Fault geometry and cumulative offsets in the central Coast Ranges, California: Evidence for northward increasing slip along the San Gregorio–San Simeon–Hosgri fault

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ABSTRACT

Estimates of the dip, depth extent, and amount of cumulative displacement along the major faults in the central California Coast Ranges are controversial. We use detailed aeromagnetic data to estimate these parameters for the San Gregorio–San Simeon–Hosgri and other faults. The recently acquired aeromagnetic data provide an areally consistent data set that crosses the onshore-offshore transition without disruption, which is particularly important for the mostly offshore San Gregorio–San Simeon–Hosgri fault. Our modeling, constrained by exposed geology and in some cases, drill-hole and seismic-reflection data, indicates that the San Gregorio–San Simeon–Hosgri and Reliz-Rinconada faults dip steeply throughout the seismogenic crust. Deviations from steep dips may result from local fault interactions, transfer of slip between faults, or overprinting by transpression since the late Miocene. Given that such faults are consistent with predominantly strike-slip displacement, we correlate geophysical anomalies offset by these faults to estimate cumulative displacements. We find a northward increase in right-lateral displacement along the San Gregorio–San Simeon–Hosgri fault that is mimicked by Quaternary slip rates. Although overall slip rates have decreased over the lifetime of the fault, the pattern of slip has not changed. Northward increase in right-lateral displacement is balanced in part by slip added by faults, such as the Reliz-Rinconada, Oceanic–West Huasna, and (speculatively) Santa Ynez River faults to the east.

INTRODUCTION

The central California Coast Ranges are an incompletely understood part of the North American–Pacific plate margin compared to the relatively well-studied San Francisco and Los Angeles urban areas. The region is roughly triangular, bounded by the San Andreas fault on the east, the San Gregorio–San Simeon–Hosgri fault on the west, and the Western Transverse Ranges on the south (Fig. 1). Within this region, multiple north-northwest–striking to west-northwest–striking faults, including the Reliz-Rinconada and the Oceanic–West Huasna faults (Fig. 2A), cut Cenozoic rocks that overlie three main Mesozoic basement types (Franciscan Complex, Coast Range ophiolite with overlying Great Valley Sequence, and Salinian basement with its overlying cover). This region must somehow have accommodated deformation produced by the ~90° clockwise rotation of the Western Transverse Ranges that began in the early to middle Miocene (Hornafius et al., 1986), in addition to regional transtension that accompanied the demise of the Farallon-Pacific spreading ridge (Nicholson et al., 1994; Wilson et al., 2005) and regional transpression and uplift that began ca. 5.5 Ma (McCrary et al., 1995). How this deformation is accommodated depends on the depth, extent, geometry, and cumulative displacement of the faults within this region.

Although the San Gregorio–San Simeon–Hosgri fault strikes nearly parallel to the direction of modern Pacific–North American plate-margin motion (Fig. 1), estimates of the depth, extent, and geometry of this fault and others in the central California Coast Ranges are controversial. One end-member model posits that the San Gregorio–San Simeon–Hosgri and other faults, such as the Reliz-Rinconada (Fig. 2A), are primarily northeast-dipping, compressional structures, becoming listric at more than 5–10 km depth and rooting into a regional thrust or detachment fault (Crouch et al., 1984; Namson and Davis, 1988a, 1990). Cross sections by Namson and Davis (1990) indicate as much as 20%–30% contraction across the region, with one section (Namson and Davis, 1988b) showing the San Andreas fault displaced at depth by an inferred low-angle or horizontal detachment fault. An example might be the causative fault(s) of the 2003 M 6.5 San Simeon earthquake; the main shock was located near the base of seismicity at a depth of nearly 10 km along a fault (defined by the aftershock distribution) dipping 45° to 60° to the north-northeast, likely the Oceanic fault (McLaren et al., 2008). At the other end of the spectrum, the Hosgri fault and other faults are postulated to be vertical to steeply dipping, deeply penetrating faults that primarily accommodate strike-slip deformation, as originally proposed by Hill and Dibblee (1953). Hanson et al. (2004) presented evidence based on Quaternary deposits that the Hosgri fault is steeply dipping. Relocated seismicity (Hardbeck, 2010) also supports a steep to vertical dip between 3 and 12 km for the Hosgri fault, at least where the fault is associated with microearthquakes between Piedras Blancas and Point Sal (Fig. 2B). The fault dip and depth extent are critical parameters for seismic hazard assessment, as these influence patterns of ground shaking.

The amount of offset on the faults of the central California Coast Ranges since the inception of the transform margin is also controversial. Estimates for strike-slip offset on the San Gregorio–San Simeon–Hosgri fault since ca. 4 Ma range from 5 km or less (Sedlock and Hamilton, 1991; Sorlien et al., 1999a; Underwood and Laughland, 2001) to 80–185 km (Hall, 1975; Graham and Dickinson, 1978;...
Clark et al., 1984; Jachens et al., 1998; Dickinson et al., 2005; Burnham, 2009). Other faults, such as the Reliz-Rinconada and the Oceanic–West Huasna faults, also have ranges of estimated strike-slip offset, although not as widely divergent as those for the San Gregorio–San Simeon–Hosgri fault. Estimates of cumulative right-lateral displacement for the Reliz-Rinconada fault range from at least 18 km since the Pliocene (Durham, 1965) to 60 km since the Early Tertiary (Dibblee, 1976, p. 40). In the case of the Oceanic–West Huasna fault, estimates of right-lateral displacement range from 5 to 8 km (McLean, 1993) to 15 km (Hall et al., 1995, p. 87), although others (Tennyson et al., 1991) cannot find strike-slip offset on the fault, instead showing that the fault was a locus of subsidence during the early Miocene.

In this study, we use aeromagnetic and gravity data to examine the dip, depth extent, and cumulative offsets (since the late early Miocene) of the San Gregorio–San Simeon–Hosgri and other faults in the central California Coast Ranges. Prominent aeromagnetic anomalies are caused by magnetic rock types that primarily reside within the Mesozoic basement, such as the Great Valley ophiolite, certain plutons within the Salinian block, and metabasalts within the Franciscan Complex. Gravity data are sensitive to the density distribution of the subsurface, primarily the contrast between Cenozoic basin-fill and pre-Cenozoic basement in this area. Together, these data reflect density and magnetization contrasts across faults that have significant (>1 km) vertical and/or horizontal displacements and thus allow us to look at the geometry and cumulative slip of these faults over their lifetime (since the early Miocene and even earlier with the magnetic data). This study benefits from the recent acquisition of detailed aeromagnetic data that cover the entire central California Coast Ranges, providing an areally consistent data set that crosses the onshore-offshore transition without disruption. This is particularly important for the San Gregorio–San Simeon–Hosgri fault, which lies mostly offshore and offers few opportunities to estimate offset based on geologic mapping.

Based on our analysis of the aeromagnetic and gravity data, the San Gregorio–San Simeon–Hosgri and Rinconada faults dip steeply to mid-crustal depths. Displacement on these faults is primarily strike slip. Based on correlation of magnetic anomalies on either side of the fault, we propose that displacement on the San Gregorio–San Simeon–Hosgri fault increases northward because of slip on subsidiary faults to the east, accommodating the clockwise rotation of the Transverse Ranges.

GEOPHYSICAL DATA

More than 500 new gravity measurements in the region were added to earlier coverage (Roberts et al., 1990; Langenheim et al., 2002; Pan-American Center for Earth and Environmental Studies, 2010; McPhee et al., 2011; Watt et al., 2011b) for this study. Together, nearly 25,000 gravity measurements were used to create an isostatic residual gravity map of the region (Fig. 3). The isostatic correction (using a sea-level crustal thickness of 25 km, a crustal density of 2670 kg/m³, and a mantle-crust density contrast of 400 kg/m³) removes the long-wavelength effect of deep crustal and/or upper-mantle masses that isostatically support regional topography, assuming an Airy-Heiskanen model of isostatic compensation (Jachens and Griscom, 1985). Modifying the parameters or using a Pratt-Hayford model of compensation produces changes of such long wavelength that the shapes of the residual anomalies are changed only slightly (Jachens and Griscom, 1985; Oliver, 1973). Measurement distribution onshore is on average 1 station per 2 km² south of latitude 36°15′N (courtesy of the agency formerly known as the Defense Mapping Agency). North of latitude 36°15′N, measurement distribution onshore in the Gabilian and Santa Lucia Ranges may be as low as 1 measurement per 10 km². Offshore, data are generally taken from gridded compilations of shiptrack gravity data.
Figure 2. (A) Simplified geologic and (B) shaded-relief topographic maps of the study area. Geology is from Jennings et al. (1977). Faults shown in thin red lines are modified from Jennings and Bryant (2010). Thick black dotted line—Nacimiento fault; dashed magenta line—Russell fault. Thick gray dotted line in A shows outline of onshore Santa Maria Basin. Abbreviations in A: CF—Casmalia fault; ChF—Chimineas fault; EHF—East Huasna fault; LHF—Lions Head fault; LOF—Los Osos fault; LPF—Little Pine fault; MBFZ—Monterey Bay fault zone; OF—Oceanic fault; SCF—South Cuyama fault; SMRF—Santa Maria River fault; SYF—Santa Ynez fault; SYRF—Santa Ynez River fault; WHF—West Huasna fault. Star in B is location of 2003 M 6.5 San Simeon main shock.
Isostatic residual gravity anomalies reflect density variations in the upper 10–15 km (Simpson et al., 1986), with one of the most prominent density contrasts being that between low-density Neogene sedimentary rocks and dense Mesozoic basement rock types. Pronounced gravity lows within the central California Coast Ranges coincide with deep sedimentary basins in the Cuyama, Santa Maria, Jolon, and Salinas Valleys (Figs. 2B and 3). Gravity lows also coincide with the Ventura Basin and its offshore extension beneath the Santa Barbara Channel (Fig. 3). Gravity highs coincide with exposures of Salinian basement rocks in the Santa Lucia, Gabilan, and La Panza Ranges as well as with outcrops of Franciscan Complex and Great Valley ophiolite in the San Rafael, southern Santa Lucia, and western Santa Ynez Mountains. Intermediate gravity values over widespread exposures of Eocene and Cretaceous sedimentary rocks in the
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eastern Santa Ynez Mountains reflect intermediate densities between the low-density Neogene rocks and the denser basement rocks.

Prominent aeromagnetic anomalies reflect the relative abundance of magnetic minerals, primarily magnetite, in rocks from the surface to mid- to lower crustal depths. In the Coast Ranges, these anomalies are generally associated with Mesozoic basement rocks. Ultramafic rocks associated with the Coast Ranges ophiolite produce magnetic highs near Point Arguello, Point Sal, San Luis Bay, Piedras Blancas, and the western San Rafael Mountains (Figs. 2 and 4). The magnetic high associated with the Point Sal ophiolite can be traced nearly 50 km southeastward beneath the sedimentary cover of the Santa Maria Basin. Metabasalt and interleaved slices of ophiolite within the Franciscan Complex are responsible for the northwest-trending, narrow magnetic anomalies within the Santa Lucia Range.

Other magnetic sources lie within the basement of the Salinian block. The granodiorite of La Panza Range is associated with one of the more prominent magnetic anomalies in the central Coast Ranges (Figs. 2 and 4). The basement of the Salinian block, however, is not uniformly magnetic; exposures of batholithic rocks in the northern Gabilan and Santa Lucia Ranges coincide with a generally flat magnetic field. Magnetic anomalies associated with the Salinian block tend to be broader and blockier than the elongate anomalies associated with the Franciscan Complex.

Other possible magnetic rock types, such as Tertiary basaltic rocks, are generally thin (<150 m) within the study area (Cole and Stanley, 1998). Several drill holes have penetrated thicker sections of Tertiary volcanic rocks in the Pismo syncline, along the Santa Maria River and Santa Ynez River faults, and west of the Hosgri fault (Cole and Stanley, 1998), although the volcanic section there appears to consist mainly of weakly magnetic tuffs (Ron Cole, 2011, written commun.). Sedimentary rocks are weakly magnetic, except for locally magnetic conglomerate and sandstone that coincide with a narrow, northwest-trending magnetic anomaly located on the southwest flank of the La Panza Range. Thus, the magnetic data allow us to infer basement type beneath the Cenozoic basin fill in most places.

Potential-field gradients mark stretches of the major faults in the region. The Hosgri fault not only coincides locally with magnetic gradients along its length, but it also separates more westerly trending anomalies to the east from more northerly trending anomalies to the west. The more westerly trending anomalies appear to be truncated by the fault, especially between

Figure 4. Aeromagnetic map. White line—coastline. Gray line—seismic-reflection profile SJ-6. Blue lines—modeled profiles. Thick gray dotted line shows outline of onshore Santa Maria Basin. Thick black dotted line—Nacimiento fault; dashed magenta line—Russell fault. Abbreviations: LHF—Lions Head fault; LOF—Los Osos fault; LPF—Little Pine fault; OF—Oceanic fault; SYRF—Santa Ynez River fault; WHF—West Huasna fault; CSM—Cape San Martin; PA—Point Arguello; PB—Point Buchon; PS—Point Sal; SLB—San Luis Bay; SLO—San Luis Obispo.
Point Arguello and Cape San Martin (Fig. 4). The Hosgri fault thus marks a significant magnetic domain boundary. The San Gregorio fault, which we interpret to be a northern continuation of the Hosgri fault via the San Simeon fault, coincides with a fairly broad magnetic gradient that trends northwest across the mouth of Monterey Bay. The combined Hosgri–San Simeon–San Gregorio fault is also well expressed in the gravity field (Fig. 3). North of San Simeon, it separates the prominent gravity high of the Santa Lucia Range to the east from gravity lows offshore to the west. South of San Simeon, the fault lies near the base of a significant gravity gradient for a stretch of 70 km, consistent with northeast-side-up slip and a steep northeast dip. South of Point Sal, the gravity gradient continues in a more diffuse fashion ~30–40 km to Point Arguello, where it begins to change to a more easterly strike and wraps around the coast–line uninterrupted, merging with the striking east-west gravity gradient associated with the northern margin of the offshore Ventura Basin (Fig. 3).

The Reliz-Rinconada fault is marked by magnetic gradients for a stretch of nearly 100 km from San Ardo to the vicinity of San Luis Obispo (Fig. 4). It bounds the southwestern side of the prominent magnetic high associated with the granodiorite of the La Panza Range (Fig. 4). About 35–40 km to the north near Jolon Valley, it bounds the east side of an areally equivalent, but lower-amplitude, magnetic high, the source of which is concealed beneath Cenozoic and Mesozoic sedimentary rocks. Gravity gradients also mark this stretch of the fault zone. Continuity of the gravity gradient separating high values in the San Rafael Mountains from gravity lows in the Huasna syncline suggests that the Rinconada fault joins with the East Huasna fault to the southeast as a continuous fault system. North of Greenfield, the northern, Reliz segment of the fault lies at the base of a 40-km-long east-facing gravity gradient (Fig. 3).

Magnetic and gravity data support linking the Oceanic, West Huasna, Santa Maria River, and Little Pine faults as one major structure. Like the Hosgri fault, this fault system forms a boundary between magnetic domains. This composite fault marks the sharp southwestern margin of a prominent magnetic high associated with ophiolite north of San Luis Obispo. South of San Luis Obispo, it separates shorter-wave-length anomalies to the west from a smoother magnetic field to the east for a distance of ~60 km. Southeast of Santa Maria Valley, it again forms the southwestern margin of a prominent magnetic high that coincides with exposures of serpentinite and Franciscan Complex in the hanging wall (northeast side) of the Little Pine fault (Fig. 4). The Little Pine fault is also marked by a gravity gradient indicating northeast side up.

Other faults do not coincide with prominent magnetic or gravity gradients, notably portions of the Quaternary traces of the Los Osos and Lions Head faults. In the case of the Lions Head fault, this may indicate that the fault trace is poorly exposed or mapped (see Sylvester and Darrow, 1979), except where it is intercepted by drill-hole data (Hall, 1982). Where it is well exposed at its northwest end, it places ophiolite against Miocene sedimentary rocks and coincides with a strong magnetic gradient. To the southeast, the map trace is poorly constrained by surficial data and deviates from the southwest edge of a magnetic body, which we suggest is a better indicator of the location of the fault. In contrast, the Quaternary map trace of the Los Osos fault is well known where it forms the northeast margin of the Irish Hills (Fig. 2). We interpret the absence of prominent gravity and magnetic gradients along this fault, except along its northeasternmost extent, to reflect at most a small amount of cumulative displacement, consistent with a low slip rate, recent initiation, or both.

**GEOPHYSICAL MODELS**

**Approach**

We present several joint gravity and magnetic models across the central California Coast Ranges, focusing in particular on the geometry and depth extent of the San Gregorio–San Simeon–Hosgri and Reliz-Rinconada faults. Constraints on the geometry and depth of these faults are derived primarily from magnetic data, although gravity data provide information on fault dip for the upper 2–3 km of the crust, especially on profiles C-C’ and G-G’.

We used a 2.5-dimensional simultaneous gravity and magnetic modeling program based on generalized inverse theory. The program requires an initial estimate of model parameters (depth, shape, magnetization, and density of suspected sources), and then selected parameters are varied manually in an attempt to reduce the weighted root-mean-square misfit between the observed and calculated potential fields. The initial model estimate is based on mapped geologic relationships, physical property information, and well intercepts. The amplitude of an anomaly is not the only attribute to match; gradients and inflections are critical parameters constraining the depth to the top of the source and its shape.

Magnetic properties are assigned to match the amplitudes of the observed anomalies and to be within reasonable ranges for various rock types (e.g., Dobrin and Savit, 1988). We assume that remanent magnetization is a minor component of the total crustal magnetization, which is supported by measurements of natural remanent magnetization on the granodiorite of the La Panza Range (10\(^{-2}\) to 10\(^{-3}\) A/m; Edward Mankinen, 2008, oral commun.; Koenigsberger ratio of less than 0.01) and Koenigsberger ratios of less than 1 for Coast Ranges ophiolite (Beebe, 1986; Langenheim et al., 2012). Assignment of magnetic susceptibilities was guided by more than 1000 magnetic susceptibility measurements from hand samples and outcrops in the study area. For areas with complexly interleaved ophiolite and Franciscan Complex, we used an average susceptibility that matched both the amplitude and gradient of the anomaly. Maximum depth of the magnetic rocks is limited by the Curie isotherm for magnetite. Modeling of heat flow across the Coast Ranges suggests that temperatures are lower than 580 °C to depths of 20–25 km (Erkan and Blackwell, 2009)—essentially to the base of the crust. We did not try to fit every short-wavelength magnetic anomaly, but instead concentrated on matching the shape and amplitude of the magnetic anomalies that pertain to fault geometry.

Assignment of densities for the Mesozoic basement and overlying sedimentary cover is guided by more than 700 hand sample measurements from published sources (Ross, 1972, 1982) and this study as well as from well logs. For the Neogene sedimentary rocks, densities from hand samples are often biased toward higher values due to difficulty in obtaining a hand sample in loosely consolidated materials. The most direct measure of the density of the Neogene sedimentary sequence comes from five borehole gravity surveys in the Santa Maria Basin (Beyer et al., 1985) and a handful of density logs in northern Salinas Valley (Tiballi and Brocher, 1998).

The depth extent modeled for the crustal sources depends on the assigned density and magnetization contrasts. A higher density and magnetization contrast is needed if the modeled source is thinner, which in turn can lead to a shallower dip for the physical property contrast. The geometry of the base of modeled sources is poorly resolved by the potential-field data.

**Results**

**San Gregorio–San Simeon–Hosgri Fault**

Potential-field models, described in more detail in the following, indicate that the San Simeon and Hosgri faults are vertical to steeply northeast dipping in the upper 3–15 km. The San Gregorio fault appears to dip moderately to
the northeast where it is modeled in Monterey Bay. Depending on the physical property contrast chosen, the fault can be modeled to extend as deep as the base of the seismogenic zone at depths of 12–15 km.

In Monterey Bay, modeling across profile A-A’ (Fig. 5) indicates a moderate northeast dip for the contact between magnetic rocks on the southwest (undivided Franciscan Complex and ophiolite, serpentinite) against nonmagnetic rocks to the northeast (basement of the Salinian block). The top of the magnetic source is equal to or deeper than the base of the Miocene rocks, here defined by seismic-reflection data (Aiello, 2005) and constrained loosely by the gravity data. The dip of the fault depends on the depth extent of the magnetic property contrast. If the magnetic property contrast (0.01 SI) extends to 15 km, the dip is ~55°; if a slightly higher contrast (0.0126 SI) extends to 10 km, the modeled dip is less, ~45°. A vertical fault leads to a much steeper gradient that is west of the observed gradient. Our results are consistent with estimated dips of 50° to 70° for the San Gregorio fault in Monterey Bay based on relocated seismicity using ocean-bottom seismometers (Begnaud et al., 2000; Simila et al., 2006) and with northeast dips on seismic-reflection profiles (C. Sorlien and A. Smith, 2012, electronic commun.). We note here that the magnetic gradient becomes steeper to the south and north of profile A-A’, suggesting that the fault dip steepens away from the modeled section.

Farther south, along profile B-B’ (Fig. 6), the San Simeon fault, in one of the few places where this fault system is exposed, truncates magnetic anomalies associated with ophiolite that is exposed in outcrop (Mattinson and Hopson, 2008) on its west side. Modeling of the magnetic high indicates that the ophiolite is bounded by a vertical fault from 4 to 10 km depth (Fig. 6). A small gravity gradient is associated with the fault, but it does not help to constrain the dip of the fault.

In Estero Bay (profile C-C’ in Fig. 2), the Hosgri fault marks the base of a steep gravity gradient and the western side of a broad magnetic high. It places Cenozoic sedimentary rocks to the west against Mesozoic basement to the east. Model C-C’ (Fig. 7) indicates a steep northeast dip of ~65°–70° for the Hosgri fault in the upper 3 km of the crust, while a vertical fault leads to a substantial mismatch (~2 km) in the location of the gravity gradient. The magnetic anomaly associated with the Hosgri fault can be fit in two ways: (1) moderately magnetic material (0.0075 SI) extending vertically from depths of 3 km to 15 km, representing an average susceptibility for interleaved Franciscan Complex and ophiolite, or (2) very magnetic material (0.025 SI; ophiolite and serpentinite; polygon labeled C in Fig. 7) extending from depths of 3 km to 8 km. In both models, magnetic material does not extend along the Hosgri fault to the surface, but instead surfaces to the east of the fault, along an offshore projection of the Los Osos fault, consistent with results of Watt et al. (2011a) based on seismic-reflection and more detailed, marine magnetic data.

The southernmost model D-D’ extends across the Hosgri fault at the latitude of Point Sal. The top of the magnetic source is equal to or deeper than the base of the Miocene section, here defined by seismic-reflection data (C.R. Willingham, 2011, written commun.). Modeling of the magnetic data (Fig. 8) indicates a near-vertical fault that dips 80°–85° to the northwest and extends to a depth of 10 km.

**Reliz-Rinconada Fault**

Potential-field models across the Reliz-Rinconada fault indicate that it is generally steeply dipping, but its dip direction changes along strike. Three models cross the fault in the vicinity of the La Panza Range, where modeling indicates a near-vertical dip (Figs. 7, 9, and 10). The southernmost model F-F’ (Fig. 10) crosses through the apex of the prominent magnetic anomaly of the La Panza Range, where the Rinconada fault juxtaposes Franciscan Complex and its sedimentary cover to the southwest against granodiorite of the La Panza Range to the northeast. In order to match both the position of the magnetic gradient along the Rinconada fault and the amplitude of the magnetic high, granodiorite with a magnetic susceptibility matching the average measured value for these rocks must surround a significantly more magnetic core that extends to a depth of 20 km. The base of the magnetic body could be as shallow as 15 km, as shown in models C-C’ and E-E’, but this would require an increase in the modeled susceptibility. The base of the magnetic body may coincide with a band of gently east-dipping reflections imaged along seismic profile SJ-6 at a depth of ~15–20 km (Trehu and Wheeler, 1987). Regardless of the depth extent, modeled magnetic susceptibility, or presence of a concealed more magnetic core, a near-vertical dip is needed to match the location of the

Figure 5. Gravity and magnetic model across profile A-A’. D and S are density and magnetic susceptibility in kg/m³ and SI units. If no value for S is given, S equals zero. The eastern edge of the magnetic rocks (unit Jsp) projects to the base of the Quaternary and Tertiary sedimentary strata (unit QTs) along the San Gregorio fault zone. Dashed black line on cross section is an alternate geometry of the magnetic high, granodiorite with a magnetic susceptibility for interleaved Franciscan Complex and ophiolite, or (2) very magnetic material (0.025 SI; ophiolite and serpentinite; polygon labeled C in Fig. 7) extending from depths of 3 km to 8 km. In both models, magnetic material does not extend along the Hosgri fault to the surface, but instead surfaces to the east of the fault, along an offshore projection of the Los Osos fault, consistent with results of Watt et al. (2011a) based on seismic-reflection and more detailed, marine magnetic data.

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Figure 6. Gravity and magnetic model across profile B-B’. D and S are density and magnetic susceptibility in kg/m³ and SI units, respectively. If no value for S is given, S equals zero. Dotted body at eastern end is a magnetic pluton within the Salinian block that lies out of the plane of the section to the south. Units in cross section: QTs—Cenozoic sedimentary rocks and deposits; QTp—Paso Robles Formation; Tm—Monterey Formation; Ts—Tertiary sedimentary rocks; Tv—Vaqueros Formation; KT—Cretaceous and Tertiary sedimentary rocks; Ks—Cretaceous sedimentary rocks; Kgr—Salinian basement; KJf—Franciscan Complex; KJfv—metavolcanic rocks of the Franciscan Complex; Jo—ophiolite; Jsp—serpentinite. Bodies marked by dotted pattern denote rocks overlying Mesozoic basement. Note that the geometry of the Oceanic fault is not constrained by gravity and magnetic data but is based on relocated aftershocks of the 2003 San Simeon earthquake. V.E.—Vertical exaggeration.
magnetic gradient along the Reliz-Rinconada fault. A more magnetic core is not needed for models E-E’ and C-C’, which cross the magnetic anomaly where it has a lesser amplitude.

Along seismic profile SJ-6, model E-E’ shows the degree of mismatch of the magnetic anomaly with moderate southwest or northeast dips of the Rinconada fault; a steep dip of 77° to the northeast provides a calculated curve that best fits the observed magnetic data (inset in Fig. 9). A slight northeast dip is consistent with the apparent termination of the deep, gently east-dipping reflections on SJ-6, just east of the surface trace of the Rinconada fault and with higher terrain east of the Rinconada fault.

About 50 km to the northwest, geologic analysis and modeling of magnetic data along B-B’ (Fig. 6) may indicate a more complicated geometry and history for the Rinconada fault. Magnetic data indicate a near-vertical dip for the magnetic contrast under the surface trace of the Rinconada fault below ~3 km. Steeply dipping fault strands in the upper 3 km are based on folded Cenozoic sedimentary strata and on drill-hole data and a seismic-reflection profile 5–10 km to the northwest of B-B’ (Graham et al., 1991). Gravity data are consistent with overall southwest-side-up displacement on the fault and with a steep southwest dip for the easternmost strand of the Rinconada fault. Although the magnetic contrast beneath 3 km may reflect a vertical plutonic contact rather than a fault, the magnetic gradient produced by this contrast is roughly collinear with the surface trace of the Rinconada fault for at least 25 km along strike (Fig. 4), suggesting a fault origin is more likely. The steeply dipping strands inferred from field attitudes and other data likely reflect transpressional slip across the Rinconada fault since the late Miocene (Titus et al., 2007), while the deeper magnetic contact may reflect older, more purely strike-slip displacement along the fault. The idea of an older (Miocene), near-vertical fault was also proposed by Graham et al. (1991), likely because the dipping Rinconada fault was not deemed compatible with tens of kilometers of strike slip attributed to the fault.

The northernmost model G-G’ (Fig. 11) crosses the Reliz segment of the Reliz-Rinconada fault where it lies at the base of a gravity gradient arising from the density contrast between Salinian block basement to the southwest and Cenozoic deposits to the northeast. The fault is not readily imaged by the magnetic data along the profile. We show two models for the geometry of the Reliz fault, assuming two different density contrasts. Assuming a typical density contrast of ~400 kg/m³ between the basement complex and the overlying sediments indicates a fault that dips moderately (~45°) to the southwest. Assuming a somewhat lower density contrast of ~300 kg/m³, the dip steepens to ~70°. A lower density contrast is supported by several density logs in the broader Salinas Valley region (Tiballi and Brocher, 1998). Regardless of the density contrast chosen, the Reliz fault dips to the southwest in the upper 1–2 km of the crust.

Other Faults

Our models locally provide constraints on the attitudes of other faults in the central California Coast Ranges. Models C-C’ (Fig. 7) and
F-F′ (Fig. 10) cross the West Huasna fault where it forms the southwestern margin of a prominent magnetic anomaly originating in serpentinite and ophiolite. In both models, the fault dips steeply northeast (70°–80°) to a depth of ~6 km. Generally higher topography northeast of the fault along much of its length (Fig. 2B) suggests a reverse component of slip. Geologic mapping shows that the West Huasna fault is vertical to northeast-dipping, but with down-to-the-northeast displacement in the Tar Spring Ridge and Lopez Mountains quadrangles (McLean, 1994, 1995), located a short distance southeast of F-F′ (Fig. 10). Our modeled dip is steeper than the focal mechanism determined for the 2003 San Simeon main shock (46° northeast; McLaren et al., 2008), ~40 km northwest of our modeled profiles and where the Oceanic fault—interpreted here as a northwestward continuation of the West Huasna fault—has a more westerly trend and presumably becomes more transpressional or compressional. Alternatively, the West Huasna fault may become more listric at depths greater than 6 km, below the sensitivity of our model.

The Nacimiento fault, although primarily active during the Late Cretaceous (Dickinson, 1983), is a major structure that separates the Franciscan Complex from the Salinian block. The geometry of the Nacimiento fault is locally constrained by modeling of magnetic data along profile B-B′ (Fig. 6). Downward projection of serpentinite and ophiolite exposed just southwest of the fault precludes a vertical or southwest dip for the Nacimiento fault in the upper 5–6 km. The concealed southwest margin of magnetic Salinian block basement (Kgr in Fig. 6) requires the fault to dip steeply. Geologic mapping in the southern Santa Lucia and San Rafael Mountains (Vedder et al., 1991) also indicates a northeast dip for the Nacimiento fault. The steep northeast dip of the fault derived from the magnetic data is consistent with results from a seismic-refraction study (Howie et al., 1993) 50 km to the southeast of profile B-B′. However, the significant seismic-velocity contrast across the fault is not accompanied by an equally significant gravity gradient. The Nacimiento fault even strikes across a major, continuous gravity high in the Santa Lucia Range (Fig. 4). The absence of a significant density contrast suggests that the fault places relatively coherent, higher-velocity Salinian block rocks (granite and gneiss) against fractured, lower-velocity, but equally dense Franciscan Complex rocks (as exemplified by units of mélange and broken formation).

Model D-D′ (Fig. 8) sheds light on the geometry of the Lions Head and Casmalia faults in the Santa Maria Basin. Although the profile crosses both faults obliquely, it crosses the Lions Head fault where it coincides with a pronounced magnetic gradient caused by the southeast edge of the Point Sal ophiolite. The difference in location between the gravity and magnetic gradients along the northeast margin of the ophiolite suggests that the Casamalia fault truncates the

![Figure 8. Gravity and magnetic model across profile D-D′. D and S are density and magnetic susceptibility in kg/m³ and SI units, respectively. Units in cross section: QTs—Quaternary and Tertiary sedimentary rocks; KJf—Espada Formation; Jo—ophiolite; KJf—Franciscan Complex; Jo/KJf—ophiolite and Franciscan Complex, undivided. Faults: CF—Casmalia fault; HF—Hosgri fault; LHF—Lions Head fault. V.E.—Vertical exaggeration.](https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/5/1/29/3723410/29.pdf)
Ophiolite at ~3 km depth. Modeling of the magnetic data indicates steep dips for both faults in the upper 5 km, with the Lions Head fault dipping to the northeast and the Casmalia fault dipping to the southwest. Our results are consistent with a seismic-reflection profile interpreted by Seeber and Sorlien (2000) ~25 km to the south-west of D-D'.

Lastly, model F-F' (Fig. 10) highlights structures that bound the Irish Hills. The model crosses the Pismo syncline, characterized by a gravity low originating in Miocene and younger sedimentary rocks. Modeling of the magnetic data indicates that fairly magnetic rocks underlie the syncline, likely the same ophiolite and serpentinite that are exposed in uplifted blocks on both sides of the syncline. The Los Osos fault, a Quaternary reverse or thrust fault, forms the northern topographic margin of the Irish Hills. Along F-F', the surface trace of the fault coincides with a modeled, near-vertical magnetic boundary (Fig. 10), but it deviates away from the more linear magnetic boundary along strike out of the cross section. This relationship suggests that the Los Osos fault is not a major structure with significant cumulative displacement. Rather, we suggest that the pronounced linear magnetic boundary, slightly northwest of the mapped Los Osos fault, is a major structure, possibly as old as Mesozoic. This boundary coincides with an alignment of Oligocene volcanic necks (the Morro Rock–Islay Hill volcanic complex of Ernst and Hall, 1974).

The southwest margin of the Irish Hills corresponds with a linear magnetic boundary that lies just offshore. The southern edge of the magnetic body, as modeled along profile F-F', is nearly vertical and also coincides with the Shoreline fault, a linear and near-vertical lineament defined by seismicity (Hardebeck, 2010) and scarp on the seafloor (Nishenko et al., 2010). The model indicates a depth extent of 6 km, although the body could be thinner, deeper, and more magnetic, and still fit the data. For example, Watt et al. (2011a) fit more detailed marine and helicopter marine data by extending the magnetic source to 8 km depth, with thin, near-vertical slices of ophiolite extending nearly to the surface. Note that the magnetic gradient caused by the southwest margin of the ophiolite extends farther to the southeast than does the relocated seismicity.

**Implications of Potential-Field Modeling**

Potential-field modeling indicates that the San Gregorio–San Simeon–Hosgri and Reliz-Rinconada faults are generally characterized by steep dips through seismogenic depths. The San Gregorio–San Simeon–Hosgri fault, where it is not vertical, always dips to the northeast. The Reliz-Rinconada fault, where not vertical, tends to dip southwest along its northern stretch and northeast along its southern stretch. Modeled dips are consistent with those imaged by microearthquakes during the past three decades, primarily along the Morro Bay stretch of the San Gregorio–San Simeon–Hosgri fault (Hardebeck, 2010). Because the contacts modeled by the potential-field data represent long-term displacements, the similarity in fault geometry between the potential-field data and the microseismicity suggests that the fault geometry has been roughly constant over the lifetime of the faults in these two places. This is contrary to interpretations of shallow dips based on seismic-reflection data along the Hosgri fault (Crouch et al., 1984) and balanced cross sections across both the Hosgri and Rinconada faults (Namson and Davis, 1988a, 1988b, 1990). The shallow dip...
dips interpreted by Crouch et al. (1984) could be out-of-plane reflectors or artifacts of processing; however, only line drawings of the data across the fault are published. A key assumption in producing the area-balanced fault-bend fold-style cross sections by Namson and Davis (1988a, 1988b, 1990) was that no material has moved in or out of the line of the section, an assumption that is violated by significant strike slip.

Although our models indicate generally steep dips for major faults, two exceptions are the San Gregorio fault in Monterey Bay and possibly the northern part of the Reliz-Rinconada fault. The moderate dip of the San Gregorio fault likely steepens to the south and north in Monterey Bay as indicated by tightening of the magnetic gradient to the south and north. The profile crosses the San Gregorio fault close to its intersection with the Monterey Bay fault zone, and the deviation from a steep dip may reflect interaction between the two fault systems, rather than from reactivation of an earlier extensional or even subduction-related fault. The geometry of the northern stretch of the Reliz-Rinconada fault may reflect transpression that began during the late Miocene or possibly a complicated transfer of slip from the Reliz-Rinconada fault to the San Gregorio–San Simeon–Hosgri fault through the Santa Lucia Mountains. In either case, we speculate that more moderate dips may be the result of local fault interactions or transfer of slip between faults. If so, deviations from near-vertical faults should be considered along other stretches of these faults where fault interaction or slip transfer is known, even though physical property contrasts are lacking or microseismicity is absent.

Steeply dipping faults that cut the whole seismogenic crust indicate that much of the displacement on these faults should be characterized by strike-slip displacement, rather than by mostly reverse or normal offsets. Exceptions may be the result of fault interactions, as noted in the previous paragraph, or of subsequent deformation of previously vertical fault planes by regional transpression that began during the late Miocene. Next, we estimate cumulative strike-slip offset along major faults by correlating magnetic and gravity anomalies and then compare these estimates with those derived from geologic observations.

ESTIMATES OF CUMULATIVE FAULT OFFSET

Identifying offset magnetic and gravity anomalies across faults is analogous to identifying offset geologic features at the surface. We search along the trace of a candidate fault for elongate magnetic anomalies that are subparallel to the fault and that are truncated at the fault trace. We then search the opposite fault block for similar anomalies that are truncated against the opposite side of the fault and estimate the magnitude of offset by measuring the along-fault separation between corresponding distinctive features of the anomaly. In most cases, that distinctive feature is the inferred lateral boundary of the causative magnetic body. Such boundaries (black dots on Fig. 12A) are determined automatically from the digital aeromagnetic grid by the technique of Blakely and Simpson (1986), modified slightly to focus the technique on the top edge of the magnetic body. This technique has been used to measure offsets along faults in the Mojave Desert, yielding results for right-lateral offset along these faults consistent with geologic data (Jachens et al., 2002). Uncertainty in the offset estimate arises from (1) possible misidentification of offset features, (2) imprecision in defining the offset features from the magnetic data, (3) dip-slip offsets
that give rise to apparent strike-slip offsets, and (4) nonrigid behavior of the blocks on either side of the fault, and (5) location errors in the original magnetic surveys, which are less than 10 m. Given these factors, 5 km is a reasonable upper bound of the estimate of offset uncertainty. In the central California Coast Ranges, strike-slip offsets defined on the basis of magnetic and gravity data are generally in good agreement with and in several cases refine those from geologic data for the major through-going faults (Table 1).

San Gregorio–San Simeon–Hosgri Fault Zone

This fault zone is more than 400 km long, extending north from Point Arguello to just offshore of San Francisco, where it merges with the San Andreas fault (Fig. 1). Seismic-reflection data south of Point Arguello imply that the fault widens as it curves around the coastline and, although poorly imaged, may be a northeast-dipping thrust (Steritz and Luyendyk, 1994). At its southern end, the Hosgri thus becomes either a westward continuation of the North Channel fault system or is truncated by that fault system (Sorlien et al., 1999b). A pronounced gravity low (Fig. 3) and long-wavelength magnetic highs of the Ventura Basin and Santa Barbara Channel (Fig. 4) wrap west and northwest around the coastline without interruption, suggesting that the Hosgri fault does not continue south to the Channel Islands with any significant offset. This interpretation of the potential-field data supports previous interpretations of seismic-reflection profiles (Steritz and Luyendyk, 1994; Sorlien et al., 1999b) indicating that the fault zone does not extend across the Santa Barbara Channel.

We start our correlation of magnetic features across this fault system at its southern end. The southern extent of the Hosgri fault forms the western edge of a magnetic body near Point Arguello (PA on Fig. 12B) that consists of Franciscan Complex and serpentinite exposed south of the Santa Ynez River fault to the south of Lompoc. On the west side of the Hosgri fault at this latitude, there is a broad magnetic high underlying the offshore Santa Maria Basin, the edge of which most clearly coincides with the Hosgri fault ~20–30 km north of the Point Arguello magnetic high. However, the poorly defined edges of the western magnetic body may reflect in part relief on the surface of the magnetic basement rather than horizontal offset on the Hosgri fault. Furthermore, interpretation of seismic-reflection data suggests 3.5 km of strike-slip offset since 4 Ma between Point Sal and Point Conception (Sorlien et al., 1999a), based on restoring folds that deform the top of the Sisquoc Formation. An equally viable, and our preferred, interpretation is that the Hosgri fault offsets the magnetic basement (presumed to be Mesozoic) horizontally by no more than 5–10 km, which is consistent with the interpretation of the offshore seismic-reflection data.

The next prominent magnetic anomaly east of the Hosgri fault north of Point Arguello is the band of concealed magnetic rocks that bisects the Santa Maria Basin and surfaces at the Jurassic Point Sal ophiolite. As shown by the magnetic data, the edges of this body extend offshore northwest of Point Sal and are truncated at the Hosgri fault (body 1 in Fig. 12B). The next prominent magnetic anomaly with similar character west of the fault is located near San Simeon (body 1’ in Fig. 12B). The anomalies are the same width where truncated by the Hosgri and San Simeon faults. One of the first studies that estimated strike-slip offset along the Hosgri fault zone correlated the ophiolite and its overlying sedimentary section at Point Sal with a similar ophiolite at San Simeon, giving a minimum estimate of 80 km of strike-slip offset (Hall, 1975). Correlation of the magnetic anomalies supports that geologic estimate and arguably refines the estimate to 86–89 km because the magnetic data can be used to extrapolate the ophiolite exposed at Point Sal more than 10 km to the northwest offshore where it is truncated by the Hosgri fault.

Recent, high-precision U-Pb zircon ages for the ophiolites at Point Sal and San Simeon are indistinguishable at 165.580 ± 0.038 Ma (Mattinson and Hopson, 2008), supporting the correlation of at least the Jurassic ophiolites. As discussed by Sedlock and Hamilton (1991), however, much of this displacement may be older than Neogene and predate initiation of slip on the San Andreas system. The key correlation is therefore that between the Tertiary nonmarine conglomerates (Lospe Formation) that overlie the ophiolite. The type Lospe Formation is located south of Point Sal, where isotopic and biostratigraphic data indicate deposition between 18 and 17 Ma (Stanley et al., 1996). The conglomerates of the type Lospe Formation near Point Sal include clasts from the ophiolite and from various rock types of the Franciscan Complex, whereas the so-called Lospe section near San Simeon contains clasts mostly of ophiolitic debris. The differences in clast compositions between the two areas probably reflect local differences in sediment source areas during the deposition of the Lospe.
Figure 12 (on this and following page). (A) Aeromagnetic map with maximum horizontal gradients (black dots) that mark edges of magnetic bodies. Brown lines—faults (solid—Quaternary; dotted—older); blue line—coastline. (B) Annotated aeromagnetic map with correlated magnetic anomalies. Dark-gray lines outline correlated anomalies (labeled a, a', etc.) across the Reliz-Rinconada, Chimineas, East Huasna (EHF), and South Cuyama (SCF) faults; purple lines mark edges of magnetic bodies (labeled 1, 1', etc.) correlated across the San Gregorio–San Simeon–Hosgri and West Huasna faults. EHF—East Huasna fault; RF—Russell fault; SCF—South Cuyama fault; SCM—Santa Cruz Mountains; SM—Stanley Mountain; SYRF—Santa Ynez River fault. Anomalies PA and SRM are discussed in text. Red lines—faults (solid—Quaternary; dotted—older); blue line—coastline. (C) Reconstruction of horizontal offset on faults based on matching magnetic anomalies. No offset was restored on the Santa Ynez River fault. Two positions of the Western Transverse Ranges are shown, one at its present-day location and the other after restoring 90° of clockwise rotation. Note that north is rotated ~45° counterclockwise.
Formation. The youngest detrital zircon ages of the conglomerates in the type Lospe Formation at Point Sal and the conglomerates that overlie the San Simeon ophiolite are the same (J.P. Colgan, 2011, written commun.) and thus are consistent with the two sections at Point Sal and San Simeon being part of the same late early Miocene depositional system.

The next prominent magnetic anomaly east of the fault north of Point Sal is near Point Buchon, with a pair of Mesozoic ophiolites that bracket the Pismo syncline. The anomaly pattern consists of two magnetic highs bracketing a low (body 2 in Fig. 12B). The cross-fault counterpart is located 122–128 km to the northwest along the Hosgri–San Simeon fault near Point Sur, which also shows a double-peak magnetic high (body 2’ in Fig. 12B). Geologic support for correlation of these magnetic anomalies is indicated by Miocene sedimentary strata overlying the Franciscan Complex near Point Sur that are correlated with the Edna and Miguelito Members of the Pismo Formation exposed between Cambria and Pismo Beach, some 90–160 km to the southeast (Hall, 1991).

Based on their similar depositional environments, Dickinson et al. (2005) argued that the Cretaceous Point Sur rocks correlate with the Point Sal Luvis, indicating 155 km of displacement. We concur with this correlation, but our data allow more precise mapping of the Lockwood high than the scattered drill holes. Our cumulative offset estimate is also within the error of Graham’s (1978) estimate of 43 ± 4 km based on offset early Miocene paleo-isobaths, suggesting that our estimate, which can only be constrained as post-Cretaceous, is refined to be post–early Miocene. Similar estimates argue against pre-Miocene displacement along the Reliz-Rinconada fault, such as might be interpreted from earlier estimates of 64–72 km of post-Cretaceous offset (Schwade et al., 1958; Dibblee, 1976).

Another geophysical correlation of gravity lows (R1 and R2 in Fig. 3), originating mostly in Miocene sedimentary rocks across the Reliz-Rinconada fault (Jachens et al., 1998), provides an estimate of 20–25 km of presumably post-Miocene displacement. This estimate is similar to the estimate of 18 km of offset of Pliocene facies rocks along the Rinconada fault by Durham (1965). As pointed out by Graham (1978), these offset estimates suggest episodic slip on the Reliz-Rinconada fault.

Continuation of slip south of the Rinconada fault onto the East Huasna fault is supported by the offset Nacimiento fault. The Nacimiento fault, forming the western margin of Salinian rocks, appears to be offset ~35 km along a connected Rinconada–East Huasna fault and aligns two, relatively low-amplitude, curvilinear magnetic anomalies northeast of the fault. The magnetic high at Stanley Mountain, however, appears to be offset ~26 km from a broad high west of the East Huasna fault and may suggest that some slip is also partitioned onto other faults. A magnetic high in the lower plate of the South Cuyama fault appears to have been underthrust in a southeast direction (direction of strike slip) by ~10 km. In this same area, the fault is clearly a thrust or reverse fault, as shown by well data (Vedder and Repenning, 1975).

**Other Faults**

**Reliz-Rinconada Fault**

We correlate the prominent magnetic high of the La Panza Range east of the Reliz-Rinconada fault with the somewhat less prominent magnetic high that encompasses the Lockwood Valley high west of the Reliz-Rinconada fault (Fig. 12B). This correlation indicates 38–42 km of right-lateral displacement on the Reliz-Rinconada fault. The higher estimate comes from matching the southern edges of the bodies and may be lower given the oblique angle between the southern edge of the western body and the fault. The amplitude of the anomaly west of the Reliz-Rinconada fault is lower because the source is everywhere concealed beneath Cenozoic and Cretaceous cover; however, drill holes confirm the presence of granitic rocks along the Lockwood Valley high. Dibblee (1976) also correlated the granitic basement of the Lockwood Valley high with a similar basement high north of Paso Robles (35 km of right-lateral offset), but our data allow more precise mapping of the Lockwood high than the scattered drill holes. Our cumulative offset estimate is also within the error of Graham’s (1978) estimate of 43 ± 4 km based on offset early Miocene paleo-isobaths, suggesting that our estimate, which can only be constrained as post-Cretaceous, is refined to be post–early Miocene. Similar estimates argue against pre-Miocene displacement along the Reliz-Rinconada fault, such as might be interpreted from earlier estimates of 64–72 km of post-Cretaceous offset (Schwade et al., 1958; Dibblee, 1976).

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**TABLE 1. COMPARISON OF FAULT OFFSETS FROM GEOLOGIC (AND OTHER) DATA AND GEOPHYSICAL INTERPRETATIONS (FIG. 12B)**

<table>
<thead>
<tr>
<th>Fault</th>
<th>Offset from geologic data (km)*†</th>
<th>Offset from geophysical data (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnetic anomalies</td>
<td>Gravity anomalies</td>
</tr>
<tr>
<td>San Gregorio–San Simeon–Hosgri fault at Point Arguello</td>
<td>&lt;5*</td>
<td>10 &lt;10</td>
</tr>
<tr>
<td>Point Sal</td>
<td>&lt;10–156* (90)</td>
<td>86–89</td>
</tr>
<tr>
<td>Point Buchon</td>
<td>&lt;10–115*–155*</td>
<td>122–128</td>
</tr>
<tr>
<td>Cape San Martin</td>
<td>&lt;10–160* (156*)</td>
<td>148–154</td>
</tr>
<tr>
<td>Reliz-Rinconada</td>
<td>18–74*</td>
<td>39–43 20–25</td>
</tr>
<tr>
<td>San Juan–Chimineas–Russell</td>
<td>13–37*</td>
<td>28</td>
</tr>
<tr>
<td>West Huasna</td>
<td>5–15*</td>
<td>25–30 25–30</td>
</tr>
<tr>
<td>East Huasna</td>
<td>NA</td>
<td>26</td>
</tr>
</tbody>
</table>

*Most recent estimate in parentheses.
†Superscript numbers indicate the following: a—since ca. 4 Ma (Sorlien et al., 1999a); b—since ca. 12 Ma (Dickinson et al., 2005); c—since 38 Ma (Underwood and Laughland, 2001); d—Pliocene and younger (Durham, 1965); e—since Late Cretaceous (Schwade et al., 1958); f—since Oligocene (Bartow, 1974; Dibblee, 1976); g—since Miocene (McLean, 1993); h—Miocene and younger (Hall et al., 1995); i—since Jurassic (Mattinson and Hopson, 2008); j—since early Miocene (Graham and Dickinson, 1978); k—Clark (1998).
this offset correlation is valid, this might argue for underthrusting accommodating strike slip. These correlations are difficult to test with existing geologic information because the sources of these correlated magnetic anomalies (except for Stanley Mountain) are not exposed.

San Juan–Chimineas–Russell Fault
We posit that the prominent magnetic anomaly at Barrett Ridge is offset from the equally prominent magnetic high of the La Panza Range by the San Juan–Chimineas–Russell fault, giving a maximum estimate of 28 km of right-lateral slip since the Late Cretaceous. Our estimate is similar to that based on drill holes by Yeats et al. (1989), 26–29 km, for the concealed Russell fault to the south. Schwade et al. (1958, p. 85) estimated 37 km based on offset of the contact between the granite and overlying Cretaceous strata, whereas Dibblee (1976, p. 21) reduced the estimate to 13 km based on his mapping of the contact. Bartow (1974, p. 139) refined the estimate to 13–15 km using a Vaqueros (Oligocene) subcrop. The estimates based on the unconformity may suffer from inherent uncertainty because of the oblique angle between the northwest trends of the contacts between the basement rocks and the overlying strata and the Chimineas fault (Powell, 1993, p. 51) and because of incomplete knowledge of the Oligocene erosion surface.

Others have postulated that the San Juan–Chimineas–Russell fault may have reactivated an older, pre-Cenozoic structure because the basement at Barrett Ridge (mostly gneiss) is petrologically dissimilar to much of what is exposed (granodiorite) in the La Panza Range (Ross, 1972). The two are nearly identical, however, in terms of their magnetic signature. Furthermore, the easternmost outcrops of the granodiorite of the La Panza Range are interleaved with mica schist, and are darker and more inclusion rich than typical La Panza granodiorite, leading Ross (1972, p. 27) to state “the east end of the La Panza outcrop indicates nearness to significant amounts of metamorphic rocks that are not now exposed.” These may be the rocks that were displaced to the southeast by the San Juan–Chimineas–Russell fault. The nearly identical ages of the alaskite that intrudes the gneiss at Barrett Ridge (U/Pb age of 80 Ma; Mattinson and James, 1985) and the La Panza granodiorite (79 Ma; Colgan et al., 2012) indicate that these rocks were of the same intrusive event, possibly now displaced by post–80 Ma displacement. Given that the offset estimate from the magnetic anomalies is similar to the estimate of 26–29 km between 23 and 4 Ma on the Russell fault to the south (Yeats et al., 1989), we suggest that the Chimineas–San Juan fault offset occurred during the same time frame. We also suggest that the full 26–29 km of offset from the concealed Russell fault was transferred to the Chimineas fault, rather than half partitioned onto a postulated fault east of Barrett Ridge (Yeats et al., 1989). The magnetic anomaly pattern is most easily explained by offset solely on the Chimineas fault.

West Huasna Fault
We correlate a magnetic high-low-high pattern across the West Huasna fault (bodies 2 and 2’ in Fig. 12B) for an estimated right-lateral offset of ~25–30 km since the Mesozoic. This anomaly pattern is the southwest continuation of the pair of ophiolites that bracket the Pismo syncline. We also note that the gravity low of the Neogene Pismo syncline also appears to be offset 25–30 km from a gravity low east of the fault (P1, P2 in Fig. 3). Other published estimates for offset are considerably lower, but not well documented. Based on distribution of various Oligocene and Miocene strata, Hall et al. (1995, p. 87) inferred ~15 km of right-lateral offset. In an abstract, McLean (1993) stated that the outcrop distribution of an erosion-resistant andesite within the Obispo Formation appeared to limit offset on the West Huasna fault to 5–8 km. Clearly, further work is necessary to test these offset estimates.

DISCUSSION
The correlation of magnetic anomalies suggests that right-lateral offset on the San Gregorio–San Simeon–Hosgri fault zone increases northward, from nearly zero south of Point Arguello to ~155 km between Cape San Martin and Año Nuevo since the Mesozoic, and we posit, based on supporting correlations of Miocene and younger strata discussed herein, that the initiation of the fault during the Miocene (Clark, 1998; Dickinson et al., 2005). This set of geophysical correlations suggests that previous estimates ranging from <10 km to 155 km may all be correct, depending on the location along the fault. Even greater displacement north of our study area has been proposed by correlating the magnetic anomaly beneath the Santa Cruz Mountains (SCM in Fig. 12B; likely originating in Mesozoic ophiolite) with a prominent magnetic anomaly in the Gualala block (see Fig. 1 for location), 175 km to the north (Jachens et al., 1998).

Our correlations disagree with previous studies that argue for a constant amount of offset along the entire length of the fault, such as that of 156 ± 4 km since 12 Ma postulated most recently by Dickinson et al. (2005). Our correlations benefit from an areally consistent data set that covers the entire fault system, both onshore and offshore. The few rock-unit correlations, although critical for determining the age of displacement, are limited by the paucity of outcrops west of the fault and by uncertainty in offshore projections of onshore geology to the eastern side of the fault. Nevertheless, our geophysical correlations across the San Gregorio–San Simeon–Hosgri fault are supported by other data sets, and most are supported by rock-unit correlations.

Northward-increasing right-lateral displacement on the San Gregorio–San Simeon–Hosgri fault helps to resolve the discrepancy that arises if 156 ± 4 km of Neogene right-lateral offset were to be accommodated by crustal shortening across the Santa Maria Basin (Fig. 12 of Dickinson et al., 2005) versus the amount of shortening that has been documented. More than 50% shortening (or ~70 km) distributed from Morro Bay to Point Arguello is implied if 156 ± 4 km of offset is reduced to zero at Point Arguello. Balanced cross sections assuming that folds are kinematically linked to ramp-flat faults at depth indicate only 9.2 km of shortening across the Santa Maria Basin (Namson and Davis, 1990). More recently, Graymer et al. (2010) estimated only 4 km of Neogene shortening between Point Sal and Point Arguello based on restoration of compression of Miocene strata. To reconcile correlation of the San Simeon with the Point Sal ophiolites and maintain a constant offset of 156 km on the Hosgri fault, at least 35 km of shortening is needed between Morro Bay and Point Sal. Drill holes and seismic-reflection data in this area indicate a gentle southward tilting of the Neogene section beneath the Santa Maria Basin north of Point Sal, consistent with ~2 km of shortening since the early Pliocene (Seeber and Sorlien, 2000). Furthermore, large amounts of convergence within the Santa Maria Basin before the Pliocene are not supported by the stratigraphic record, which argues for transpression and subsidence since ca. 18 Ma (Stanley et al., 1996; McCrory et al., 1995).

The southward decrease in slip on the San Gregorio–San Simeon–Hosgri fault is mimicked by Quaternary slip rates (albeit poorly constrained) that range from 4 to 11 mm/yr for the San Gregorio fault near Año Nuevo (Weber, 1990) to 1–3 mm/yr at San Simeon to 0.5–2 mm/yr between Point Sal and Point Arguello (Hanson et al., 2004). Slip was initiated on the fault at ca. 11 Ma, based on the age of the youngest unit (ash bed within the Monterey Formation), which is offset as much as older units between Point Lobos and Point Reyes (Clark, 1998). This suggests that, although slip rates have decreased over the lifetime of the fault, the distribution of slip has not changed.
The pattern of northward-increasing right-lateral displacement on the San Gregorio–San Simeon–Hosgri fault can be explained in part by right-lateral displacement on subsidiary faults east of the fault. For example, the difference in offset between Cape San Martin (148–154 km) and Point Buchon (122–128 km) could have been balanced by 20–32 km of right-lateral slip on the Oceanic–West Huusna fault. This amount of off-set is similar to our estimate of 25–30 km based on correlation of gravity and magnetic anomalies across the fault.

Farther north, the difference in offset between Cape San Martin (148–154 km) and the Santa Cruz Mountains (175 km) is 21–27 km. The Reliz-Rinconada fault, however, appears to have 38–42 km of right-lateral displacement, at least south of San Ardo. Several lines of evidence suggest that the fault changes character to the north and may reduce the amount of strike slip that reaches the San Gregorio fault (see also Rosenberg and Clark, 2009). North of Greenfield, late Pleistocene fans are not displaced laterally (Tinsley and Dohrenwend, 1979), and the gravity model across G-G' allows for a moderate fault dip (Fig. 11), suggestive of some component of reverse slip. Sparse subsurface data suggest no more than 23 km of right slip of schist of Mesozoic age across the fault zone (Ross, 1984). Thus, some of the right slip from the Reliz-Rinconada fault may have been accommodated by crustal shortening or transfer of slip onto other faults in the Santa Lucia Range. Dickinson et al. (2005, p. 36) calculated as much as 9 km of transpressive strike slip oriented parallel to the Reliz-Rinconada fault.

Farther south, structures that could balance the differences in offset between Point Sal (86–89 km) and Point Buchon (122–128 km) and Point Arguello (<10 km) and Point Sal (86–89 km) have not been robustly determined. As mentioned earlier, Neogene shortening within the Santa Maria Basin can account for no more than 10 km of slip. Clockwise rotation of small crustal blocks within the Santa Maria Basin could account for some of the slip, as suggested by Sorlien et al. (1999a), although paleomagnetic studies in the Santa Maria Basin are few and indicate highly variable clockwise rotations, some with large error bars (e.g., 9° ± 27° for Miocene rocks near the Lion’s Head fault; Hornafius et al., 1986). The Casmalia fault and the faults that form the southern margin of the Irish Hills could account for some of the slip discrepancy (33–42 km) between Point Buchon and Point Sal, although no definitive piercing points or blubs have yet been identified to quantify that slip. Even more difficult to explain is the nearly 90 km decrease in offset from Point Sal to Point Arguello.

One possible solution is to route much of the 90 km of slip onto a proto-Hosgri fault. Steritz and Luyendyk (1994) suggested that significant slip (~60 km) transferred from the Hosgri onto the Santa Lucia Bank fault to the west; this transfer, however, would be located to the north of San Simeon, rather than between Point Arguello and Point Sal. Another possibility is the Santa Ynez River fault, which separates very different stratigraphic sections, those of the Santa Maria Basin, where Neogene sedimentary rocks lie directly on Franciscan or Great Valley basin, versus those of the Santa Ynez Mountains, where a thick Paleogene section lies between the Mesozoic basement and the Neogene section. The amount and even the sense of offset on this fault are poorly known. Dickinson (1979) suggested 70 km of net right-lateral offset on the Santa Ynez River fault based on presumed displacements of Paleogene depositional systems. Dickinson (1983) later dismissed this correlation as being spurious because of clast compositions in Oligocene rocks. We suggest that a value of 70 km of offset is supported by the possible correlation of an unusual Paleocene and Eocene algal limestone (Sierra Blanca Limestone) that lies unconformably on Mesozoic rocks and underlies Eocene shales. One such exposure is near Point Arguello, south of the Santa Ynez River fault (Keenan, 1932); the other lies 70 km to the east, north of the fault in the San Rafael Mountains (Keenan, 1932; Walker, 1950). We also note that the Paleogene stratigraphic correlation is supported by apparent right-lateral displacement of magnetic anomalies (PA and SRM in Fig. 12B). Conglomerate clast compositions in the Eocene to Lower Miocene Sespe Formation are consistent with strike-slip displacement (Howard, 1995), but they are not sufficient to constrain the amount or even sense of displacement.

It is highly unlikely that 70 km of Neogene right-lateral offset passed through the present configuration of the Hosgri and Santa Ynez River faults. Such an abrupt bend would produce very large amounts of uplift and convergence, which are not observed. Clockwise rotation of the Western Transverse Ranges complicates a model that places right-lateral slip on the Santa Ynez River fault given (1) predictions of left-lateral slip from transrotational models (e.g., Hornafius et al., 1986) and (2) scattered kinematic indicators of left slip from striations on related faults (Sorlien et al., 1999a). Reconstruction of slip on the various faults from matching geophysical anomalies highlights the space problems in the Santa Maria Basin, which are accentuated by the large clockwise rotation of the Western Transverse Ranges and the acute angle at which the Hosgri and Santa Ynez River faults intersect (Fig. 12C). Clearly, detailed work in the Santa Maria Basin will be crucial to resolving how slip is accommodated south of Point Sal.

CONCLUSIONS

Modeling of magnetic anomalies across the San Gregorio–San Simeon–Hosgri and Reliz-Rinconada faults indicates steep dips that extend throughout the seismogenic part of the crust. These results suggest that steep or near-vertical dips of these faults determined from the decades-long record of seismicity are characteristic of the dip of the fault throughout its lifetime (Neogene) and that much of the movement on these faults has been characterized by strike slip. Exceptions are (1) a moderate dip for that stretch of the San Gregorio fault in Monterey Bay and (2) a possible moderate dip for the northern stretch of the Reliz-Rinconada fault. We speculate that these deviations from steep to near-vertical dips are likely related to local changes in fault geometry or interactions with nearby faults, a hypothesis that should be tested with rigorous modeling of fault interactions.

Magnetic ophiolites of Mesozoic age are truncated along the east side of the San Gregorio–San Simeon–Hosgri fault at Cape San Martin, near Point Buchon, and near Point Sal. Cross-fault counterparts of their associated magnetic anomalies (supported in most cases by rock-unit correlations) west of the fault suggest southward-decreasing apparent right-lateral offsets of these ophiolites of 148, 125, and 89 km, respectively, with uncertainties of <5 km. The differences in offsets can be balanced, in part, with slip added from faults east of the fault system. The mechanism by which the observed reduction in slip along the Hosgri fault is accomplished south of Point Buchon is not completely understood, but some of the slip may have been transferred onto the Santa Ynez River fault.

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