and deep erosion removed Great Valley sequence rocks and the upper units of the Coast Range ophiolite, thus exposing the basal serpentinite, which now probably is less than a kilometer thick. The Priest Valley body, present beneath Great Valley sequence and thus never having been exposed, would likely be much thicker. Thus the Yerba Buena Ridge magnetic sheet should produce a lower-amplitude magnetic anomaly, just as we observe. Alternatively, the presence of upper ophiolitic rocks on Yerba Buena Ridge suggests that the body may have been originally thinner than its offset counterpart at Priest Valley. In any case, differential deformation, before and/or after separation, resulted in the difference in thickness and depth. Furthermore, the Priest Valley body has magnetic sandstone of the Etchegoin Formation above it (Dibblee, 1971) that would tend to augment the amplitude of that anomaly.

On the basis of the geophysical observations and the palinspastic reconstruction, together with our interpretation of the Evergreen basin as a strike-
slip pull-apart basin associated with right slip on the Silver Creek fault, we propose that the Yerba Buena Ridge and Priest Valley serpentinite sheets were once a single sheet. Offset on the San Andreas system dismembered this sheet and dispersed the two pieces by movement on the Silver Creek, southern Calaveras, and central California San Andreas faults. In the following section, we expand on this proposal and examine some of its implications regarding offset on faults of the East Bay fault system.

Scenario

Our proposed model for the development of the Evergreen basin and the southern East Bay fault system is shown schematically in Figure 9; for a reconstruction that adopts much of what is presented here, but encompasses the broader Santa Clara Valley, see Langenheim et al. (2015). Prior to the initiation of the East Bay fault system ca. 12 Ma, a large flat-lying sheet of serpentinite and associated ophiolitic rocks (at least 25 km wide and >50 km long; Fig. 9A) lay concealed beneath Mesozoic and Paleogene rocks. At that time, faults developed that were later to become the southern Calaveras, Silver Creek, and Hayward faults, among others. The proto–Silver Creek and proto–southern Calaveras faults were a single, continuous fault, whereas the proto–Hayward fault was subparallel to the proto–Silver Creek fault but displaced to the east (right) ~10 km. The proto–Silver Creek fault probably extended north of the south end of the proto–Hayward fault, and to the southeast, it cut across the concealed serpentinite sheet. The central and northern Calaveras faults would develop from faults that were far to the north at this time.

As right-lateral offset began to accumulate on the southern Calaveras, Silver Creek, and Hayward faults (Fig. 9B), the eastern part of the serpentinite sheet, which eventually would become the Priest Valley serpentinite sheet, moved southeastward with respect to the western part, later to become the Yerba Buena Ridge body. Right slip on the Silver Creek fault–southern Calaveras fault was transferred to the Hayward fault across a right separation between them, which may originally have taken the form of a diffuse extensional zone. Eventually, as the slip transfer became tightly organized near the south end of the active Hayward fault, the Evergreen basin began to form as a pull-apart basin in the right step from the Silver Creek fault to the Hayward fault.

Some time after enough offset had been taken up by the Silver Creek fault to cause the complete separation of the two parts of the ophiolitic serpentinite sheet (Fig. 9C), the central (and probably northern) Calaveras faults formed and connected with the southern part of the fault. Restoration of magnetic bodies places no tight constraints on how much total offset took place on the Silver Creek fault prior to the initiation of the central Calaveras fault zone, but it must have been at least the 50 km necessary to effect the complete separation of the two parts of the serpentinite sheet. This minimum estimate is in accord with the minimum estimate of 40 km of right offset across the Silver Creek fault implied by the length of the Evergreen basin. The initiation of movement on the central Calaveras fault zone would not necessarily have caused the Silver Creek fault to be abandoned because, at least today, the angle between the Silver Creek fault and the central Calaveras fault is small enough that movement on the southern Calaveras fault could probably feed onto either fault. An alternate scenario (Graymer et al., 2015; Langenheim et al., 2015, their figure 4) posits that an active central (and northern) Calaveras fault zone was translated south by movement on the Hayward fault to its present location east of the Evergreen basin. Regardless, slip on some combination of the Silver Creek fault and the southern Calaveras fault and other East Bay faults eventually resulted in the total separation of 174 km (Jachens et al., 1998) between the Priest Valley and Yerba Buena Ridge ophiolite bodies seen today.

A variant of the scenario presented above has been proposed by Wentworth et al. (2010; also adopted in Langenheim et al., 2015) and is shown in Fig. 9D. They suggested that sometime after sufficient offset had occurred to completely separate the Yerba Buena Ridge and Priest Valley magnetic bodies, a new fault, the Mount Misery fault, broke across the basin, directly connecting the southern Hayward fault with the southern Calaveras fault, thus bisecting the basin. Such faults are common in the extinction phase of some pull-apart basins (Zhang et al., 1989; Anderson et al., 2004). Wentworth et al. (2010) argued that this scenario accounts for the shape of the present basin (significantly narrower at its southeast end) and the fact that the present-day southern part of the central Calaveras fault truncates the Evergreen basin at its southeast end rather than forming the northeast boundary of the basin. The proposed Mount Misery fault is everywhere concealed today so that obtaining further information about its existence (or more accurately, whether the present-day northeastern boundary of the basin is a basin-bisecting fault) is difficult. We favor this proposed scenario, but whether it or the previous scenario characterizes the later stages of development of the Evergreen basin does not change the basic arguments and conclusions presented here.

Today, seismicity indicates that most of the slip on the central California San Andreas fault is transferred to the East Bay fault system along the southern and central Calaveras fault, through a left bend (Fig. 9E; Waldhauser and Ellsworth, 2002; Manaker et al., 2005; Ponce et al., 2004; Simpson et al., 2004) to the Hayward fault. This path bypasses the Silver Creek fault and largely passes northeast of the Evergreen basin (Graymer et al., 2015). The change from a right step to a left step would have been accompanied by a change from an extensional regime to one of compression. Cross-basin compression provides an explanation for the reverse and thrust faults that today characterize both margins of the Evergreen basin. Graymer et al. (2003, 2015) proposed that the reorganization of the regional Calaveras fault–Hayward fault junction from a releasing to a restraining geometry began ca. 2.5 Ma and was largely completed by ca. 1.5 Ma and that since then, most of the slip on the southern Calaveras fault probably bypassed the Silver Creek fault. Total offset during that period probably amounted to no more than ~20 km, and likely much less on the present-day Calaveras fault north of its junction with the Silver Creek fault (Jachens et al., 2002).

According to our proposed scenario, the geometric aspects of the Evergreen basin and the dismembered serpentinite sheet predict that, at a minimum, half of the roughly 100 km of offset across the Hayward fault (Gray-
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Duration of Activity on the Silver Creek Fault

If our identification of the Yerba Buena Ridge serpentinite sheet and the inferred Priest Valley serpentinite sheet as cross-fault counterparts is correct, then movement on the Silver Creek fault must have begun very close to the time of inception of the East Bay fault system ca. 12 Ma. Such early initiation is required by the fact that the two serpentinite sheets now are separated by 174 km, the total offset believed to be accommodated on the East Bay fault system. Furthermore, the Silver Creek fault had to have accommodated at least 40 km of offset prior to initiation of movement on the Mount Misery fault and/or the central Calaveras fault, thus implying that the Silver Creek fault was active during a significant part of the 12 m.y. lifetime of the Hayward fault. The presence of basalts with K-Ar ages of 2.5 and 3.6 Ma (Nakata et al., 1993) and containing upper mantle and lower crustal xenoliths (Jové and Coleman, 1998) adjacent to the southern Evergreen basin near the southeastern end of the Silver Creek fault suggests that the extensional regime associated with movement on the Silver Creek fault existed in Pliocene time. Jové and Coleman (1998) pointed out that some of these basalts are located near local right steps in the Calaveras fault, however, which could have produced local extension favorable for the movement of magmas from great depth. Thus, not all of the basalts necessarily indicate active formation of the Evergreen basin. However, Graymer et al. (2007) showed that the right steps in the Calaveras system probably do not extend >5 km deep.

As shown earlier, three lines of evidence suggest minor late Quaternary activity on the Silver Creek fault: a small structural sag and negative flower structure in the late Quaternary strata above the fault (Wentworth et al., 2010), InSAR results that point to a groundwater barrier (Hanson et al., 2004) above the deeper fault (Schmidt and Bürgmann, 2003; Choussard et al., 2014), and relocated seismicity on the deep Calaveras fault (Simpson et al., 2004) that shows a discontinuity at depth at its intersection with the Silver Creek fault. In addition, two ~M6 earthquakes occurred in A.D. 1903 in the Santa Clara Valley. Estimates of the locations of the epicenters of these earthquakes based on historical reports interpreted in terms of intensities (Bakun, 1999) place the earthquakes near the Silver Creek fault. However, the data are not sufficiently diagnostic to permit unequivocal identification of these earthquakes as Silver Creek fault events. Precisely relocated microseismicity (Waldhauser and Schaff, 2016) indicates a rather diffuse, steeply dipping, ~10-km-long lineament that lies along the west margin of Yerba Buena Ridge, parallel to and 3 km southwest of the Silver Creek fault; however, these events cannot at this time be attributed uniquely to the Silver Creek fault, but could also be related to the Silver Creek thrust or faults mapped along the west margin of Yerba Buena Ridge.

CONCLUSIONS

Combined analysis of geologic and geophysical information from the Santa Clara Valley reveals a large Cenozoic basin, the Evergreen basin, along the northeastern edge of the valley. The basin is 40 km long, 8 km wide, and –5.5 km deep at its deepest. It is fault bounded, with the Silver Creek fault defining its southwest margin and the Hayward fault and its probable on-strike continuations defining the northeast margin. Reverse faults exist along both margins, and in the central section, Mesozoic rocks rooted to the northeast are thrust entirely across the Cenozoic deposits that fill the basin. We propose that the Evergreen basin formed as a pull-apart basin in the wake of the right step from the Silver Creek fault to the Hayward fault and that >40 km of San Andreas fault system offset was transferred across this right step. Later in the evolution of the basin, the stress regime changed, resulting in cross-basin compression manifest as reverse and thrust fault movement along the bounding faults. The timing of this change is not obviously tied to changes in relative motion between the Pacific and North American plates, as discussed by Graymer et al. (2015) and Langenheim et al. (2015), but may be more related to local fault reorganization.

We elaborate on this proposal by searching for the offset counterpart of the 50-km-long, fault-bounded serpentinite sheet that crops out on Yerba Buena Ridge and occupies the southwest rim of the Evergreen basin. Within the constraints of known offset on the central California San Andreas fault and the amount of offset believed to have been partitioned onto the East Bay fault system, the only viable candidate for an offset counterpart of the Yerba Buena Ridge serpentinite is a comparable-length, mostly concealed serpentinite sheet east of the San Andreas fault in central California roughly centered over Priest Valley. If this identification is correct, then the two parts of the serpentinite sheet dismembered by the Silver Creek fault are separated by the full 174 km of offset believed to be accommodated by the East Bay fault system. This, in turn, would suggest that the Silver Creek fault and its stepover to the Hayward fault was active at the initiation of movement on the East Bay fault system, and that the central Calaveras fault north of its junction with the Silver Creek fault zone formed later. Additional information such as the presence around the Evergreen basin of Pliocene basalts interpreted to have been erupted in an extensional setting, a groundwater barrier in Pleistocene deposits coincident with the Silver Creek fault zone, and a marked kink in the pattern of current seismicity on the Calaveras fault at its junction with the Silver Creek fault all suggest that the Silver Creek fault has been active much of the 12 m.y. lifespan of the East Bay fault system.

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