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Net Dextral Slip, Neogene San Gregorio–Hosgri Fault Zone, Coastal California: Geologic Evidence and Tectonic Implications



Net Dextral Slip, Neogene San Gregorio–Hosgri Fault Zone, Coastal California: **Geologic Evidence and Tectonic Implications**

Figures-Tables Errata for GSA SPE 391

Figure 1 (p. 3): NTD in caption (for “Navarro tectonic discontinuity” should be NSD (for Navarro structural discontinuity) to match figure as drafted [or vice versa]

Figure 2 (p. 4): should be a tie line from TTJ label to Tofino triple junction

Figure 3 (p. 6): on B, “Of” should be Cf (Calaveras fault)
on B, “Cv” should not appear (labels nothing)
on B, should be turkey-track symbol in SM area

Figure 5 (p. 9): “TF” label (for Tularcitos fault) should be Tf (to match caption)

Figure 6 (p. 10): Figure cited for location should be 3B (not 2B)

Figure 7 (p. 12): Tie line for NPP (Nacimiento piercing point) drawn to wrong place on Rinconada fault (bad goof that I hope does not lead pilgrims astray!)

Figure 10 (p. 22): CH (charnockitic rocks of Compton) of legend not marked on figure (but located at “0.07076 (n=12)” data site near Santa Lucia coast)

Figure 14 (p. 32-33): NSD in caption (for “Navarro structural discontinuity”) should be NTD (for Navarro tectonic discontinuity) to match figure [or vice versa]

Figure 15 (p. 34): “CPF” label (for Cypress Point fault) should be CPf (to match caption)

Table 2 (p. 35): referral in last line of note should be to Fig. 15 (not to Fig. 13).

Net dextral slip, Neogene San Gregorio–Hosgri fault zone, coastal California: Geologic evidence and tectonic implications

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ABSTRACT

Reinterpretation of onshore and offshore geologic mapping, examination of a key offshore well core, and revision of cross-fault ties indicate Neogene dextral strike slip of 156 ± 4 km along the San Gregorio–Hosgri fault zone, a major strand of the San Andreas transform system in coastal California. Delineating the full course of the fault, defining net slip across it, and showing its relationship to other major tectonic features of central California helps clarify the evolution of the San Andreas system.

San Gregorio–Hosgri slip rates over time are not well constrained, but were greater than at present during early phases of strike slip following fault initiation in late Miocene time. Strike slip took place southward along the California coast from the western flank of the San Francisco Peninsula to the Hosgri fault in the offshore Santa Maria basin without significant reduction by transfer of strike slip into the central California Coast Ranges. Onshore coastal segments of the San Gregorio–Hosgri fault include the Seal Cove and San Gregorio faults on the San Francisco Peninsula, and the Sur and San Simeon fault zones along the flank of the Santa Lucia Range.

Key cross-fault ties include porphyritic granodiorite and overlying Eocene strata exposed at Point Reyes and at Point Lobos, the Nacimiento fault contact between Salinian basement rocks and the Franciscan Complex offshore within the outer Santa Cruz basin and near Esalen on the flank of the Santa Lucia Range, Upper Cretaceous (Campanian) turbidites of the Pigeon Point Formation on the San Francisco Peninsula and the Atascadero Formation in the southern Santa Lucia Range, assemblages of Franciscan rocks exposed at Point Sur and at Point San Luis, and a lithic assemblage of Mesozoic rocks and their Tertiary cover exposed near Point San Simeon and at Point Sal, as restored for intrabasinal deformation within the onshore Santa Maria basin.

Slivering of the Salinian block by San Gregorio–Hosgri displacements elongated its northern end and offset its western margin delineated by the older Nacimiento fault, a sinistral strike-slip fault of latest Cretaceous to Paleocene age. North of its juncture with the San Andreas fault, dextral slip along the San Gregorio–Hosgri fault augments net San Andreas displacement. Alternate restorations of the Gualala block imply that nearly half the net San Gregorio–Hosgri slip was accommodated along the offshore Gualala fault strand lying west of the Gualala block, which is bounded on the east by the current master trace of the San Andreas fault. With San Andreas and San Gregorio–Hosgri slip restored, there remains an unresolved proto–San Andreas mismatch of ~100 km between the offset northern end of the Salinian block and the southern end of the Sierran–Tehachapi block.

On the south, San Gregorio–Hosgri strike slip is transposed into crustal shortening associated with vertical-axis tectonic rotation of fault-bounded crustal panels that form the western Transverse Ranges, and with kinematically linked deformation within the adjacent Santa Maria basin. The San Gregorio–Hosgri fault serves as the principal link between transrotation in the western Transverse Ranges and strike slip within the San Andreas transform system of central California.

Keywords: California, Hosgri fault, Nacimiento fault, Salinian block, San Andreas fault, San Gregorio fault.

INTRODUCTION

Hill and Dibblee (1953, p. 454–455) noted that the San Gregorio fault on the San Francisco Peninsula is one of a family of faults in coastal California related to the master San Andreas fault (Fig. 1), but they were unaware of its offshore extensions or its underwater linkage to the north with the San Andreas fault beneath the Gulf of the Farallones off the Golden Gate. The San Gregorio fault was later recognized as a major strand of the San Andreas transform boundary between Pacific and North American plates (Silver, 1978a), with connotations for the evolution of the transform system. Because its southernmost segment (the offshore Hosgri fault zone) passes within ~5 km of the Diablo Canyon nuclear power plant, the San Gregorio–Hosgri fault also has major implications for evaluation of seismic hazard (Hall, 1975).

Merging of the San Andreas and San Gregorio faults at Bolinas Lagoon north of the Golden Gate indicates that slip on the two structures is additive north of San Francisco Bay, largely accounting for apparently greater net San Andreas slip in northern California than in central California (Graham and Dickinson, 1978a, 1978b; Howell and Vedder, 1978). San Gregorio–Hosgri displacements lengthened the Salinian block of plutonic and metamorphic basement rocks by slivering its western edge and shifting a segment of the block to the north (Johnson and Normark, 1974; Graham, 1978; Clark et al., 1984). The southern end of the San Gregorio–Hosgri fault terminates at the western Transverse Ranges, where vertical-axis tectonic rotation has accommodated part of the lateral slip between Pacific and North American plates (Dickinson, 1996; Dickinson and Wernicke, 1997).

Estimates of net Neogene dextral slip across the San Gregorio–Hosgri fault vary from <5 km (Sedlock and Hamilton, 1991)

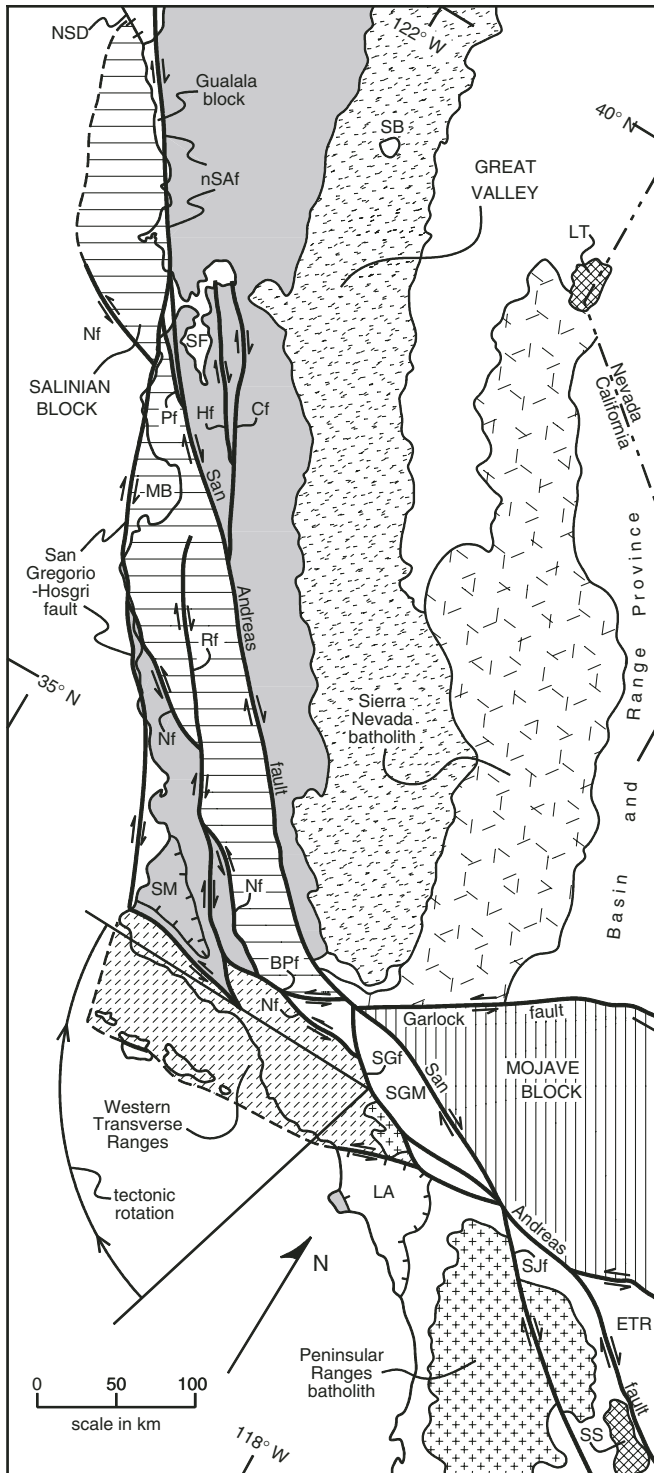


Figure 1. Tectonic setting of San Gregorio–Hosgri and Nacimiento faults in central California (Franciscan substratum shaded except within Transverse Ranges). Faults (heavy lines): BPf, Big Pine; Cf, Calaveras; Hf, Hayward; Nf, Nacimiento; Pf, Pilarcitos; Rf, Rinconada; nSaf, northern San Andreas; SGf, San Gabriel; SJf, San Jacinto. Sedimentary basins (inside hachured lines): LA, Los Angeles; SM, Santa Maria. Other features: ETR, eastern Transverse Ranges; LT, Lake Tahoe; MB, Monterey Bay; NTD, Navarro tectonic discontinuity; SB, Sutter Buttes; SF, San Francisco Bay; SGM, San Gabriel Mountains; SS, Salton Sea.

to ~180 km (Burnham, 1998, 1999), a level of uncertainty that is unacceptable for a significant strand of the San Andreas system. We undertook a reappraisal of evidence for cross-fault displacements, and infer net San Gregorio–Hosgri dextral slip of 156 ± 4 km, in agreement with a previous estimate of 150–160 km by Clark (1998).

A key facet of our investigation was petrographic examination of pre-Tertiary sandstone recovered at the bottom of an offshore exploratory well in the outer Santa Cruz basin off the San Francisco Peninsula. Originally correlated by implication with the onshore Cretaceous Pigeon Point Formation (Hoskins and Griffiths, 1971), the sandstone is actually part of the Franciscan subduction complex and has different implications for San Gregorio–Hosgri fault offset than previously thought. For regional analysis of net offset, we treat the San Gregorio–Hosgri fault as a single structure, although each well-known segment of the fault zone consists of multiple strands that bifurcate and rejoin along strike, as shown on subregional maps that depict different segments of the fault.

TECTONIC SETTING

The western margin of North America is the only continental margin in the world delineated largely by transform fault systems (Dickinson et al., 1986; Dickinson, 2004): the Queen Charlotte and San Andreas, with strands aligned along the continental slope or within the edge of the continental block (Fig. 2). The transform continental margin was formed when migratory spreading centers within the Pacific Ocean basin reached the Franciscan paleotrench subducting seafloor beneath the edge of the continental block. A remnant of the convergent plate boundary at the continental margin forms the Cascades subduction zone, which intervenes between Queen Charlotte and San Andreas segments of the transform plate boundary. Remnants of the oceanic spreading system form the East Pacific Rise where it enters the mouth of the Gulf of California and the Juan de Fuca and Gorda Ridges west of the Cascades subduction zone.

The Queen Charlotte fault and several subsidiary strands of the San Andreas fault system lie offshore (Fig. 2) where offset geologic features cannot be observed on outcrop. The San Gregorio–Hosgri fault is the only major strand of the San Andreas system that lies closer to the edge of the continental block than the master fault trace, yet comes onshore at enough places to make determination of net offset feasible from outcrop relations supplemented by offshore mapping and coring. At the latitude of central California, assessment of net offset across the San Gregorio–Hosgri fault is needed to evaluate net displacement across the San Andreas system as a whole.

Farther south, San Andreas tectonism involved transrotational deformation of the western Transverse Ranges as an integral facet of transform motion of the Pacific plate past the North American plate (Dickinson, 1996). Fault offset along the San Andreas fault at the latitude of the western Transverse Ranges does not, therefore, provide a full estimate of transform

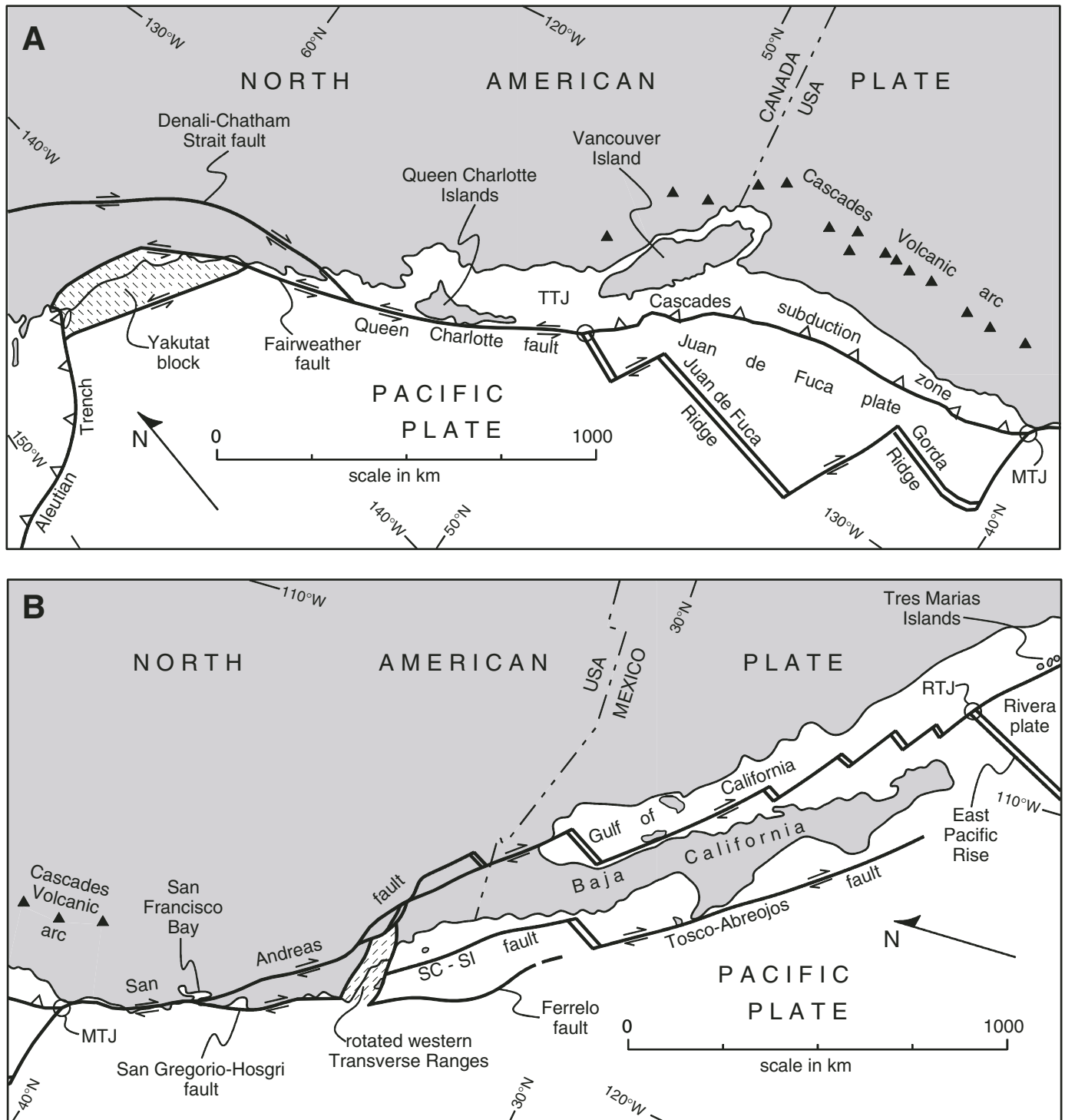


Figure 2. Compound transform fault system along the western margin of North America linking the East Pacific Rise spreading center (panel B) on the south to the subduction zone at the Aleutian Trench (panel A) on the north (panels A and B overlap near MTJ). The San Andreas fault system extends from the Rivera triple junction (RTJ) to the Mendocino triple junction (MTJ), and the Queen Charlotte fault system extends northward from the Tofino triple junction (TTJ). Solid triangles denote stratocones of the Cascades arc lying parallel to the Cascades subduction zone at the foot of the continental slope between San Andreas and Queen Charlotte segments of the transform system. SC-SI denotes Santa Cruz–San Isidro fault of the California continental borderland.

movement between the two plates. Summation of net slip across the San Andreas and San Gregorio–Hosgri fault zones and their principal splays farther north does provide an estimate of full transform slip, apart from oblique Basin and Range extension within the interior Basin and Range province (Dickinson and Wernicke, 1997).

Understanding the full course of the San Gregorio–Hosgri fault along the continental margin and assessing net dextral slip across the fault zone are also required to understand relationships of key lithic assemblages and other major structural features in central California. The tectonic history of California cannot be appreciated correctly without insights derived from analysis of the San Gregorio–Hosgri strand of the San Andreas system.

SLIP RATE OVER TIME

We focus on resolving uncertainties about net Neogene strike slip along the San Gregorio–Hosgri fault. Determining variations in slip rate over time is beyond the scope of our study, but there are indications that the slip rate has declined since late Miocene initiation of faulting.

The youngest stratum that records the full cumulative offset of 156 km across the fault is an ash bed in mid-late Miocene (ca. 11 Ma) diatomite of the Monterey Formation (Clark, 1998). The indicated average Neogene slip rate is ~14 mm/yr, a rate compatible with offset of upper Miocene (ca. 8 Ma) petroliiferous Santa Cruz Mudstone by ~115 km (Stanley and Lillis, 2000). The estimated late Quaternary slip rate of 6–9 mm/yr (best estimate of ~8 mm/yr) for the San Gregorio segment of the fault on the San Francisco Peninsula (Weber, 1990, 1999), and a comparable maximum slip rate of ~8 mm/yr across the San Simeon segment of the fault farther south (Hanson and Lettis, 1994, p. 145), is little more than half the average slip rate over time. Moreover, the best estimate of the current slip rate along the San Simeon segment of the fault is no more than 3 mm/yr (Hanson et al., 2004). A slip rate in the range of 6 to 9 mm/yr is insufficient to account for aggregate San Gregorio–Hosgri displacement unless it has continued since early Miocene time (17–26 Ma), which predated development of the San Andreas fault system in central California (Nicholson et al., 1994; Bohannon and Parsons, 1995; McCrory et al., 1995; Dickinson, 1996, 1997). The difference between long-term and current slip rates implies that San Gregorio–Hosgri motion has gradually slowed over time from a peak as high as ~25 mm/yr (Clark, 1998) near the time of fault initiation.

The indicated high initial San Gregorio–Hosgri slip rate is nearly half the average motion between Pacific and North American plates of lithosphere since ca. 11 Ma (Dickinson and Wernicke, 1997; Atwater and Stock, 1998a, 1998b) and is comparable to the average post-11 Ma slip rate along the San Andreas fault proper in central California (Graham et al., 1989). The San Gregorio–Hosgri fault was apparently a principal strand of the San Andreas transform system in late Miocene time, and then a more significant locus of strike slip in central California than it is today.

COURSE OF THE FAULT

The structural relations of the type San Gregorio fault zone of the San Francisco Peninsula with other faults of coastal California are controversial, but we conclude that San Gregorio dextral slip continued southward down the California coast along Sur, San Simeon, and Hosgri segments of an integrated San Gregorio–Hosgri fault zone without significant reduction by transfer of strike slip into the Santa Lucia Range.

San Gregorio Segment

The course of the San Gregorio fault northward from its type locality near Pigeon Point along the coastal fringe of the San Francisco Peninsula is not in dispute (Fig. 3A). The fault zone passes offshore across the mouth of Half Moon Bay, comes onshore locally as the Seal Cove fault transecting Pillar Point between Half Moon Bay and Montara Point, and then obliquely crosses the Gulf of the Farallones, as multiple offshore strands including the Potato Patch fault, to merge with the San Andreas fault near Bolinas Lagoon (Fig. 4). Multiple fault strands form a complex geometric array near the fault juncture. Strain partitioning by slip stepover between fault strands has caused dilatational components of deformation along the edges of crustal blocks in contact along both the San Andreas and San Gregorio fault zones off the Golden Gate (Zoback et al., 1999).

Near Pigeon Point, the Frijoles fault is a local splay (Fig. 3A) of the San Gregorio fault that probably connects northward with a minor offshore fault passing west of Montara Mountain (Fig. 4). The trace of the Frijoles fault lies entirely within the crustal block west of the San Gregorio fault and represents a faulted unconformity between Cretaceous and Neogene strata (Weber, 1990; Brabb et al., 1998).

Monterey Bay Segment

The offshore course of the San Gregorio fault zone southward into Monterey Bay as far as its crossing of the Monterey submarine canyon is not in dispute (Figs. 3 and 4). The position of the fault zone as multiple branches aligned along the trend of the Carmel submarine canyon, a tributary to the Monterey submarine canyon offshore from the Monterey Peninsula (Fig. 5), is also clear from marine surveys (Eittreim et al., 2000, 2002). Farther south, however, alternate connections to the Sur fault zone (Graham and Dickinson, 1978a, 1978b) or to the Palo Colorado fault (Palo Colorado–San Gregorio fault of Greene, 1990) have been inferred (Fig. 5).

The Garrapata fault (Fig. 5), apparently a splay of the Palo Colorado fault, offsets late Quaternary marine terraces (Richardson, 1923) and is marked by a near-vertical shear zone 55 m wide displaying horizontal slickensides, but strikes N45°–55°W (Rosenberg and Clark, 1999) at ~30° to the trend of the San Gregorio fault across Monterey Bay. At the coast, the Palo Colorado fault itself, dipping ~70°NE, is marked by a gouge zone only ~1 m

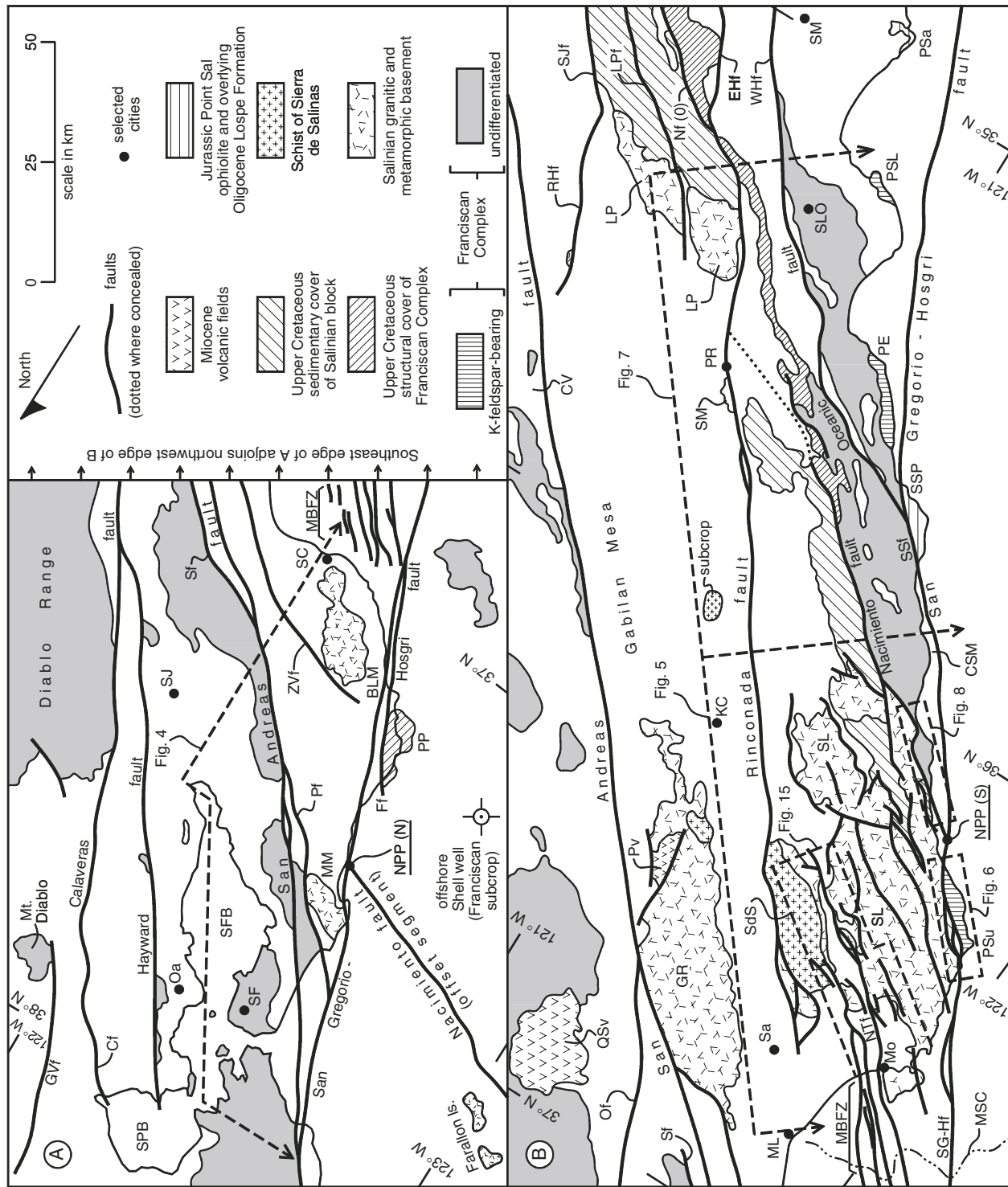


Figure 3. Trend of San Gregorio-Hosgri fault of coastal and offshore central California north (A) and south (B) of Monterey Bay in relation to San Andreas and Nacimiento faults adapted after Dickinson (1966), Hall and Corbató (1967), Clark and Rietman (1973), Ross (1976b), Jennings (1977), Greene (1977, 1990), Wagners and Bortugno (1982), Vedder et al. (1986), McCulloch (1989b), McCulloch and Greene (1990), Weber (1990), Steritz and Luyendyk (1994), Greene et al. (2002), McLaughlin et al. (2004), and Figures 4-5 and 7 (small outcrop areas omitted for reasons of scale). NPP, piercing points (N, north; S, south) of Nacimiento fault on San Gregorio-Hosgri fault. Major onshore Salinian basement exposures: BLM, Ben Lomond Mountain; GR, Gabilan Range; LP, La Panza Range; MM, Montara Mountain; SdS, Sierra de Salinas; SL, Santa Lucia Range (internally dislocated); SM, San Marcos Creek. Miocene volcanic fields: Pv, Pinnacles; QSV, Quien Sabe. Key faults: Cf, Calaveras (-Franklin); GVf, Green Valley (-Concord); EHF, East Huasna (= Rinconada); MBFZ, Monterey Bay fault zone; Nf(o), Nacimiento fault (as offset by Rinconada fault); NTF, Navy-Tularcitos; Pf, Pilarcitos; RHf-SJf, Red Hills-San Juan; Sf, Sargent; SSf, San Simeon (onshore segment of San Gregorio-Hosgri); WHf, West Huasna (= Oceanic); ZVf, Zayante-Vergeles. Coastal features: CSM, Cape San Martin; MSC, Monterey submarine canyon; PE, Point Estero; PP, Pigeon Point; PSa, Point Sal; PSL, Point San Luis; PSu, Point Sur; SFB, San Francisco Bay; SPB, San Pablo Bay; SSP, San Simeon Point. Selected cities and towns: KC, King City; ML, Moss Landing; Mo, Monterey; Oa, Oakland; PR, Paso Robles; SLO, San Luis Obispo; Sa, Salinas; SC, Santa Cruz; SF, San Francisco; SJ, San Jose; SM, Santa Maria.

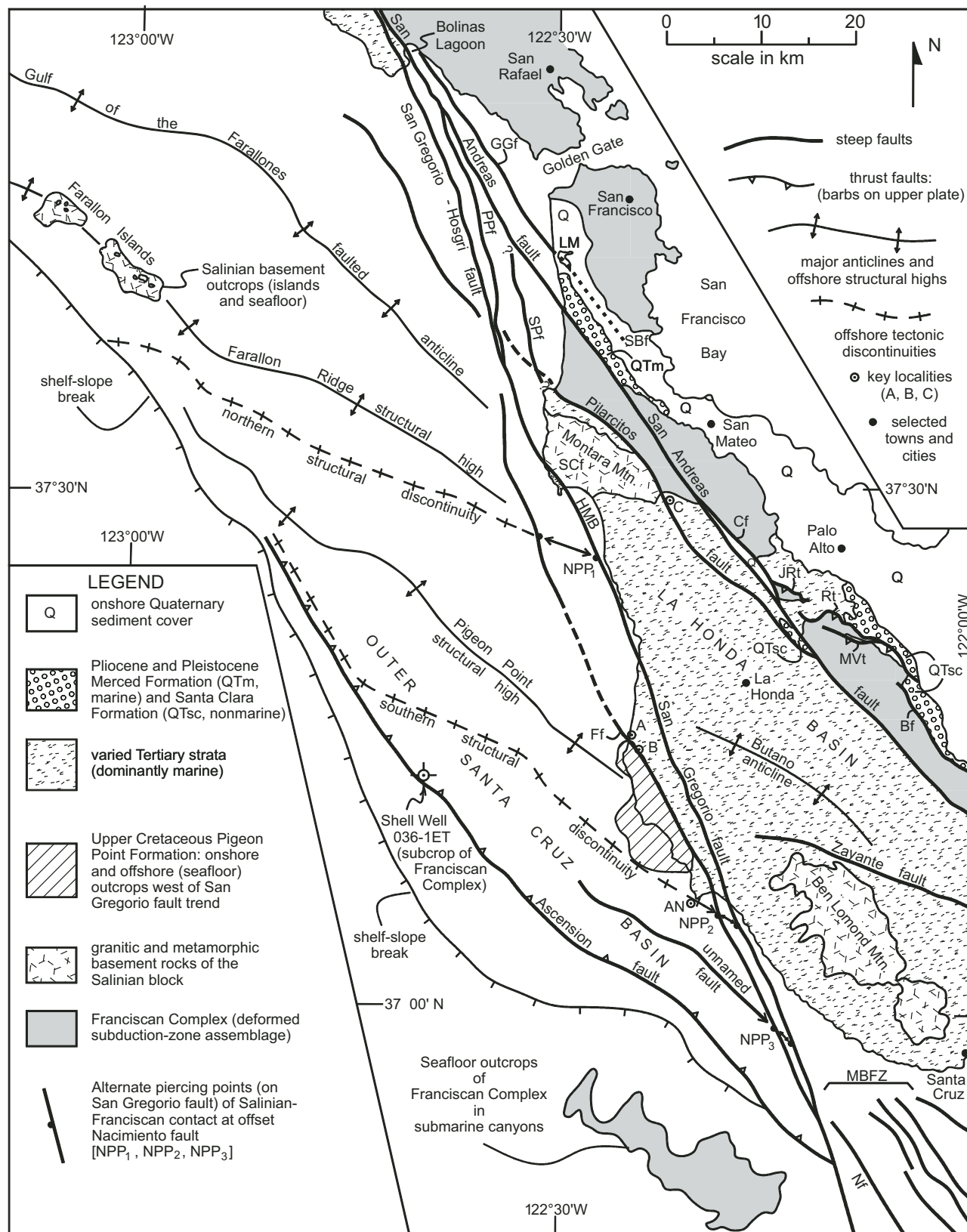
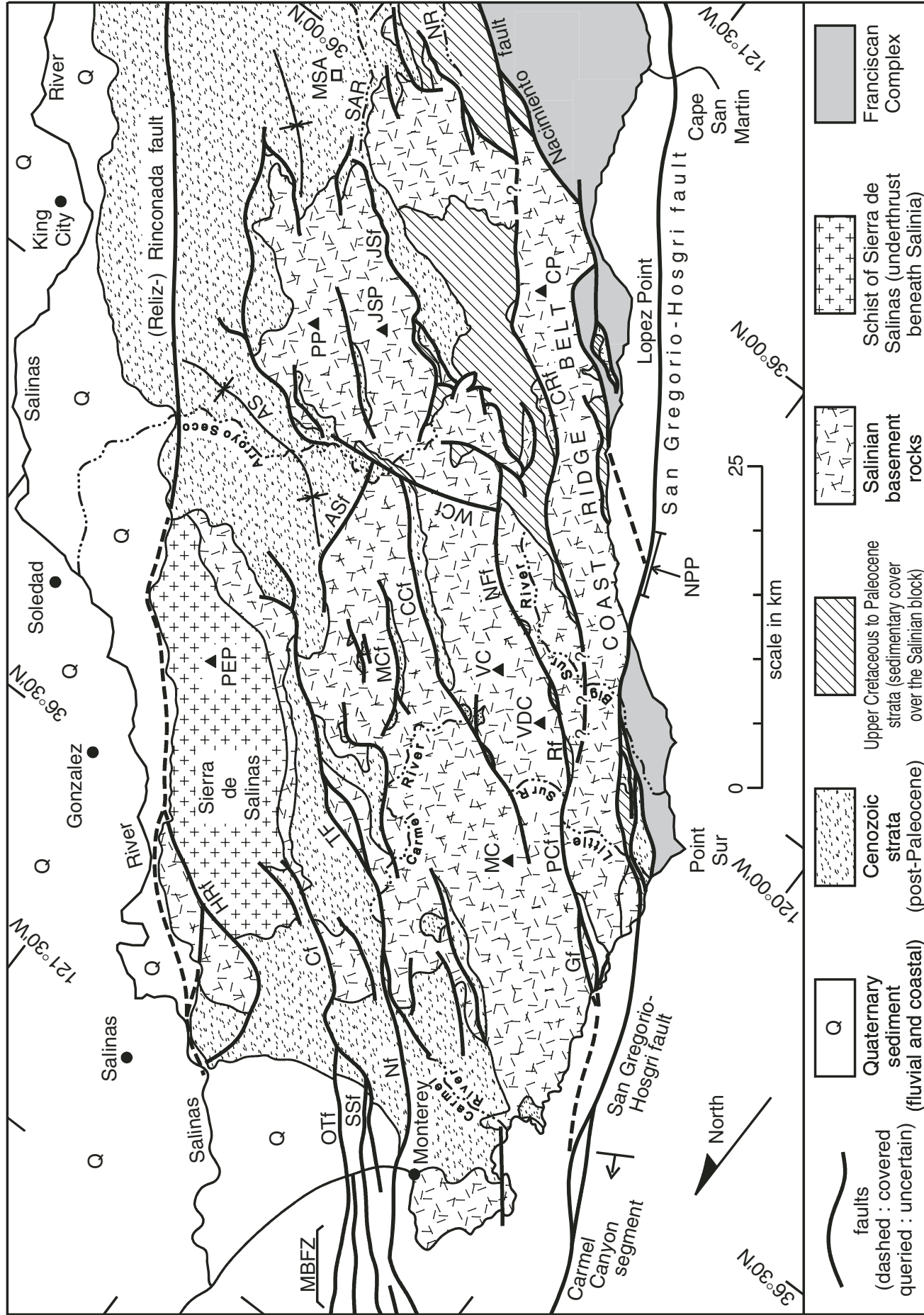


Figure 4. Tectonic position of Shell Oil Company offshore well 036-1ET (OCS well P-036 #1 of Heck et al., 1990) in outer Santa Cruz basin (see Fig. 3A for location) adapted after Jennings and Burnett (1961), Hoskins and Griffiths (1971), Clark (1981), Nagel and Mullins (1983), Nagel et al. (1986), McCulloch (1987), Brabb (1989, 1993), McCulloch and Greene (1990), Mullins and Nagel (1990), Weber (1990), Brabb et al. (1998), Bruns et al. (2002), and Jachens et al. (2002), with Monterey Bay fault zone (MBFZ) after Greene et al. (2002); Nacimiento piercing point NPP₁ preferred over NPP₂-NPP₃ (see text for discussion). Selected minor faults (dashed where masked by alluvium): Bf, Berrocal; Cf, Cañada; GGf, Golden Gate (= SBF); JRt, Jasper Ridge thrust; MVt, Monta Vista thrust; Nf, Navy (continuation offshore); PPf, Potato Patch; Rt, Roble thrust; SBF, San Bruno (= GGf); SCf, Seal Cove (onshore segment of San Gregorio-Hosgri); SPf, San Pedro. Key localities (circled dots): A, Miocene basalt at Pescadero Beach; B, Oligocene felsite on Pescadero Creek; C, Cretaceous conglomerate near Skyline Boulevard. Local geographic features: AN, Año Nuevo Island and Point; HMB, Half Moon Bay; LM, Lake Merced.



wide, typical for multiple reverse faults (dipping 50°–80°NE) that break Salinian basement rocks of the northern Santa Lucia Range (Fig. 5). Near-horizontal slickensides within the Palo Colorado gouge zone imply at least limited strike slip. The salient tectonic question is whether the master San Gregorio slip surface curves abruptly to follow the Palo Colorado fault, or whether indications of strike slip in coastal exposures of the Palo Colorado fault and its Garrapata splay record intra-Salinian strain imposed along en echelon structures near where the offshore trace of the San Gregorio–Hosgri fault transects Salinian basement rocks (Figs. 1 and 5). The nature and magnitude of intra-Salinian deformation during the time span of San Gregorio–Hosgri displacements is discussed further in a later section.

Ross (1976a) inferred that the Palo Colorado fault is contiguous to the southeast with the Coast Ridge fault (dashed fault trace of Fig. 5), along which he postulated major strike slip to explain the juxtaposition of deep-seated charnockitic plutons and granulite-facies metamorphic rocks, exposed along the Coast Ridge (Compton, 1960), with Salinian basement rocks to the northeast that formed at shallower crustal levels. No major break in Salinian basement was mapped at the Coast Ridge fault by Compton (1966), who interpreted the Coast Ridge fault as a local normal fault dipping steeply to the northeast and bounding the flank of an elongate tract of Cretaceous sedimentary strata. Recent paleobarometric studies indicate that the northern Santa Lucia Range exposes an east-tilted (at ~30°) crustal profile embracing a range of paleodepths reflected by a gradual increase in metamorphic grade from ~10 km on the northeast to 25–30 km on the southwest (Ducea et al., 2003; Kidder et al., 2003). The continuously exposed transition in paleodepth requires no significant offset across the Coast Ridge fault, which can be viewed as the product of local faulting along an unconformity between Salinian basement and its Cretaceous sedimentary cover (Seiders et al., 1983).

Figure 5. Structural fabric of the northern Santa Lucia Range and adjacent offshore (see Fig. 3B for location; southeast edge adjoins northwest edge of Fig. 7) adapted after Trask (1926), Reiche (1937), Fiedler (1944), Compton (1960, 1966), Wiebe (1966), Dibblee (1976, 1979, 1999), Graham (1976a, 1976b, 1979), Ross (1976a, 1976b, 1984), Ruetz (1979), Seiders et al. (1983), Seiders and Joyce (1984), McCulloch and Greene (1990), Clark et al. (1997, 2000), Eittreim et al. (2000, 2002), Rosenberg (2001), Greene et al. (2002), Wagner et al. (2003), and Figures 6, 8, and 15. Segment of San Gregorio–Hosgri fault controlling course of Carmel (submarine) Canyon indicated on left. NPP, Nacimiento piercing point (on San Gregorio–Hosgri fault) at Salinian–Franciscan contact (bracket denotes uncertainty of ±2.5 km). Selected intra-Salinian faults: ASf, Arroyo Seco; CCf, Church Creek; Cf, Chupines; CRf, Coast Ridge; Gf, Garrapata; HRf, Harper Ranch; JSf, Junipero Serra; MCf, Miller Creek; Nf, Navy; NFf, North Fork; OTf, Ord Terrace; PCf, Palo Colorado; Rf, Redwood; SSf, Seaside; Tf, Tularcitos; WCf, Willow Creek. Major peaks: CP, Cone Peak; JSP, Junipero Serra Peak; MC, Mount Carmel; PEP, Palo Escrito Peak; PP, Pinyon Peak; VC, Ventana Cone; VDC, Ventana Double Cone. Other features: AS, axis of Arroyo Seco synclinorium; MBFZ, Monterey Bay fault zone; MSA, Mission San Antonio; NR, Nacimiento River; SAR, San Antonio River.

Past interpretations that the Coast Ridge fault may have accommodated major strike slip were encouraged by speculation that the Salinian block as a whole is a “little stranger” (Ross, 1977) or “orphan” (Ross, 1978) exotic to the California continental margin. If the Salinian block were in fact a far-traveled terrane, the Coast Ridge belt (Fig. 5) might be a subterranean unrelated to other parts of the Salinian block. Subsequent studies have shown, however, that the Salinian block has been displaced from a position southwest of the Mojave block (Fig. 1) for only the distance recorded by offset ties across the San Andreas fault (Ross, 1984; James et al., 1993; Dickinson, 1996).

Previous regional mapping has shown that the Palo Colorado fault continues to the southeast as the intra-Salinian Redwood and North Fork faults (Fig. 5), rather than the Coast Ridge fault. The combined Palo Colorado–Redwood–North Fork fault system trends into an area of complex transverse structures associated with continuous exposures of Cretaceous sedimentary strata, unconformably overlying Salinian basement, which preclude significant strike slip. The continuity of Eocene depositional systems (Graham, 1976a, 1978; Link and Nilsen, 1979) across the trend of this intra-Salinian fault system, as projected to the southeast, also argues against strike slip. We infer that no significant component of San Gregorio–Hosgri strike slip has been diverted along the Palo Colorado fault, and conclude that the master slip surface continues along strike offshore into its continuation as the Sur fault zone.

Big Sur Segment

The Point Sur–Big Sur area (Fig. 6) is the principal locale where the San Gregorio–Hosgri fault trace comes onshore south of the San Francisco Peninsula (Hall, 1991; Hall et al., 1995). The master slip surface is nested within an array of branching sinuous faults (Sur fault zone) that have been given multiple names by previous workers (Fig. 6), who have proposed various interpretations for each fault strand. Local geologic relationships are difficult to discern on steep vegetated slopes scarred by numerous landslides. Our interpretations stem from extensive field checking and comparative appraisal of previous maps depicting contradictory structural relationships.

At the southeast end of the Point Sur–Big Sur area (~1 km northwest of Grimes Point), the San Gregorio–Hosgri fault is exposed at the base of high seacliffs as a steeply dipping shear zone several tens of meters wide between broken formation and mélange of the Franciscan Complex on the southwest and basement rocks of the Salinian block on the northeast (plate I of Hall, 1991). The extension of the fault to the northwest through the anastomosing array of fault traces within the Point Sur–Big Sur area is delineated by the contact between Mesozoic Salinian and Franciscan bedrock, or between disparate units of sedimentary cover that respectively overlie the two contrasting rock assemblages (Fig. 6). Cretaceous strata overlie Salinian basement, whereas Miocene strata overlie the Franciscan Complex.

A prominent strand of the San Gregorio–Hosgri fault system slices through the edge of the Salinian block, as the Serra or

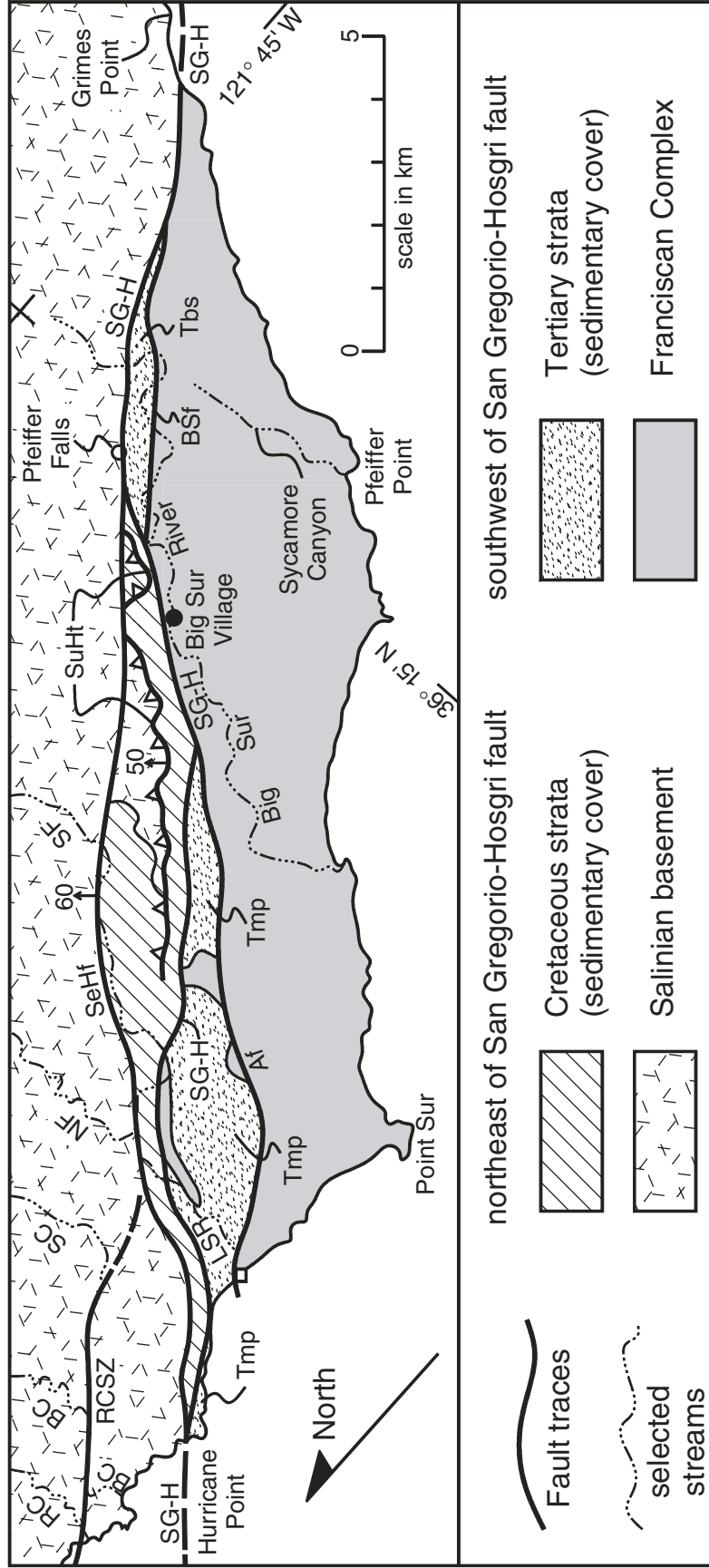


Figure 6. San Gregorio-Hosgri fault (SG-H) and associated fault strands of the Point Sur-Big Sur area (see Fig. 2B for location) adapted after Trask (1926), Oakeshott (1951), Gilbert (1971), Hall (1991), Dibblee (1999), and Rosenberg (2001). Faults (arrows denote dip): Af, Aguaje fault (Trask, 1926); BSf, Big Sur fault (Gilbert, 1971), termed Sur fault by Oakeshott (1951) and mapped as a segment of the San Gregorio-Hosgri fault by Hall (1991); RCSZ, Rocky Creek shear zone (Graham and Dickinson, 1978b, p. 15); SeHf, Serra (Trask, 1926; Gilbert, 1971) or Sierra (Hall, 1991; Dibblee, 1999) Hill fault (Gilbert, 1971; Hall, 1991; Dibblee, 1999) or thrust (Trask, 1926); SG-H, San Gregorio-Hosgri fault, mapped northwest of Big Sur as the Sur thrust by Trask (1926) and Dibblee (1999), near Big Sur as the Sur Hill fault (faulty correlation) by Oakeshott (1951), and southeast of Big Sur both as the Sur fault by Dibblee (1999) and as an extension of the branching Serra/Sierra Hill fault by Gilbert (1971) and Hall (1991); SuHt, Sur Hill thrust of Trask (1926) and Gilbert (1971) termed Sur thrust by Hall (1991) and Dibblee (1999). Tertiary strata: Tbs, sandstone of Big Sur of Gilbert (1971) mapped as unnamed Miocene sandstone (Tms) by Dibblee (1999); Tmp, Miocene Pismo Formation and underlying units (Hall, 1991; Hall et al., 1995), with basal depositional contact of Tertiary strata (Tmp) on Franciscan Complex schematic (locally faulted). Key streams: BC, Bixby Creek; LSR, Little Sur River (NF, North Fork; SF, South Fork); RC, Rocky Creek.

Sierra Hill fault (same structure), placing Salinian basement rocks against their Cretaceous cover over most of its length (Fig. 6) and merging to the southeast with the San Gregorio–Hosgri fault between Salinian and Franciscan rocks. On the northwest, the Rocky Creek shear zone splays off the Serra/Sierra Hill fault to slice even farther into Salinian basement. The Rocky Creek shear zone (Graham and Dickinson, 1978b; Rosenberg and Clark, 1999), with its principal locus of displacement near the north abutment of the coastal bridge over Rocky Creek, displays near-vertical shear surfaces with near-horizontal striations over a belt ~200 m wide, dislocates Pleistocene marine terrace deposits at an elevation of ~110 m above sea level in a prominent saddle on the spur to the southeast between Rocky Creek and Bixby Creek, and controls offset of the trend of Bixby Creek by more than a kilometer in a right-lateral sense (Fig. 6). Near its juncture with the Serra/Sierra Hill fault, the course of the Rocky Creek shear zone is marked by a contact between granitic and metamorphic rocks within Salinian basement (Dibblee, 1999).

The Aguaje fault is a geometrically similar subsidiary fault strand branching off the San Gregorio–Hosgri fault to slice through Franciscan rocks and their sedimentary cover along a subparallel path to the southwest (Fig. 6). The fault is readily detectable only because it places rocks of the Franciscan Complex against overlying Miocene strata over most of its length. Cenozoic fault contacts lying entirely within the Franciscan Complex are difficult to define because the Franciscan rocks are a heterogeneous assemblage of structurally interleaved bedded turbidite units, which form internally coherent fault-bounded thrust sheets or rafts, and more pervasively sheared broken formation and *mélange* (Gilbert, 1971). The two structural components of the assemblage are exposed in domains of irregular shape (Hall, 1991), with partly gradational boundaries, to form a tectonic continuum (Gilbert, 1971). Different structural domains of the subduction complex cannot be correlated with confidence where they have been offset by postsubduction Cenozoic faulting.

The tectonic significance of two key structures within the Point Sur–Big Sur area has been widely misinterpreted in the past. The first is the Sur Hill thrust (Fig. 6), an intra-Salinian reverse fault that places Salinian basement over its Cretaceous sedimentary cover. Past inference that the Sur Hill thrust (the Sur thrust of Hall, 1991) is a strand of the fundamental fault contact between the Salinian block and the Franciscan Complex has led to interpretations that the local Salinian–Franciscan contact is an east-dipping thrust (a segment of the Sur–Nacimiento fault zone of Page, 1970a, 1970b). The contact is actually the steeply dipping San Gregorio–Hosgri fault with dominantly strike-slip displacement.

The second commonly misinterpreted structure is the depositional contact, locally disrupted by intricate faulting, between the Franciscan Complex and overlying Miocene sedimentary strata (Tmp of Fig. 6). Miscorrelation of local Upper Miocene strata with the coeval Santa Margarita Formation of the Salinian block led Gilbert (1971) to infer a largely subhorizontal thrust contact, viewed as a segment of the so-called Sur–Nacimiento

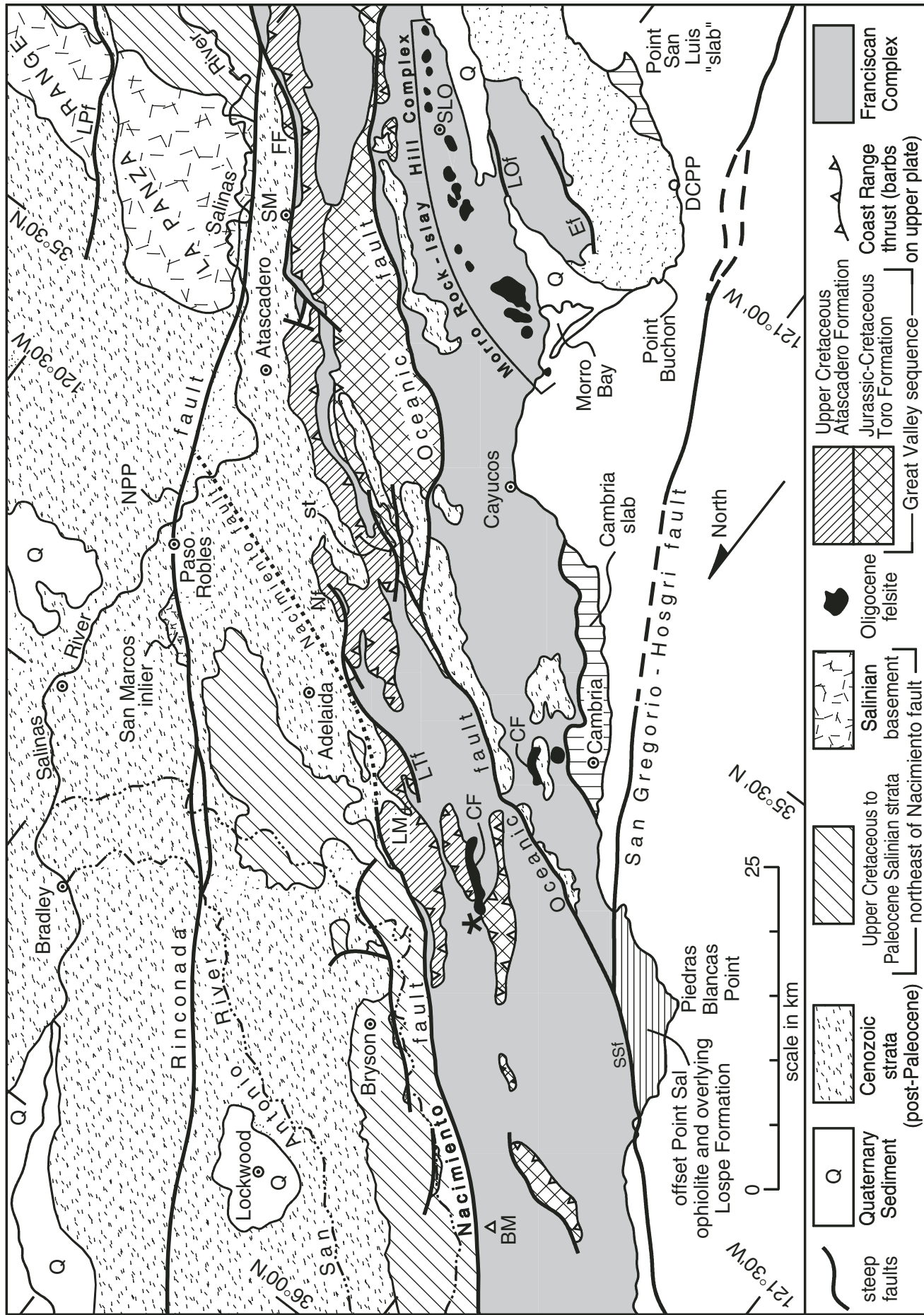
fault, between Miocene strata and subjacent Franciscan Complex. Hall (1991), however, showed that the Upper Miocene strata correlate instead with the Edna and Miguelito Members of the Pismo Formation, offset across the San Gregorio–Hosgri fault from an initial position in the Cambria–Pismo Beach area now lying 90–160 km southeast of the Point Sur–Big Sur area (Hall et al., 1995). Recognition of their stratigraphic identity shows that a thrust contact between the Miocene strata and the Franciscan Complex is an unnecessary postulation, because the Miocene strata are not part of the sedimentary cover of the adjacent Salinian block. Moreover, indistinctly bedded sedimentary breccia composed of Franciscan detritus is preserved locally along a depositional contact at the base of uppermost Oligocene to Lower Miocene Vaqueros Formation and Lower Miocene Rincon Shale lying concordantly beneath the Pismo Formation (Hall, 1991). Clasts of felsite and rhyodacite in the Upper Miocene Pismo Formation, a progradational deltaic complex derived mainly from Franciscan source rocks, represent detritus from the Oligocene Cambria Felsite or rhyodacitic necks and plugs of the related Morro Rock–Islay Hill complex, now exposed only across the San Gregorio–Hosgri fault 90–160 km southeast of the Point Sur–Big Sur area (Hall et al., 1995).

A fault sliver of sedimentary rocks of uncertain age (sandstone of Big Sur, Tbs, of Fig. 6), but of lithology compatible with a Miocene age (Gilbert, 1971; Dibblee, 1999), is present adjacent to the San Gregorio–Hosgri fault to the southeast of Big Sur. Hall (1991) concluded that the strata are part of the Cretaceous cover sequence resting upon Salinian basement. Near Pfeiffer Falls (Fig. 6), however, and in cutbanks of the Big Sur River to the southeast, clasts of black chert, misidentified by Oakeshott (1951) as Franciscan chert, were derived in our view from the Miocene Monterey Formation, and document a Miocene or younger age for the strata. Their correct stratigraphic assignment is not significant, however, for regional tectonic interpretations, for it does not matter in that context whether the master trace of the San Gregorio–Hosgri fault bounds the fault sliver of sandstone on the northeast (Fig. 6) or on the southwest (Big Sur fault of Fig. 6).

San Simeon Segment

After passing offshore south of Big Sur, the San Gregorio–Hosgri fault comes onshore again as the locally named San Simeon fault zone (Figs. 3B and 7), which is contiguous with the Hosgri fault of the offshore Santa Maria basin to the southeast (Leslie, 1981). Near San Simeon, the Oceanic fault (Fig. 7) branches inland from the San Simeon fault to connect on the southeast with the West Huasna fault, and the two linked structures accommodate ~15 km of dextral Neogene strike slip (Hall et al., 1995, p. 87). This partial transfer of San Gregorio–Hosgri strike slip inland from the coast may have diminished the net strike slip across the offshore Hosgri segment of the fault zone.

The epicenter of the 22 December 2003 San Simeon (“Paso Robles”) earthquake lay ~7.5 km northeast of the Oceanic



fault within exposures of Franciscan *mélange* ~5 km from the Nacimiento fault (Fig. 7). Preliminary first-motion solutions indicating thrust displacement imply that deformation associated with the seismic event had no direct relationship to strike slip along the San Gregorio–Hosgri fault or its splays. Crustal shortening within the southern Santa Lucia Range analogous to the crustal shortening reflected by the 1983 Coalinga earthquake (Dickinson, 2002) was probably responsible for the fault slip that generated the earthquake.

Hosgri Segment

The San Gregorio–Hosgri fault passes through the offshore Santa Maria basin as a steeply dipping to subvertical fault zone (Miller and Meltzer, 1999), but not past the rotated crustal panels of the western Transverse Ranges (Fig. 1). Speculation that the offshore Hosgri fault is a gently dipping thrust system (Crouch et al., 1984) is not borne out by detailed seismic profiles showing that the fault is steep and marked by flower structures indicative of major strike slip (Hanson et al., 2004).

OFFSET NACIMIENTO FAULT

The most fundamental geologic feature offset by the San Gregorio–Hosgri fault is the western flank of the Salinian block marked by the Nacimiento fault (Figs. 1 and 3). The Salinian block is an elongate domain of Cretaceous plutons and metamorphic wall rocks of uncertain protolith bounded on both sides by parallel tracts exposing the Franciscan Complex, a record of late Mesozoic subduction unaffected by thermal effects of Salinian plutons. The eastern flank of the Salinian block is delineated by the Neogene San Andreas fault, along which the Salinian block was displaced to the northwest from initial alignment with analogous igneous and metamorphic rocks of the Sierra Nevada Batholith belt (Fig. 1). Matching of lithologic units and structures

(fig. 14 of Ross, 1984) from the northern end of the Gabilan Range in the Salinian block (Fig. 3B) to the Tehachapi tail of the Sierra Nevada near the Garlock fault (Fig. 1) indicates that the Salinian block restores, by reversal of San Andreas dextral slip, to an initial position adjacent to the Mojave block (Grove, 1993; fig. 11 of Dickinson, 1996).

The western flank of the central Salinian block was termed the Sur-Nacimiento fault zone by Page (1970a). He defined the structure as an “arbitrarily delimited elongate belt of faults of various kinds and ages extending southeast from the Sur fault zone which is included [within it]” (Page, 1970a, p. 670—bracketed phrase added for clarity). He later explicitly noted that the structure is a “poorly defined assemblage of different kinds of faults of different ages” (Page, 1982, p. 1700). The different fault surfaces assigned to the fault zone have in common only their placement of Franciscan Complex against either Salinian basement rocks or non-Franciscan Mesozoic strata.

The Sur-Nacimiento fault of Page (1970a, 1970b, 1981, 1982) included a segment of the Neogene San Gregorio–Hosgri fault within the Sur fault zone (Fig. 6), the steeply dipping Nacimiento fault of the southern Santa Lucia Range (Figs. 5 and 7), and a folded but subhorizontal tectonic contact between subjacent Franciscan Complex and structurally overlying, internally imbricated Jurassic to Cretaceous strata exposed southwest of the Nacimiento fault (Fig. 7). The folded thrust is a “counterpart or displaced continuation” (Page, 1981, p. 372) of the Coast Range thrust between the Franciscan Complex and the Great Valley sequence east of the San Andreas fault within the inner Coast Ranges adjacent to the Great Valley (Fig. 1). Tectonic analysis of central California requires separation of these three structural components of the so-called Sur-Nacimiento fault zone, an unnecessary and potentially misleading term.

Cross-Fault Contrasts

The subvertical Nacimiento fault of its type area, inland from beyond Cape San Martin on the north to beyond Piedras Blancas Point on the south (Figs. 5 and 7), places Salinian basement against Franciscan *mélange* and associated rocks for ~50 km along strike. Southwest of the fault, the Upper Mesozoic strata structurally overlying the Franciscan Complex along the local analogue of the Coast Range thrust are Late Jurassic to Early Cretaceous as well as Late Cretaceous in age (Page, 1972; Seiders, 1982; McLean, 1994). Mesozoic strata resting positionally on Salinian basement northeast of the fault are exclusively Late Cretaceous. Moreover, Upper Cretaceous strata exposed on opposite sides of the fault differ in age. Strata overlying Salinian basement are mid-Maastrichtian (68–69 Ma) or younger (Almgren and Reay, 1977; Saul, 1986; Seiders, 1986, 1989a; Sliter, 1986; Kidder et al., 2003), extending stratigraphically upward into Paleocene strata (Saul, 1986; Grove, 1986, 1993). Upper Cretaceous strata above the Coast Range thrust southwest of the Nacimiento fault have yielded mainly Campanian fossils and none any younger (Page, 1970a, 1972, p. 967; Seiders, 1982).

Figure 7. Nacimiento fault and associated structures of the southern Santa Lucia Range and adjacent offshore (see Fig. 3B for location; northwest edge adjoins southeast edge of Fig. 5) adapted after Page (1970a, 1970b, 1972), Graham (1976a), Dibblee (1976, 1979), Hart (1976, 1977), Howell et al. (1977), Hall et al. (1979), Leslie (1981), Seiders (1982, 1986, 1989a, 1989b), Vedder et al. (1986), McCulloch (1989b), McLean (1994), and Rosenberg (2001). Asterisk between Nacimiento and Oceanic faults denotes epicenter (depth 23 km) of 22 December 2003 San Simeon earthquake as adapted from U.S. Geological Survey Earthquake Hazards Program (National Earthquake Information Center Web Site Team). Curved bracketed line (St) is traverse for point-counted samples of sandstone from Atascadero Formation. NPP, Nacimiento piercing point (on Rinconada fault) at buried Salinian–Franciscan contact (Nacimiento fault dotted where masked by Tertiary strata). Selected local faults: Ef, Edna; LPf, La Panza; LOf, Los Osos; LTf, Las Tablas; SSf, San Simeon (onshore segment of San Gregorio–Hosgri). Other features: BM, Burro Mountain (Δ); CF, Cambria Felsite (black); DCP, Diablo Canyon nuclear power plant (o); FF, Franciscan fensters (x); LM, Lime Mountain (+); SM, Santa Margarita.

Latest Jurassic (Tithonian) to Early Cretaceous (Berriasian-Valanginian) strata in the Toro Formation (Page, 1972; Hall *et al.*, 1979; Seiders, 1982) southwest of the fault are largely volcanoclastic and rest concordantly on an ophiolitic succession (Page, 1972), the local analogue of the Coast Range ophiolite. Jurassic ophiolite does not occur anywhere on the Salinian block, and no Salinian basement rocks are present in any klippen of the Coast Range thrust system to the southwest (Page, 1970a). Arkosic Upper Cretaceous strata of the overthrust assemblage southwest of the fault are referred to the Atascadero Formation (Hart, 1976; Seiders, 1982; McLean, 1994). Unit by unit, strata of the overthrust assemblage contain petrofacies similar to those characteristic of correlative strata in the Great Valley sequence of the inner Coast Ranges adjacent to the San Andreas fault (Gilbert and Dickinson, 1970; fig. 5 of Dickinson, 1983). Only the most arkosic of the Upper Cretaceous rocks in the Atascadero Formation southwest of the Nacimiento fault resemble petrofacies of the younger Upper Cretaceous strata overlying the Salinian block (Lee-Wong and Howell, 1977).

Between Bryson and Adelaida, the Nacimiento fault cuts thrust sheets of the Coast Range thrust system (Page, 1970a), to place supra-Franciscan and supra-Salinian Cretaceous strata of contrasting ages and tectonic positions in juxtaposition across the fault (Fig. 7). The geologic contrast across the fault is heightened by knowledge that Salinian granitic plutons underlying Maastrichtian strata were emplaced during the interval 93–76 Ma (Mattinson, 1978, 1990; Barth *et al.*, 2003; Ducea *et al.*, 2003; Kidder *et al.*, 2003), overlapping the deposition of Campanian strata (84–72 Ma) that structurally overlie Franciscan rocks southwest of the fault. The Campanian strata nowhere overlie the Franciscan Complex depositionally, but were offset with the latter by the Nacimiento fault (Fig. 7).

Nature of Faulting

Across the full width of the central Salinian block, granitic plutons display petrologic characteristics and isotopic signatures akin to central and eastern parts of the Sierra Nevada and Peninsular Ranges Batholiths (Fig. 1), but lack any granitic rocks similar to western fringes of either batholith (Ross, 1978; Saleeby, 2003). Page (1982) noted accordingly that the Nacimiento fault is a surface of truncation along which belts of rock analogous to those represented by the Sierra Nevada foothills and the eastern part of the Great Valley forearc trough have been tectonically removed. He suggested two processes that might have been responsible: (1) wholesale or piecemeal subduction (underthrusting by subduction erosion along his Sur-Nacimiento fault zone), or (2) lateral “mega-transport” by strike slip. Although Page (1982, p. 1724) favored the hypothesis of strike slip over subduction erosion, many subsequent workers have focused attention on the process of subduction erosion rather than strike slip (e.g., Hall, 1991).

Apart from the steep attitude of the Nacimiento fault, perhaps the prime objection to subduction erosion as the mechanism for truncation of the Salinian block is the immense width of arc

and forearc apparently excised by the Nacimiento fault (Page, 1982). The distance from exposures of the Coast Range thrust in the inner Coast Ranges east of the San Andreas fault to the central region of the Sierra Nevada Batholith is ~150 km (Fig. 1), and no analogues for any part of that span are present along the western side of the Salinian block. Nor are there any post-Campanian, pre-Miocene structures within basement rocks of the Salinian block that might be related to a megathrust system along its western flank (Page, 1982).

The schist of Sierra de Salinas (Fig. 5), which was underthrust beneath the Salinian block near ca. 70 Ma during Maastrichtian time (Barth *et al.*, 2003), is dominantly metagraywacke (Ross, 1976b) correlated provisionally with the underthrust Pelona-Orocopia assemblage of the Mojave block. The metagraywacke is lithologically unlike the varied igneous and sedimentary rocks expected for the belt of ground removed by truncation of the Salinian block. Correlation of the schist of Sierra de Salinas with Franciscan and structurally overlying sedimentary rocks southwest of the Nacimiento fault is not feasible, both because those strata are lithologically more heterogeneous and because the dominant population of detrital zircons in the schist of Sierra de Salinas is 117–81 Ma in age (Barth *et al.*, 2003). Plutons of the Salinian block may have been part of the zircon provenance, and detrital zircon populations dated from selected Franciscan rocks exposed along the coast southwest of the Nacimiento fault near Lopez Point and Cape San Martin (Fig. 5) display an analogous age peak in the range of 130–95 Ma (our unpublished data). Sedimentary strata of the Great Valley sequence southwest of the Nacimiento fault are largely too old, however, to contain such young detrital zircons, and could not be represented in Sierra de Salinas metagraywacke from which detrital zircons have been dated.

Speculation that the flank of the Salinian block once extended above Franciscan and related rocks now exposed west of the Nacimiento fault, to be removed later by erosion or tectonic denudation, fails from paleodepth considerations. Salinian basement along the Coast Ridge at the edge of the Salinian block was initially at 25–30 km depth (Ducea *et al.*, 2003; Kidder *et al.*, 2003), but unmetamorphosed strata of the Toro Formation and Atascadero Formation now exposed immediately to the southwest could not have been exhumed from such deep crustal levels. Difficulties with the hypothesis of subduction erosion for truncation of the Salinian block focus attention on the hypothesis of strike slip.

Regional Relations

Truncation of the Salinian block by dextral strike slip is unlikely because no viable candidates for an offset segment of the Salinian block are known anywhere to the north along the Cordilleran margin (Dickinson, 2004). Sinistral strike slip is possible, however, if the Salinian block were originally positioned between the Mojave block and the eastern flank of the Peninsular Ranges Batholith (fig. 11 of Dickinson, 1983). In this interpretation, strike slip along the Nacimiento fault is envisioned as a pre-Neogene

displacement of the western flank of the Salinian block from the eastern flank of the Peninsular Ranges Batholith, in effect opposite in sense but comparable in magnitude to later Neogene displacement of the eastern flank of the Salinian block from the Mojave block along the San Andreas fault (Fig. 1). From regional relations, there are tight constraints on the time span available for postulated sinistral strike slip along the Nacimiento fault zone.

The initial supposition (Dickinson, 1983, p. 629) that sinistral Nacimiento slip occurred in mid-Cretaceous time is now indefensible because Salinian plutons in contact with Franciscan rocks along the Nacimiento fault are known from U-Pb ages to have been emplaced during the interval 93–76 Ma in Late Cretaceous time (see above). Slip along the Nacimiento fault must necessarily have postdated emplacement of the Salinian plutons. Substantial exhumation of deep-seated basement rocks along the Coast Ridge belt at the western edge of the Salinian block during the Late Cretaceous interval of 76–68 Ma (Kidder et al., 2003), before deposition of Maastrichtian and younger sedimentary cover, may reflect uplift and tectonic denudation of basement rocks along a belt of intense deformation (“porpoising”) associated with incipient strike slip along the Nacimiento fault.

Depositional systems of Maastrichtian and conformably overlying Paleocene strata in the Santa Lucia and La Panza Ranges (Figs. 3B, 5, and 7) imply deposition along a steep continental margin perhaps initiated by removal of the Peninsular Ranges Batholith from the western flank of the Salinian block. Most exposures display associated fluviodeltaic, shelf-slope, and submarine fan facies deposited along and adjacent to a coastline trending generally from northwest to southeast (Howell and Vedder, 1978; Grove, 1993), but also include submarine canyon fills incised deeply into Salinian basement (Ruetz, 1979; Grove, 1993). Paleocurrents are consistently from northeast to southwest off or across the Salinian block (Grove, 1993). Conglomerate clasts include abundant felsic volcanic rocks presumably derived from the Mojave block (Seiders and Cox, 1992), which was adjacent to the Salinian block on the northeast during most of Late Cretaceous time. The volcanic clasts increase in abundance stratigraphically upward, relative to clasts derived from subjacent Salinian basement, in a pattern interpreted to reflect the gradual integration of regional drainages as paleotopography matured (Grove, 1989). Continuation of Nacimiento slip through Maastrichtian and into early Paleocene time is implied by juxtaposition of the supra-Salinian cover succession of Maastrichtian to Paleocene age against Franciscan and structurally overlying pre-Maastrichtian strata along the type Nacimiento fault.

Termination of Nacimiento slip by latest Oligocene or earliest Miocene time, well before initiation of San Andreas slip in central California, is indicated by stratal relations along strike to the southeast from the type area of the Nacimiento fault (Page, 1970b; Graham, 1978). A regionally unique barnacle-bearing bioclastic limestone facies (>50 m thick) of the Lower Miocene Vaqueros Formation at the base of the local Miocene succession west of Adelaida occurs on both sides of the fault, which passes beneath Miocene cover farther to the southeast (Fig. 7). The Nacimiento fault trace projects beneath Tertiary cover to inter-

sect the dextral Rinconada fault somewhere near Paso Robles (Fig. 7), where its piercing point is inferred from the location of its offset continuation south of the La Panza Range (Fig. 3B), where the Rinconada fault continues as the East Huasna fault (Hall et al., 1995; Dickinson, 1996).

The buried piercing point is recovered from an estimate of 44 ± 4 km of net Rinconada slip inferred from offsets of multiple Miocene shoreline trends and basin edges (Graham, 1978). The Nacimiento fault of Hart (1976) positioned west of the La Panza Range to the southeast of Paso Robles is an “ill-defined complex array of faults of diverse types and ages” (Ross, 1978, p. 511) that can be regarded as a fault (Sur-Nacimiento fault zone of McLean, 1994) within the block southwest of the Nacimiento fault. Its tectonic position well to the southwest of the true Nacimiento fault is shown by the presence of several small fensters of Franciscan Complex exposed structurally beneath a disrupted klippe of overthrust Upper Cretaceous and Upper Jurassic to Lower Cretaceous strata within a belt of complex structure between the fault trace and the Rinconada fault (Fig. 7).

Intra-Paleocene (60–65 Ma) termination of Nacimiento slip is suggested by internal stratigraphic relationships in strata overlying the Salinian block, where unconformities of enigmatic origin between Lower Paleocene and Upper Paleocene or Lower Eocene strata are widespread (Dickinson, 1965; Graham, 1976a, 1976b, 1978, 1979; Clark and Brabb, 1978; Greene and Clark, 1979; Clark, 1981). In the central Santa Lucia Range, where stratigraphic relationships are perhaps best displayed, the unconformity is angular and reflects erosional removal of ~2000 m of Cretaceous to Paleocene submarine canyon or fan-valley turbidites within just a few million years (Graham, 1979; Ruetz, 1979). Local faulting associated with the development of the unconformity terminated a regime of turbidite sedimentation and was followed by deposition of a marine banktop carbonate facies developed atop denuded basement blocks (Graham, 1979). Later interruptions of sedimentation on the Salinian block by disconformities and hiatuses are known (Brabb, 1964), but were less severe.

A change in tectonic regime related to termination of Nacimiento strike slip is a possible reason for the development of the regional unconformity and accompanying shifts in depositional style and loci. The continuation of Nacimiento sinistral slip from ca. 75 Ma to ca. 62.5 Ma would imply offset at a mean slip rate in the range of 40–48 mm/yr to achieve a total offset of 500–600 km (Fig. 1). Lateral motion at 40–48 mm/yr is comparable in rate to transform movements, and is difficult to reconcile with inferences that convergence between North America and the subducting Farallon plate was approximately normal to the coast during the interval 75–60 Ma (fig. 5 of Page and Engebretson, 1984; fig. 3 of Engebretson et al., 1985; fig. 5 of Debiche et al., 1987; fig. 5 of Norton, 1995). Recent evidence that the Hawaii hotspot was not fixed during Late Cretaceous and Paleogene time (Tarduno et al., 2003) may negate past inferences of plate motions at the California coast to the extent the latter are based on the supposedly fixed hotspot reference frame. For the moment, however, truncation of the

western flank of the Salinian block remains a “great and murky problem” (Page, 1981, p. 397), which still cannot be resolved conclusively. In any case, however, the abrupt western edge of the Salinian block at the Nacimiento fault existed before the end of Paleogene time. Dextral offset of the contact of the Salinian block with the Franciscan Complex can accordingly be taken as a measure of net Neogene displacement across the San Gregorio–Hosgri fault.

NACIMIENTO PIERCING POINTS

Both Page (1970a) and Hall (1991) suggested that the type Nacimiento fault might continue to the northwest as the Coast Ridge fault (Fig. 5), but as discussed previously that structure lacks either the magnitude of offset or the structural style to be comparable. Instead, the Nacimiento fault trends offshore to intersect the San Gregorio–Hosgri fault at a piercing point south of Big Sur (Figs. 3B and 5). A northern piercing point, where the offset Nacimiento fault emerges west of the San Gregorio–Hosgri fault, lies offshore from the San Francisco Peninsula (Fig. 3A).

Big Creek Enclave

Where the Salinian–Franciscan contact along the Nacimiento fault passes offshore near Lopez Point toward its underwater intersection with the San Gregorio–Hosgri fault, structural relations are complex and not fully understood (Fig. 8). East of Lopez Point near Mill Creek, the Nacimiento fault trends across switchbacks on the Nacimiento Road (three roadcuts) as a near-vertical shear zone ~200 m wide between Salinian basement rocks and intensely deformed mélangé of the Franciscan subduction complex. Farther northwest, however, the Salinian–Franciscan contact is sinuous and repeated at the margins of the fault-bounded Big Creek Salinian enclave (Fig. 8), composed of Salinian basement and overlying Upper Cretaceous sedimentary cover surrounded by Franciscan rocks.

Hall (1991) interpreted the Big Creek Salinian enclave as an overthrust outlier or klippe of Salinian basement and cover thrust across the Franciscan Complex by the so-called Sur fault, inferred to be a thrust dipping gently to the northeast. Previous workers (Gilbert, 1971; Seiders et al., 1983) had designated the fault bounding local Franciscan exposures on the northeast as the “Sur fault” (Fig. 8), even though it marks the same lithologic break as the Nacimiento fault along tectonic strike to the southeast and does not correlate with any structure near the Big Sur River, where the Salinian–Franciscan contact lies along the San Gregorio–Hosgri fault (Fig. 6).

The faults bounding the Big Creek Salinian enclave are steeply dipping ($>45^\circ$), and transect steep topography without deflection, as does the so-called Sur fault to the northeast (Fig. 8). Accordingly, the Big Creek Salinian enclave and a nearby smaller enclave of Salinian Cretaceous strata also surrounded by Franciscan exposures (Fig. 7) are regarded here as fault slivers bounded by steep

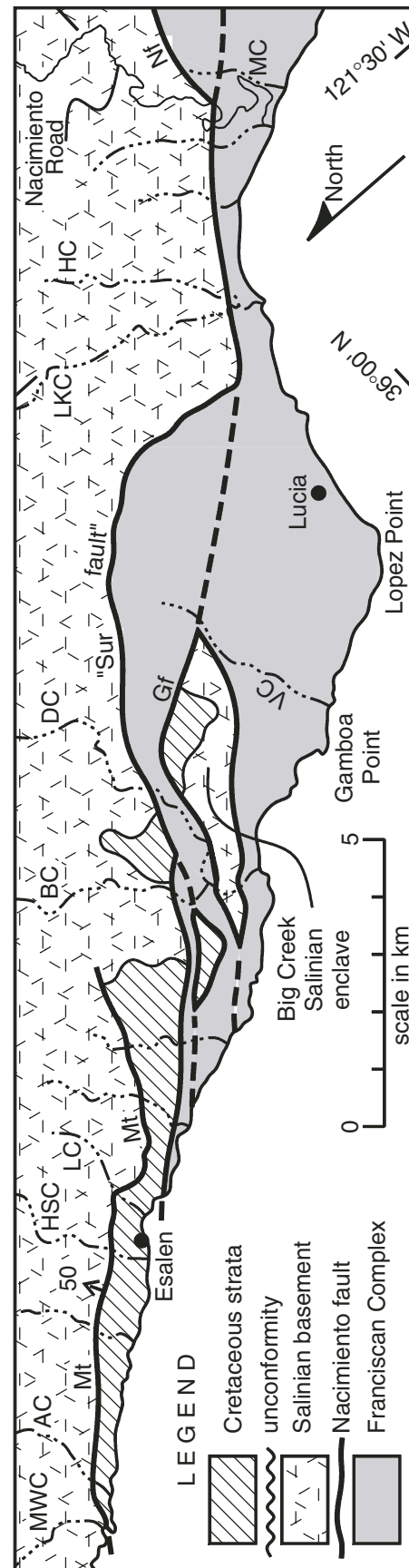


Figure 8. Fault pattern in the Esalen–Lucia area (see Fig. 3B for location) adapted after Reiche (1937), Gilbert (1971), Ross (1976a), Hall (1991), and Seiders et al. (1983). Faults (heavy lines, dashed where inferred; arrows denote dip): Gf, Gamboa fault (Gilbert, 1971; Seiders et al., 1983); Mt, McWay thrust (Reiche, 1937; Gilbert, 1971) or fault (Seiders et al., 1983); Nf, Nacimiento fault. Key streams: AC, Anderson Canyon; BC, Big Creek; DC, Devils Canyon; HSC, Hot Springs Canyon; HC, Hare Canyon; LKC, Lime Creek; LKC, Limekiln Creek; MC, Mill Creek; MWC, McWay Canyon; VC, Vicente Creek.

strike-slip faults lying subparallel to the Nacimiento fault trace. It remains unclear, however, whether all the faults bounding the enclaves are branching strands of the sinistral Nacimiento fault or are in part younger dextral faults, related to San Gregorio–Hosgri slip offshore, which locally offset and repeat the Nacimiento fault.

The Gamboa fault (Fig. 8) on the northeastern side of the Big Creek Salinian enclave may overprint or merge with the Nacimiento fault along strike to the southeast, although tracing the inferred course of the Gamboa fault through intervening pervasively sheared Franciscan *mélange* is equivocal. Northwestward from the Nacimiento Road through Hare Canyon and Limekiln Creek, the course of the near-vertical Salinian–Franciscan contact (the extension of the Nacimiento fault or the projection of the Gamboa fault) lies through saddles on steep spurs in the manner of strike-slip faults elsewhere in coastal California.

Regardless of how the Big Creek Salinian enclave is interpreted, the steep Salinian–Franciscan contact, regarded here as a northwestern segment of the Nacimiento fault, passes offshore in the cove south of Esalen (Fig. 8). Its juncture with the offshore San Gregorio–Hosgri fault, to form a piercing point for the Salinian–Franciscan contact, can be inferred within ± 2.5 km from the respective trends of the two structures (Figs. 3B and 5). The subparallel McWay thrust (Fig. 8) northeast of Esalen is an intra-Salinian reverse fault analogous to the Sur Hill thrust near Big Sur. Hall (1991) regarded the McWay thrust as a depositional contact of Upper Cretaceous sedimentary strata over Salinian basement, but that interpretation is not favored here for two reasons. First, the contact appears to dip northeast beneath Salinian basement in coastal ravines and canyons (e.g., Lime Creek of Fig. 8). Second,

steep seaward dips in the Cretaceous sedimentary strata would require an unconformity to dip seaward, but all mappable lithic components of Salinian basement rocks on the face of the Coast Ridge are uniformly inclined landward (Kidder et al., 2003). An unconformable rather than faulted contact between Salinian basement and the Cretaceous strata would imply a near-vertical attitude of foliation and lithologic units in the basement before tilting of its Cretaceous cover, but such a structural relation is not seen elsewhere within the Santa Lucia Range.

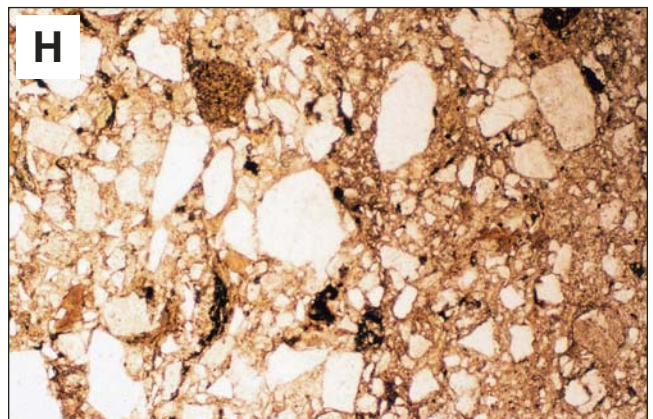
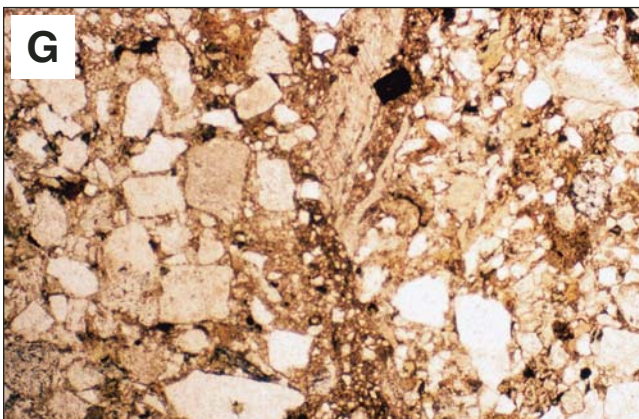
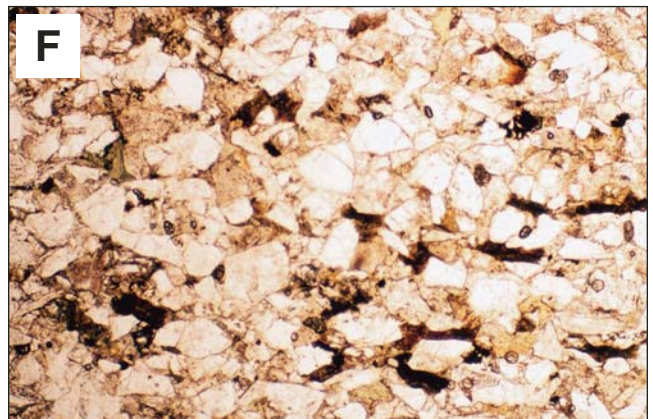
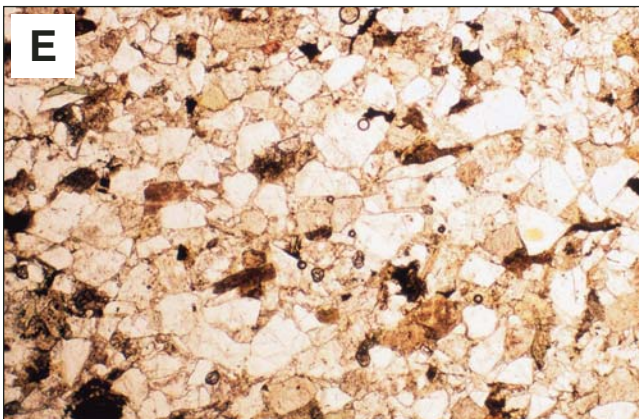
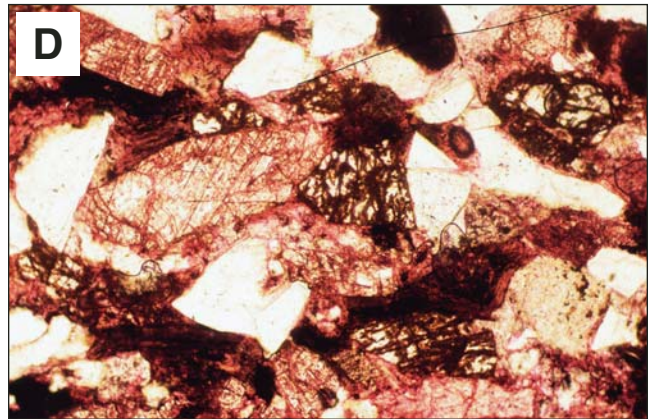
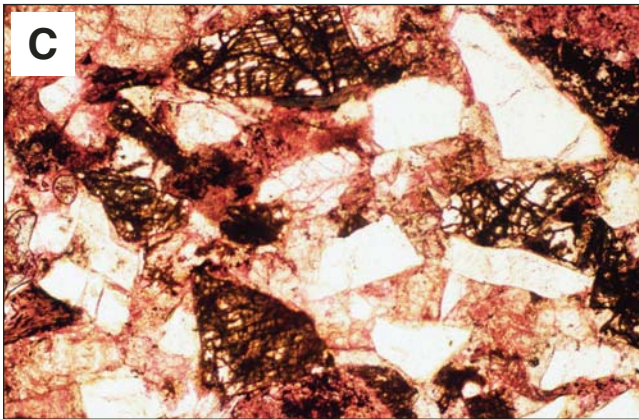
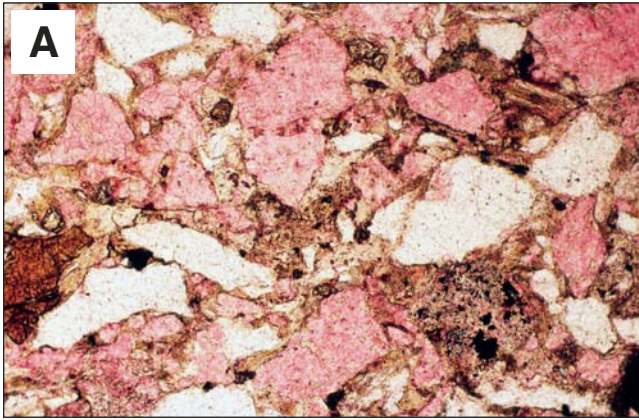
Shell Well Core

Control for the northern piercing point of the Nacimiento fault on the San Gregorio–Hosgri fault is provided by offshore data from the outer Santa Cruz basin (Fig. 4). In the past, estimates of the position of the offshore Nacimiento fault north of Monterey Bay have been influenced by correlation of strata at the base of an offshore well with onshore exposures of the Upper Cretaceous Pigeon Point Formation, which has been regarded as part of the Salinian block even though its stratigraphic base is nowhere exposed (Clark and Brabb, 1978; Clark, 1981; Howell and Joyce, 1981). Petrographic study of a bottomhole core reveals, however, that the well penetrated rocks of the Franciscan Complex, not the Pigeon Point Formation. Evaluation of the stratigraphy and petrography of the Pigeon Point Formation further indicates that the unit does not represent part of the Salinian Upper Cretaceous succession, but instead is part of the overthrust Upper Cretaceous succession that structurally overlies the Franciscan Complex southwest of the Nacimiento fault.

TABLE 1. DETRITAL MODES OF SELECTED FRANCISCAN AND NON-FRANCISCAN (CRETACEOUS) SANDSTONE SUITES IN COASTAL CENTRAL CALIFORNIA

| Sample suite | n | Qt | F | L | M | P | K | P/K | data |
|---|----|-------|-------|-------|------|-------|-------|---------|------|
| A. Samples from offshore Shell well 036-1ET and Franciscan rocks from Lucia block (Lopez Point and Cape San Martin): compositional ranges | | | | | | | | | |
| Shell well | 6 | 36–39 | 40–44 | 15–20 | 3–5 | 38–41 | 0–tr | ~100 | (1) |
| Lucia block | 3 | 38–46 | 25–38 | 17–35 | 1–3 | 25–38 | 0–1 | ~100 | (1) |
| B. Pigeon Point Formation of San Francisco Peninsula, Atascadero Formation of southern Santa Lucia Range, and Upper Cretaceous strata of Salinian block in northern Santa Lucia Range (Junipero Serra and Lake Nacimiento areas): compositional ranges except mean for Salinian block | | | | | | | | | |
| Pigeon Point Formation | 3 | 37–47 | 36–50 | 11–17 | 3–6 | 22–33 | 14–17 | .61–.66 | (1) |
| Atascadero Formation | 3 | 41–49 | 34–41 | 12–16 | 3–5 | 22–28 | 12–17 | .56–.70 | (1) |
| “Upper GVS” (~Atascadero) | 3 | 40–46 | 36–55 | 5–19 | 6–10 | 21–37 | 15–18 | .59–.67 | (2) |
| Salinian block | 30 | 45 | 48 | 7 | 7 | 24 | 24 | ~0.50 | (3) |
| C. K-feldspar-bearing assemblages in coastal exposures of Franciscan Complex (Point Sur block, Cambria slab, and Point San Luis “slab” of Figure 11): compositional means | | | | | | | | | |
| Point Sur | 26 | 39 | 48 | 13 | 4 | – | – | – | (3) |
| Cambria | 13 | 39 | 49 | 11 | 7 | – | – | – | (3) |
| Point San Luis | 5 | 39 | 52 | 9 | 8 | – | – | – | (3) |

Note: n—number of sandstone samples (400 detrital grains counted per sample for refs. 1–2 and 150–300 grains for ref. 3); Qt—total quartzose grains (monocrystalline and polycrystalline); F—total feldspar grains (P—plagioclase; K—K-feldspar); L—polycrystalline lithic fragments; M—mica flakes (dominantly biotite, minor muscovite); percentage figures are %QFL population except for M as %framework grains; sources of data: (1) this study; (2) Table 2 of Gilbert and Dickinson (1970); (3) Table 1 of Lee-Wong and Howell (1977).



Pre-Tertiary rock penetrated at the bottom of offshore Shell OCS Well 036-1ET (Fig. 4) was initially described as “marine sandstone [with some shale], tight and dense, locally brecciated and chloritized” (fig. 7 of Hoskins and Griffiths, 1971; fig. 16 of McCulloch, 1987; fig. 14 of McCulloch, 1989a). Discontinuous dark brown “silt pods” and abundant calcite veining have also been noted within the bottomhole rock (Heck et al., 1990). Although the indicated lithology is atypical of the unmetamorphosed Pigeon Point Formation, correlation with the latter unit has been implied by identification of the bottomhole strata as “Cretaceous” without mention of affinity with the Franciscan Complex (Hoskins and Griffiths, 1971; McCulloch, 1987, 1989a).

Examination of 17 ft (~5 m) of core preserved from the bottom of the well reveals structural and petrographic features that are characteristic of the Franciscan Complex but preclude correlation with the onshore Pigeon Point Formation. Most diagnostic is the near absence of K-feldspar in the bottomhole rock (Table 1A), as is typical for the Franciscan Complex (Dickinson et al., 1982). By contrast, sandstones of the Pigeon Point Formation (Table 1B) contain ~15% detrital K-feldspar (Lee-Wong and Howell, 1977). Photomicrographs of stained thin sections (Fig. 9A–D) illustrate the contrast in feldspar content.

The percentages of detrital grain types in the bottomhole rock overlap with percentages observed in Franciscan rocks of the Lucia block (Table 1A), which embraces exposures near Lopez Point and Cape San Martin (Figs. 3B and 5) west of the Nacimiento fault. The similarity in petrofacies is expected from inferred offset of the bottomhole rock northward from central California by dextral slip along the San Gregorio–Hosgri fault. The failure of detrital modes from the offshore well samples to embrace the full range of detrital modes represented by Fran-

ciscan graywackes from the Lucia block (Table 1A) is expected because all the offshore well samples derive from only 5 m of core, and can be regarded in combination as a point sample of Franciscan rock.

Distinctive microstructural features are well displayed in the well core, which is 4¼ in (~11 cm) in diameter, and are compatible with a Franciscan affinity but not observed in either the Pigeon Point Formation or any other non-Franciscan Cretaceous strata of coastal California. Severe compaction has imparted a planar, though crenulated or wavy, mesoscopic and microscopic fabric to the dominant graywacke of the core. Seams and discontinuous wisps of indurated black argillite (presumably the “silt pods” of Heck et al., 1990), sliced by shiny internal shear surfaces and terminating in feathery appendages, are reminiscent on a mesoscale of the structural fabric of *mélange* or broken formation. Calcite veinlets occupying shattered zones in graywacke resemble those observed in isolated resistant blocks of Franciscan *mélange* and broken formation. Closely spaced thin bands and discontinuous stringers of internal structural granulation visible in thin section (Fig. 9G–H) reflect internal deformation of the graywacke by dislocation along pervasive microfractures that are absent within sandstones of the Pigeon Point Formation (Fig. 9E–F).

Alternate Piercing Points

Recognition that the pre-Tertiary substratum at the offshore Shell well is Franciscan Complex and not Pigeon Point Formation forces reappraisal of the substratum beneath the outer Santa Cruz basin as a whole, but does not alone specify the location of the offset Nacimiento fault. Candidate structures within the basin include the Ascension fault (Greene, 1990) and two discontinuities in Neogene structural trends that might reflect the presence of buried faults (Fig. 4). The two structural discontinuities (northern and southern) are interpreted as marking contacts between fault-bounded structural blocks (McCulloch, 1987, 1989a), but the nature of the controlling structures at depth is uncertain. The offshore Ascension fault can be excluded as the position of the Nacimiento fault because its trace passes southwest of the well penetrating Franciscan rock (Fig. 4). The Ascension fault dips northeast toward the well (McCulloch, 1989c) but not gently enough to intersect the well bore, in which no major fault zones were detected (Hoskins and Griffiths, 1971).

Poorly developed reflections on seismic profiles suggest that the substratum beneath the outer Santa Cruz basin is Franciscan (McCulloch, 1989a, p. 449) at least as far to the northeast as the Pigeon Point structural high (Fig. 4). A structural discontinuity along the southwest flank of the Pigeon Point structural high could reflect the buried trace of the Nacimiento fault (McCulloch, 1987, 1989a), to define piercing point NPP₂ of Figure 3 (Mullins and Nagel, 1981; Nagel and Mullins, 1983). The location of the Shell well also allows the inferred offshore position of the Nacimiento fault to lie still farther to the southwest, along an unnamed offshore fault, to define piercing point NPP₃ of Figure 3 (Nagel et al., 1986). The farthest

Figure 9. Comparative photomicrographs of thin sections (A–D stained, E–H unstained) of Franciscan graywacke (A–B, G–H) from bottomhole core of Shell well 036-1ET (offshore Outer Santa Cruz basin) and Pigeon Point Formation (C–D, E–F) from onshore outcrop at Bolsa Point (near Pigeon Point). (A–B) Franciscan graywacke with evenly tinted pink plagioclase grains, clear quartz grains, and murky lithic fragments (note absence of K-feldspar). (C–D) Pigeon Point sandstone with irregularly tinted pink plagioclase grains, clear quartz grains, and K-feldspar grains stained yellowish to brownish (with grid-like etching of internal cleavages). (E–F) Pigeon Point sandstone showing preservation of detrital fabric unaffected by penetrative deformation (dark mica flakes impart weak depositional foliation oriented parallel to bedding, which is subhorizontal within field of view). (G–H) Franciscan graywacke showing disruption of detrital fabric by stringers and bands of granulation and reduction in grain size formed by postdepositional structural dislocation of detrital fabric. In G, discrete up-down zone of granulation (irregular width) in middle of view, with discontinuous calcite vein (to left of opaque black object) tapering downward to feather edge in center of view adjacent to darkest part of dislocation stringer. In H, wider dislocation band of pervasive granulation occupies entire right half of view. Fields of view 1.5 mm (A–D) or 3.5 mm (E–H) wide. Core samples (Franciscan) from depths of 9472–9473 ft (~2888.2 m) and 9486–9487 ft (~2892.4 m) in Shell well for A–B and G–H, respectively.

to the northeast that the Nacimiento fault might lie offshore is the structural discontinuity along the southwest flank of the granitic Farallon Ridge structural high to define piercing point NPP_1 (Fig. 4).

The Farallon Ridge separates the outer Santa Cruz basin from the offshore Bodega basin developed farther north within the Salinian block (figs. 5 and 10 of Hoskins and Griffiths, 1971; fig. 10–6 of Silver, 1978b; fig. 21 of McCulloch, 1987; fig. 13 of McCulloch, 1989a). Reverse faults that break subsurface Tertiary strata on reflection profiles are present along the southwest flanks of both the Pigeon Point and Farallon Ridge structural highs (McCulloch, 1987, p. 369), hence they do not resolve which structural discontinuity might be the Nacimiento fault. Potential piercing points lying between NPP_1 and NPP_2 – NPP_3 are not attractive, however, because onshore exposures of the Pigeon Point Formation (Fig. 4) presumably lie entirely on one side or the other of the Nacimiento fault.

Piercing points NPP_2 and NPP_3 would imply net San Gregorio–Hosgri displacement in the range of 100–115 km, encompassing a number of previous estimates (Graham and Dickinson, 1978a, 1978b; Nagel and Mullins, 1983; Nagel et al., 1986; Dickinson, 1996). Piercing point NPP_1 implies greater net San Gregorio–Hosgri slip of 156 ± 4 km, compatible with the previously suggested offset of Point Reyes to the Monterey Peninsula (Clark et al., 1984). The uncertainty of ± 4 km in estimated San Gregorio–Hosgri displacement is derived from combining an uncertainty of ± 2.5 km in the offshore position of the southern piercing point (NPP of Fig. 5) with a comparable uncertainty of ± 2.5 km in the inferred position of the northern piercing point (NPP_1 of Fig. 4) owing to the complex geometry of the principal strand of the San Gregorio fault and its Frijoles splay (Figs. 3A and 4). A choice between the alternate northern piercing points can be made by considering stratigraphic offsets that favor the larger net displacement (156 km) on the San Gregorio–Hosgri fault.

Pigeon Point–Atascadero Correlation

Interpretations favoring net San Gregorio–Hosgri slip of only 110–115 km assume that the outcrops of Pigeon Point Formation on the San Francisco Peninsula are part of the Salinian block, whereas net slip of 156 km requires correlation of the Pigeon Point Formation with the Atascadero Formation of the southern Santa Lucia Range (Fig. 7). Several considerations indicate that the latter postulation is correct. Displacement of the onshore and nearshore exposures of the Pigeon Point Formation (Figs. 3A and 4) from south of the southern piercing point of the Nacimiento fault (NPP of Figs. 3B and 5) requires more than 135–140 km of dextral slip on the San Gregorio–Hosgri fault, and favors NPP_1 over NPP_2 – NPP_3 as the northern piercing point (Fig. 4).

The Pigeon Point Formation has yielded Campanian fossils (Hall et al., 1959; Almgren and Reay, 1977; Howell et al., 1977; Clark and Brabb, 1978; Clark, 1981; Elder and Saul, 1993), also common in the Atascadero Formation, whereas supra-Salinian

Cretaceous strata are exclusively Maastrichtian in age (see above). Grove (1989, 1993) also noted that clast assemblages in conglomerates of the Pigeon Point Formation more closely resemble those in overthrust strata west of the Nacimiento fault in the Santa Lucia Range than those in Cretaceous strata depositional on the Salinian block east of the Nacimiento fault. Paleocurrent indicators in both the Pigeon Point and Atascadero Formations indicate mean paleoflow toward the southwest off the California continental margin (McClure, 1969; Howell and Joyce, 1981). The Pigeon Point Formation includes pebbly mudstone (López-Gamundí, 1993) associated with a depositional system of strandline and related turbidite deposits filling the head of a submarine canyon or slope channel (Lowe, 1972; Tyler, 1972; Elder and Saul, 1993). Pebbly mudstone is also known within the Atascadero Formation (Seiders, 1982) but not from supra-Salinian Cretaceous strata.

For petrographic comparison with the Pigeon Point Formation, we collected sandstones from the exposures of Atascadero Formation located closest to the San Gregorio–Hosgri fault (traverse St 10–12 km northeast of Cayucos on Fig. 6). The sampled outcrops are roadcuts mapped by Seiders (1982) along State Highway 46 (leading from Cambria to Paso Robles) in the area south of York Mountain between Cienega Creek on the west and Paso Robles Creek on the east. Compositional parameters derived from detrital modes determined from point counts overlap for Pigeon Point and Atascadero samples, whereas Cretaceous sandstones of the Salinian block tend to be less lithic and richer in K-feldspar (Table 1B). The petrographic comparison is not conclusive, however, because nearly all Upper Cretaceous sandstones of coastal California are broadly arkosic, with detrital modes appropriate for derivation from the dissected magmatic arc of the California continental margin.

Supportive Tertiary Exposures

Support for correlation of the Pigeon Point with the Atascadero Formation is provided by two exposures of volcanic rocks west of the San Gregorio–Hosgri fault near Pigeon Point. One is felsic volcanic rock correlated here with the Cambria Felsite of the southern Santa Lucia Range, and the other is basaltic volcanic rock similar in age and lithology to counterparts also present in the southern Santa Lucia Range.

Near lower Butano Creek west of Pescadero (point B of Fig. 3), microporphyrritic rhyolite or rhyodacite with quartz and feldspar phenocrysts set in a devitrified and partly spherulitic microcrystalline groundmass is locally exposed beneath marine terrace cover (Clark and Brabb, 1978; Brabb et al., 1998). The nature of contacts with the Pigeon Point Formation exposed to either side of the areally restricted outcrop on the eroded face of the terrace cannot be discerned, but the volcanic rock probably lies within a fault sliver bounded by minor faults associated with the Frijoles splay of the San Gregorio fault (Howell and Joyce, 1981). The volcanic rock was initially thought to underlie the Pigeon Point Formation as part of the Salinian block (Clark and Brabb, 1978; Clark, 1981), but no unmetamorphosed Cretaceous

or older felsic volcanic rocks are known on the Salinian block elsewhere in central California.

The Pescadero volcanic rock bears a close lithologic resemblance to extrusive Oligocene Cambria Felsite (Ernst and Hall, 1974) of the southern Santa Lucia Range, and to related intrusive plugs and stubby domes of the nearby Morro Rock–Islay Hill complex (Figs. 7 and 10). Thin sections of the felsic volcanic rock display microspherulitic growths that are visually indistinguishable from groundmass features in rocks of the Morro Rock–Islay Hill complex (fig. 3AB of Ernst and Hall, 1974). Rounded and embayed quartz grains of probable xenocrystic origin present in some thin sections are also common in the Cambria Felsite. Outcrops of porphyritic dacite of the Cambria Felsite occur in close proximity to exposures of the Atascadero Formation north of Cambria (Fig. 7). Correlation of the Pigeon Point Formation with the Atascadero Formation implies that the felsic volcanic rock near Pescadero overlay the Pigeon Point Formation before incorporation into a local fault sliver.

At nearby Pescadero Beach (point A of Fig. 3), pillowed and peperitic basalt that has yielded an early Miocene K–Ar age of 22.0 ± 0.7 Ma (Taylor, 1990) conformably overlies marine sandstone and calcarenite (or doloarenite) of the Vaqueros Formation, which in turn lies with angular unconformity on the Pigeon Point Formation. Closely related volcanoclastic strata (Clark, 1981; Taylor, 1990) are intercalated within the Vaqueros Formation farther southeast near Año Nuevo Point (AN of Fig. 3). Related lavas and tuffs are also interbedded offshore with Lower Miocene shale over stratigraphic intervals 335–460 m thick near the base of the Tertiary succession resting unconformably on the Franciscan substratum examined from the Shell well core (Hoskins and Griffiths, 1971, p. 218; McCulloch, 1987, p. 369; McCulloch, 1989a, p. 451).

Offset counterparts of the volcanogenic Miocene strata across the San Gregorio–Hosgri fault are represented by Lower Miocene basalt that is present near the stratigraphic horizon of the Vaqueros Formation in the southern Santa Lucia Range (Seiders, 1982), and massive basalt is also associated with more felsic volcanic rocks of the Cambria Felsite (Hall et al., 1979). Moreover, the bioclastic facies of Vaqueros Formation underlying the basaltic rocks at Pescadero Beach more closely resembles the bioclastic facies (Graham, 1976a, 1978) overlapping the trace of the Nacimiento fault in the southern Santa Lucia Range than any other lithofacies within the Vaqueros Formation of the Santa Lucia Range. The time of eruption of the basalt at Pescadero Beach overlaps with Oligocene–Miocene K–Ar ages (22.7 ± 0.9 – 28.0 ± 1.0) for the Morro Rock–Islay Hill complex, although $^{40}\text{Ar}/^{39}\text{Ar}$ ages (26.5–27.0 Ma) for extrusive Cambria Felsite are uniformly somewhat older (Cole and Stanley, 1998).

TECTONIC RECONSTRUCTIONS

Tectonic reconstructions that restore ~155 km (vs. 110–115 km) of dextral strike slip on the San Gregorio–Hosgri fault help to constrain the best estimate of net slip. The most infor-

mative restorations reconstruct the pre-slip configuration of the northern Salinian block and the pre-slip position of the Point Sur Franciscan block.

Northern Salinian Block

Reversal of ~155 km of dextral slip on the San Gregorio–Hosgri fault achieves a satisfactory restoration of the northern Salinian block, with plutons that have yielded similar U–Pb ages and initial Sr isotopic ratios in close juxtaposition (Fig. 10). Although areal patterns of age and Sr isotopic ratio are complex in detail, there is an overall gradient from older ages and lower Sr isotopic ratios on the northwest to younger ages and higher Sr isotopic ratios on the southeast. The reconstruction of Figure 10 clarifies regional gradients in the isotopic characteristics of Salinian plutons by eliminating areal disjunctures without introducing others. Reversal of only 110–115 km of dextral slip on the San Gregorio–Hosgri fault, by favoring piercing point NPP_1 – NPP_3 over piercing point NPP_2 (Fig. 4), would place the granitic rocks of the Point Reyes Peninsula near granitic rocks of western Ben Lomond Mountain with distinctly lower Sr isotopic ratios (by ~0.002), and would place the Upper Cretaceous strata of Pigeon Point against the northern Santa Lucia Range where no close stratal counterparts are known (see above).

The most attractive single facet of the reconstruction (Fig. 10) is the alignment of lithologically indistinguishable porphyritic granodiorite bodies and unconformably overlying Lower Eocene strata exposed at the tip of Point Reyes and at Point Lobos south of the Monterey Peninsula (Clark et al., 1984). The porphyritic granodiorite of Monterey is lithologically the most distinctive pluton of the central Salinian block (Ross, 1978; Howell and Vedder, 1978), and no plutonic rocks of comparable lithology are exposed anywhere to the north of Monterey Bay except at Point Reyes (Ross, 1984). Average initial Sr isotopic ratios for the two offset granitic bodies are even closer (Fig. 10) than formerly appreciated (Clark et al., 1984).

The close similarity of Salinian basement rock at Point Reyes and on the Monterey Peninsula is matched by the close similarity of immediately overlying sedimentary strata (Clark et al., 1984). The strata nonconformably overlie porphyritic granodiorite as the sedimentary fills (210–220 m thick) of local submarine canyons or submerged slope ravines (Clifton, 1981, 1984; Clifton and Hill, 1987; Burnham, 1999). Paleocurrent indicators in both successions document generally westward flow (Howell and Vedder, 1978; Burnham, 1999), and both successions contain correlative foraminiferal faunas of early Eocene age (Kristin McDougall, 1997, personal commun.).

Lower Eocene conglomerates at Point Reyes and Point Lobos contain distinctive “smoked salmon” (Bachman and Abbott, 1988) or “purple porphyry” (Burnham, 1999) clasts forming 9%–13% of the clast population in each case. The distinctive clasts are rhyolitic felsite containing euhedral salmon-colored feldspar phenocrysts set in a smoky gray aphanitic groundmass of uniform appearance (Bachman and Abbott,

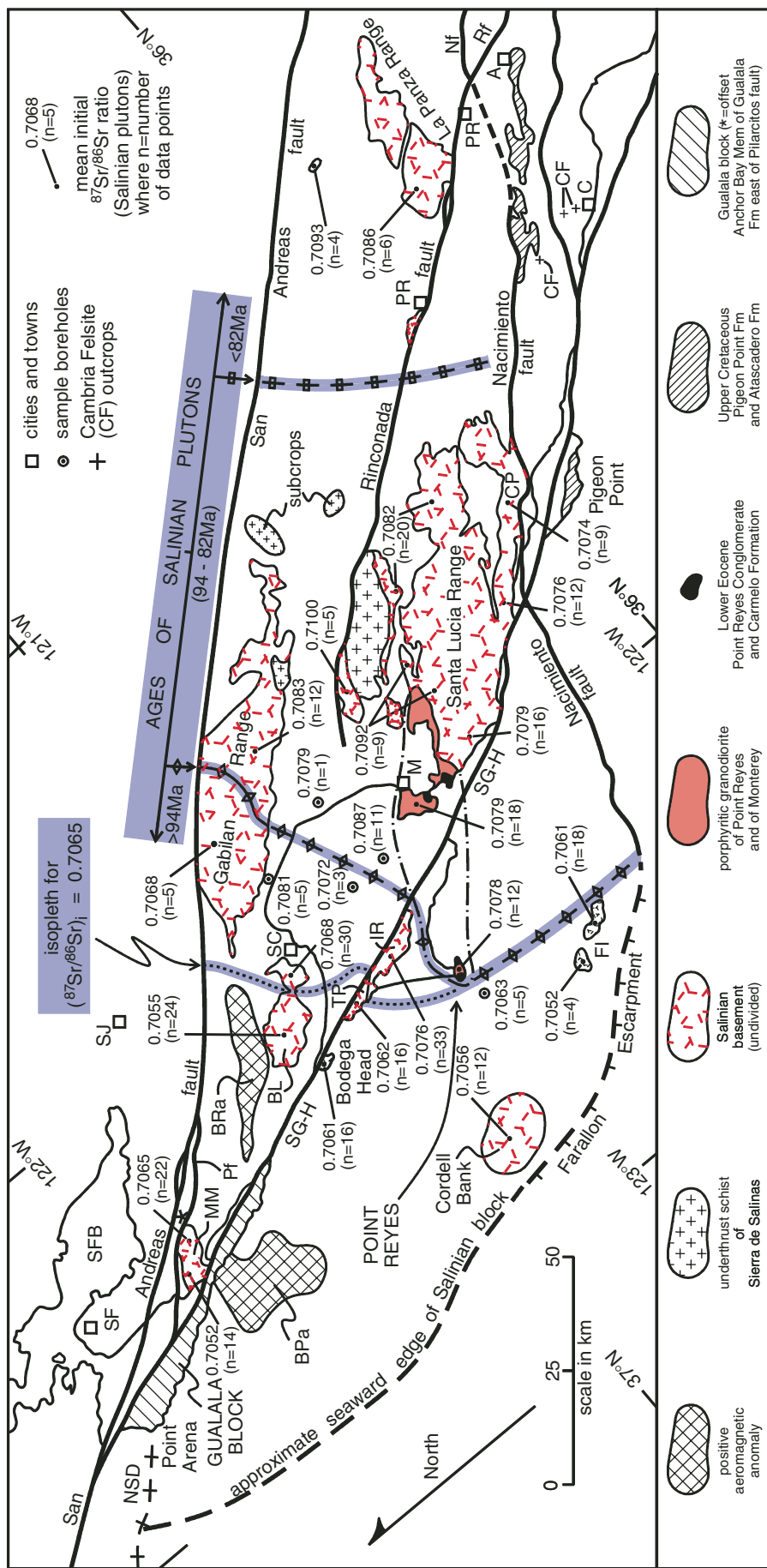


Figure 10. Late Miocene reconstruction of northern end of Salinian block (placing Point Reyes off Monterey Bay) by restoration of 155 km of dextral slip along San Gregorio-Hosgri fault (SG-H) and San Andreas fault north of Golden Gate (San Andreas slip not restored south of San Gregorio-Hosgri junction), and 44 km of dextral slip along southern Rinconada fault decreasing northward to 35 km near Monterey Bay (latitude-longitude grid applies to central Salinian block between San Gregorio-Hosgri and Rinconada faults). Resulting position of restored Gualala block is uncertain (see text for discussion). Geologic relations adapted after Ross and Brabb (1973), Ross (1976a, 1984), Galloway (1977), Clark et al. (1984), McCulloch (1987, 1989a, 1989c), Wentworth et al. (1998), Jachens et al. (1998), and Figures 4–5 and 7. Approximate ages of Salinian plutons from U-Pb data of Mattinson and James (1985), Barth et al. (2003), and Kidder et al. (2003). Initial Sr isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) for Salinian plutons are mean whole-rock values from Mattinson (1990), Kistler and Champion (2001), and our data (at CP, Cone Peak), where n is the number of measurements for each site or area (total n = 338). Geologic and geographic features: BL, Ben Lomond Mountain; BPa, Black Point anomaly; BRa, Butano Ridge anomaly (= Boulder Creek anomaly of Ross, 1984); CH, charnockitic rocks of Compton (1960) near Grimes Point; FI, Farallon Islands; IR, granodiorite of Inverness Ridge; MM, Montara Mountain; NF, Nacimiento fault; NSD, offshore Navarro structural discontinuity; Pf, Pilarcitos fault; RF, Rinconada fault; SFB, San Francisco Bay; TP, tonalite of Tomales Point. Key cities: A, Atascadero; C, Cambria; M, Monterey; PR, Paso Robles (disrupted by offset across Rinconada fault); SC, Santa Cruz; SF, San Francisco; SJ, San Jose.

1988), and they have yielded indistinguishable Late Jurassic U–Pb ages of 151.6 ± 2.6 Ma from both localities (Burnham, 1999). No similar clasts are present in either the Pigeon Point Formation or any Cretaceous strata of the Santa Lucia Range (Bachman and Abbott, 1988).

Point Sur Franciscan Block

Reversal of only 110–115 km of dextral slip on the San Gregorio–Hosgri fault would place the Point Sur block of Franciscan rocks adjacent to the Cambria slab of Franciscan rocks (Fig. 11), as postulated by Graham and Dickinson (1978a, 1978b). This inference is untenable, however, because of contrasts in both lithology and paleothermal history. Net displacement of the Point Sur block by the full ~155 km inferred for the northern San Gregorio–Hosgri fault leads to a more satisfactory tectonic reconstruction.

The Cambria slab was deposited within a trench-slope basin (Howell et al., 1977; Smith et al., 1979) perched atop more deformed rocks of the Franciscan Complex. Mélange is present only as diapirs penetrating upward into strata of the Cambria slab (Becker and Cloos, 1985). Although early accounts of the Point Sur block inferred a partially analogous origin (the Pfeiffer Beach slab of Underwood, 1977), more recent mapping has shown that the Point Sur block is composed of broken formation and mélange, including local rafts of more intact strata separated by disrupted sheets or belts of intensely sheared rock (Hall, 1991). Isolated blocks within mélange locally contain stratal successions incorporating pillow basalt overlain depositionally by ribbon chert which in turn is overlain depositionally by graywacke-argillite intervals, suggesting that the Point Sur assemblage originated as trench fill, rather than within a slope basin.

Vitrinite reflectance data (Fig. 11) show that the Point Sur block and the Cambria slab have experienced distinctly different thermal histories (Underwood and Howell, 1987; Underwood et al., 1995). Mean vitrinite reflectance values are consistently higher (1.0+) in the Point Sur block than in the Cambria slab (<1.0). This contrast is consistent with the interpretation that the Point Sur block is mélange and broken formation formed at deeper structural levels within the Franciscan Complex than the comparatively surficial slope basin of the Cambria slab. The contrast in paleothermal history is heightened by the observation that vitrinite reflectance values in the Cambria slab increase from southeast to northwest (0.6–0.8), whereas in the Point Sur block they increase from northwest to southeast (1.0–2.6).

The hypothesis that the contrast in vitrinite reflectance might imply little or no lateral displacement of the Point Sur block along the San Gregorio–Hosgri fault (Underwood et al., 1995) does not seem viable because of sharp contrast in both detrital petrofacies and metamorphic grade between the Franciscan Complex of the Point Sur block and of the nearby Lucia block (including exposures around Lopez Point and Cape San Martin, cf. Fig. 7). Graywackes of the Point Sur block contain significant proportions

of detrital K-feldspar, whereas graywackes of the Lucia block are nearly devoid of K-feldspar (Gilbert, 1973). Graywackes of the Lucia block (and throughout the Franciscan Complex of the southern Santa Lucia Range) contain mineral assemblages indicative of the prehnite-pumpellyite and lawsonite-pumpellyite mineral zones (Ernst, 1980), which are wholly lacking within the Point Sur block, where the laumontite zone is the highest grade present (Gilbert, 1973). The higher-grade assemblages are also lacking in the Cambria slab and the so-called Point San Luis slab east of Point Buchon (Fig. 11).

Reversal of 155 km of dextral slip on the San Gregorio–Hosgri fault would place the Point Sur block offshore from the Point San Luis slab (Fig. 11) in a position compatible with the respective lithology, petrofacies, metamorphic grade, and paleothermal history of the two assemblages. The Point San Luis “slab” includes mélange and broken formation as well as intact blocks or rafts of less dislocated strata (Underwood and Laughland, 2001) and is comparable lithologically to Point Sur Franciscan exposures. For the tectonic reconstruction of Figure 11, the segments of the Point Sur and Point San Luis assemblages closest to one another have yielded generally coordinate vitrinite reflectance values (1.0–1.2 for Point Sur; 1.0–1.4 for Point San Luis). Vitrinite reflectance values from the Franciscan Complex inland and adjacent to the Point San Luis assemblage lie in the slightly higher range of 1.2–1.6 (Fig. 11). Substantially higher vitrinite reflectance values (1.9–2.6) from the Point Sur block lie to the southeast beyond the close juxtaposition of the two assemblages in the preferred reconstruction (Fig. 11).

Sandstone petrofacies of the Point Sur, Cambria, and Point San Luis successions are too similar (Table 1C) to permit either correlation or discrimination among the three. All display quartzofeldspathic, lithic-poor frameworks containing detrital K-feldspar (Lee-Wong and Howell, 1977) and similar proportions of detrital mica flakes (Table 1C). In common with other Upper Cretaceous strata of central California, all were apparently derived from a dissected magmatic arc along the continental margin.

Approximately 15 km of San Gregorio–Hosgri dextral strike slip may have been diverted along the Oceanic fault (Figs. 7 and 11), which connects on the southeast to the West Huasna fault (Hall et al., 1995; Dickinson, 1996). Reducing the net inferred displacement of the Point Sur block from 155 km to 140 km ($155 - 15 = 140$) would place the Point Sur block off Point Buchon in a position where onshore Franciscan rocks are masked by Tertiary cover (Fig. 11). The alternate placement of the Point Sur block is not favored, however, by available vitrinite reflectance data, because the anomalously high values (1.9–2.6) for the Point Sur block would then plot much closer to the Point San Luis assemblage, which displays lower values. Abundant felsite pebbles and cobbles in the Upper Miocene Pismo Formation near Big Sur (Hall et al., 1995) could readily have reached the depositional site from the Morro Rock–Islay Hill complex of Oligocene–Miocene plugs and domes near San Luis Obispo (Fig. 6) with the Point Sur block in either its preferred (155 km offset) or its alternate (140 km offset) position (Fig. 11).

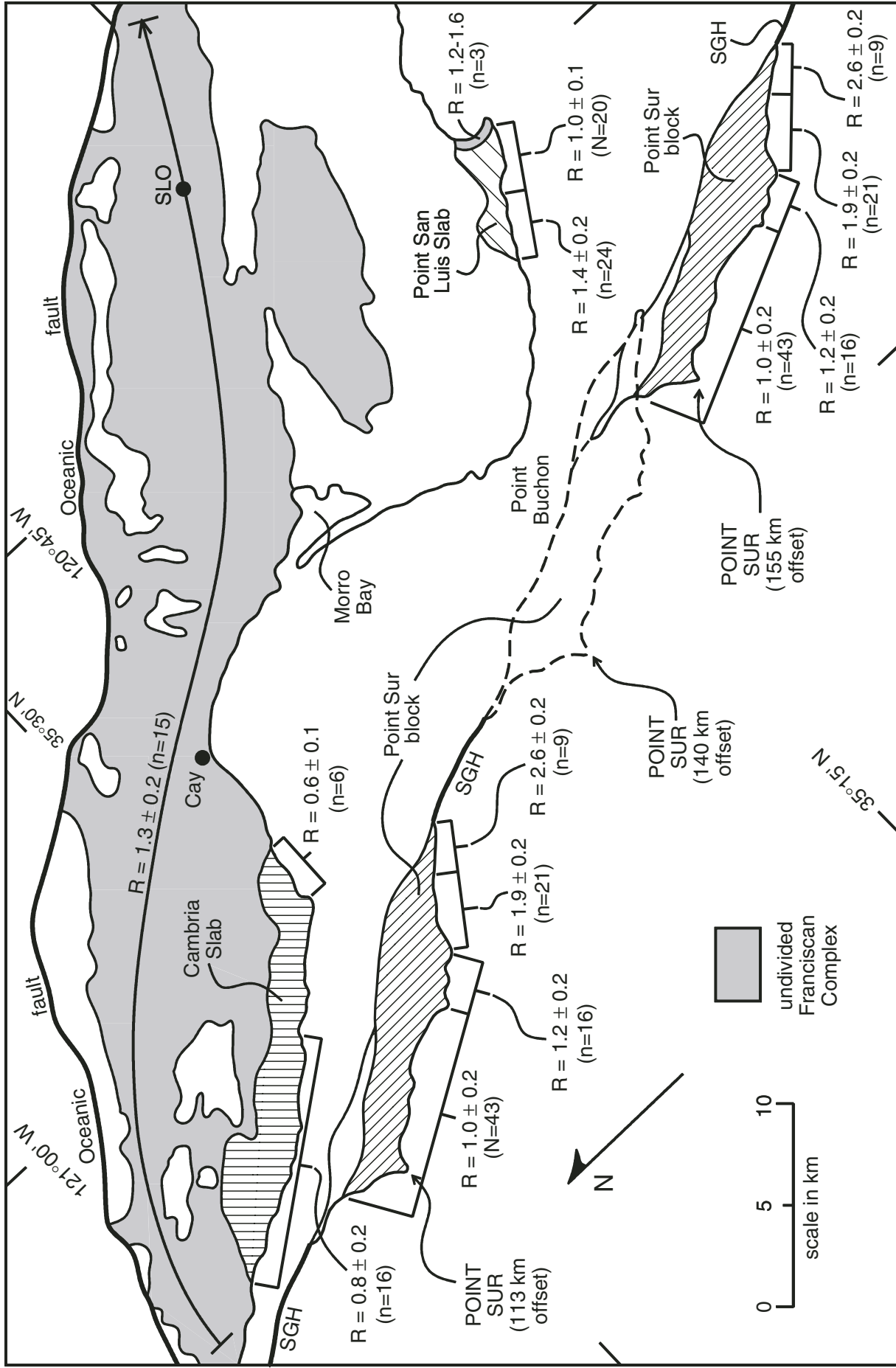


Figure 11. Alternate restorations of Point Sur Franciscan block for 113 km (Graham and Dickinson, 1978a, 1978b), 140 km (dashed outline), and 155 km (preferred) of net slip on offshore San Gregorio-Hosgri fault (SGH). Vitrinite reflectance values (R, where \pm indicates standard deviation of n measurements) mostly from seaciff outcrops except for inland exposures of Franciscan rocks (undivided) after Underwood and Howell (1987), Underwood et al. (1995), and Underwood and Laughland (2001). Outcrop patterns modified after Figures 5 and 7 (alluvial-coastal sediment, Cenozoic strata and non-Franciscan Mesozoic rocks blank). Explanation: Cay, Cayucos; SLO, San Luis Obispo.

San Simeon and Point Sal

The lithic assemblage of pre-Tertiary rocks and their Tertiary cover exposed on the southwest side of the San Simeon segment (Fig. 7) of the San Gregorio–Hosgri fault may have been offset from the vicinity of Point Sal (Hall, 1975, 1981; Hall et al., 1995). The speculative correlation apparently requires only 100 ± 10 km of net dextral slip along the San Gregorio–Hosgri fault zone (Fig. 3B). Although the correlation may not be unique (Seiders, 1979; Sedlock and Hamilton, 1991), outcrops of pre-Tertiary rock overlain unconformably by Lower Miocene strata at Point Sal are limited in extent (Johnson and Stanley, 1994; McLean and Stanley, 1994), and subsurface data suggest that similar subcrop elsewhere within the Santa Maria basin is rare (fig. 3 of McLean, 1991). As the Santa Maria basin has been deformed internally in response to transrotational tectonism in the western Transverse Ranges (Dickinson, 1996; Stanley et al., 1996), the Point Sal lithic assemblage has been transported northward from the position it occupied prior to Neogene tectonism. If so, the present distance from Point Sal to San Simeon is less than the pre-middle Miocene distance before San Gregorio–Hosgri slip.

The relationship of San Gregorio–Hosgri displacements to transrotational tectonism in the western Transverse Ranges is perhaps the most difficult facet of coastal California tectonics to comprehend (Sorlien et al., 1999a, 1999b). The southern end of the San Gregorio–Hosgri fault curves into alignment with the trend of the western Transverse Ranges between Point Arguello and Point Conception (Fig. 12A), suggesting that dextral slip along the San Gregorio–Hosgri fault is transposed into crustal shortening within the rotating Transverse Ranges. Kinematic coordination of Transverse Ranges rotation with deformation farther inland to the north is also implied. Dextral slip on longitudinal faults in the Southern Coast Ranges and crustal shortening across the Santa Maria basin are both required to allow rotation of the western Transverse Ranges to proceed (Luyendyk et al., 1980, 1985; Hornafius, 1985; Luyendyk and Hornafius, 1987; Luyendyk, 1991; Dickinson, 1996).

Lower to Middle Miocene (18–14 Ma) volcanic rocks (Dickinson, 1997; Cole and Stanley, 1998; Luyendyk et al., 1998; McCulloch et al., 2002) in the western Transverse Ranges record similar amounts of tectonic rotation (Dickinson, 1996). This relationship implies that most rotation occurred within the past 12–13 m.y., and has been broadly coeval with San Gregorio–Hosgri slip (younger than 12 Ma). Consequently, the pre-slip position inferred for Point Sal (Fig. 12B) depends upon retrodeformation of transrotational tectonism within the Santa Maria basin.

Anticlockwise rotation of the western Transverse Ranges by $\sim 85^\circ$ since ca. 15 Ma (fig. 7 of Luyendyk, 1991) is reversed for the Middle Miocene tectonic reconstruction of Figure 12B. Inferred dextral slip on the Oceanic–West Huasna and Rinconada–East Huasna faults was also reversed (by 15 km and 44 km, respectively), and the Santa Maria basin was expanded to accommodate back-rotation of the western Transverse Ranges.

The southern alternate position (S) of Point Sal was plotted by proportionally expanding the extent of the Santa Maria basin in a direction parallel to the San Gregorio–Hosgri fault. The northern alternate position (N) of Point Sal was plotted by proportionally shifting Point Sal in a direction normal to fold trends within the Santa Maria basin to recover a shortening rate of 6 ± 2 mm/yr normal to the fold trend inferred from geodetic measurements of current intrabasinal deformation (Feigl et al., 1990). The San Gregorio–Hosgri fault serves as the structural boundary (Lettis et al., 2004) between the deforming onshore Santa Maria basin and the largely rigid outer Santa Maria basin (shortening ~ 0.1 mm/yr) west of the fault.

Although neither approach to retrodeformation is rigorous, either initial position for Point Sal is compatible with the position of the San Simeon block as restored for 140–155 km of dextral slip (positions N and S, respectively) on the San Gregorio–Hosgri fault. The shorter distance allows for transfer of 15 km of San Gregorio–Hosgri slip to the Oceanic–West Huasna fault. The most recent estimate of only ~ 2 mm/yr for current crustal shortening across the Santa Maria basin (Lettis et al., 2004) is less than assumed here for constructing Figure 12B, but earlier phases of Neogene deformation may have been faster.

REGIONAL PROBLEMS

Our tectonic reconstruction of the Salinian block with San Gregorio–Hosgri slip taken into account leaves unresolved two regional problems of coastal California geology: the initial position of the Gualala block and pre-Neogene proto-San Andreas fault slip.

Gualala Block Problem

The initial position of the Gualala block adjacent to the San Francisco Peninsula on Figure 10 is based on the assumption that the Gualala block remained linked to the adjacent segment of the Salinian block at Bodega Head and the Point Reyes Peninsula throughout San Gregorio–Hosgri slip, but that assumption is not necessarily valid. The Gualala block lies just south of the Navarro structural discontinuity marking the northernmost extent of Salinian basement offshore (McCulloch, 1987, 1989a, 1989c). The discontinuity is expressed by changes in the geometry of Neogene structural features and the pattern of residual magnetic anomalies, both of which are thought to reflect a change in basement type underlying the continental shelf and slope (McCulloch, 1987, 1989a). Because the Gualala block lies west of the San Andreas fault and south of the Navarro structural discontinuity, it is commonly regarded as part of the Salinian block, but that conclusion may be incorrect. In following passages, we first examine implications of the restoration of the Gualala block depicted on Figure 10 and similar but not identical restorations by others. We then discuss a tectonic history for the Gualala block that does not require its restoration adjacent to the San Francisco Peninsula.

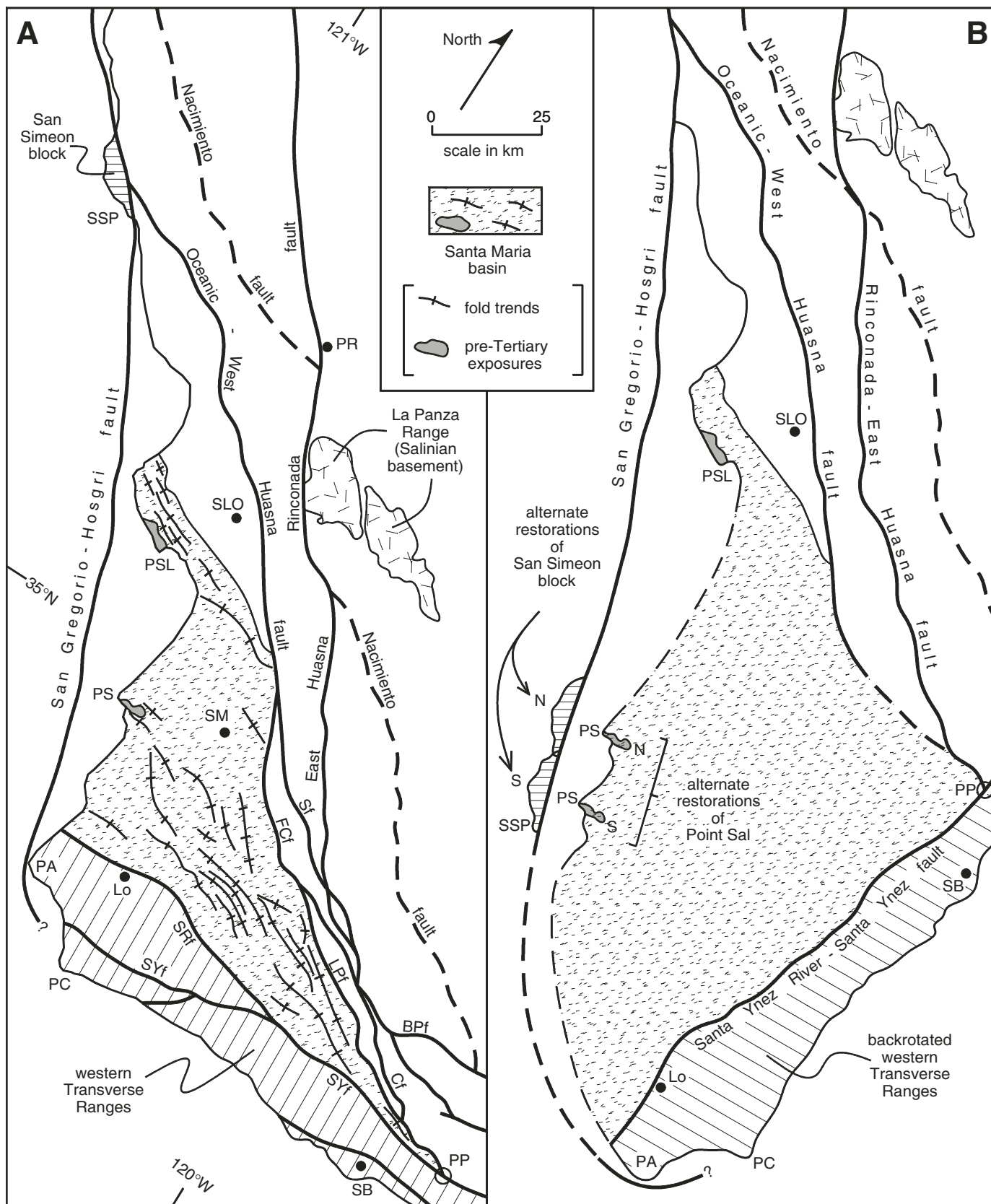


Figure 12. Tectonic reconstruction of southern end of San Gregorio-Hosgri fault in relation to western Transverse Ranges and Santa Maria basin: (A) present-day; (B) Middle Miocene time (ca. 15 Ma) before clockwise rotation of westernmost segment of Transverse Ranges ($\sim 85^\circ$ about pivot point PP after Dickinson, 1996). For B, dextral slip reversed on Rinconada-East Huasna fault (44 km), Oceanic-West Huasna fault (15 km), and San Gregorio-Hosgri fault (155 km and 140 km for alternatives S and N, respectively). Faults (heavy lines): BPf, Big Pine; Cf, Camuesa; FCf, Foxen Canyon; LPf, Little Pine; Sf, Suey; SRf, Santa Ynez River; SYf, Santa Ynez. Coastal features: PA, Point Arguello; PC, Point Conception; PS, Point Sal; PSL, Point San Luis; SSP, San Simeon Point. Cities: Lo, Lompoc; PR, Paso Robles; SB, Santa Barbara; SLO, San Luis Obispo; SM, Santa Maria (on A only).

Gualala Block Position

The tectonic reconstruction of Figure 10 achieves alignment of two prominent aeromagnetic anomalies projected parallel to the structural trend of the La Honda basin (Fig. 4) on the San Francisco Peninsula. The anomaly in the La Honda basin east of the San Gregorio–Hosgri fault is controlled by anomalously mafic basement rocks emplaced by tectonic segmentation and telescoping of the Salinian block (McLaughlin and Clark, 2004; Jachens and Griscom, 2004). The anomaly in the Gualala block west of the San Gregorio–Hosgri fault is associated with local exposures of mafic volcanic rock (spilite). Jachens et al. (1998) proposed a somewhat different initial position of the two anomalies, relative to one another, by postulating ~175 km of displacement on the San Gregorio–Hosgri fault north of Monterey Bay.

The alternate reconstruction (fig. 12 of Jachens et al., 1998) places the Black Point anomaly of the Gualala block against granitic rocks of Ben Lomond Mountain (Figs. 4 and 10). Placement of the two aeromagnetic anomalies in the alternate reconstruction stems from knowledge that the Ben Lomond granitic mass has been thrust over mafic basement rocks responsible for the nearby Butano Ridge (= Boulder Creek) anomaly (McLaughlin and Clark, 2004; Jachens and Griscom, 2004). The central core of the anomaly, however, lies within the La Honda basin north of Ben Lomond Mountain (figs. 6–7, 9–10 of Jachens et al., 1998; Jachens and Griscom, 2004). Even allowing for local thrusting of granitic basement over the flank of more mafic basement rocks responsible for the aeromagnetic anomaly, placing the centers of the Butano Ridge and Black Point anomalies along strike with the trend of the La Honda basin, as shown by Figure 10, seems more satisfactory than the alternate reconstruction of Jachens et al. (1998).

Moreover, augmented slip of 175 km on the northern San Gregorio–Hosgri fault, to displace the Gualala block more than the Point Reyes Peninsula, requires circuiting ~20 km of dextral slip (175 km–155 km = 20 km) into the Monterey Bay fault zone (Figs. 3A, 4, and 5) toward the Rinconada fault (Figs. 3 and 5). Although first-motion solutions for seismic activity within the Monterey Bay fault zone are strike slip in a dextral sense (Gardner-Taggart et al., 1993), the fault zone is a diffuse array of multiple subparallel fault strands (Greene, 1990; Greene et al., 2002), with no master fault trace transecting Monterey Bay. Perhaps the modern-day Monterey Bay fault zone overprints a buried projection of the Rinconada fault that could have represented such a master trace earlier in San Gregorio–Hosgri slip history. The Rinconada fault, however, projects along the northeastern edge of the Monterey Bay fault zone, whereas the current fault trace that is most continuous and most closely approaches a juncture with the San Gregorio–Hosgri fault is the Navy fault (Figs. 3 and 4) along the southwestern edge of the Monterey Bay fault zone. Circuiting Rinconada slip across Monterey Bay to the San Gregorio fault would require postulating a buried fault trace undetected by onshore or offshore mapping northeast of the Navy fault.

Gualala Stratal Relations

The most attractive stratigraphic correlation between the Gualala block and the La Honda basin is the similar lithology and Miocene age (ca. 24 Ma) of the Iversen Basalt in the Gualala block and the Mindego Volcanics of the La Honda basin (Loomis and Ingle, 1994, p. 927). Both volcanic units rest depositionally on thick Paleogene turbidite successions of broadly comparable sedimentology. Their correlation is not unique, however, for basalt of comparable age is known east of the San Gregorio–Hosgri fault from at least as far south as the wall of Soquel submarine canyon, a tributary to the Monterey submarine canyon in Monterey Bay (Stakes et al., 1999). At Soquel Canyon, however, Miocene basalt and associated sedimentary strata apparently rest directly on Salinian basement rocks, with no intervening Paleogene strata present.

Objections to any tectonic reconstruction placing the Gualala block along the western side of the San Francisco Peninsula are raised by significant contrasts in the stratigraphy and structure of pre-Miocene strata in the Gualala block and the onshore La Honda basin (Wentworth et al., 1998). The most notable stratigraphic discrepancy is the presence in the Gualala block of a thick succession (~3200 m) of Upper Cretaceous (Campanian to Maastrichtian) strata forming the bulk of the Gualala Formation, which extends into Paleocene strata (McDougall, 1998). No Cretaceous strata are known within the La Honda basin (Wentworth et al., 1998; Elder et al., 1998).

By analogy with stratal relations in the Santa Lucia Range, where Cretaceous strata are confined to the western flank of the Salinian block (Graham, 1976a), the absence of Cretaceous strata in the La Honda basin might reflect rapid eastward lapout of Cretaceous strata from exposures in the Gualala block. Within the depocenter of the La Honda basin, no wells have penetrated the basinal Cenozoic succession (>7500 m thick) to test the age of its base (fig. 2 of Gribi, 1990). The lowermost 1200–1500 m of the sedimentary succession along the basin axis could be pre-Eocene in age, although a maximum age of Paleocene is more likely than Cretaceous (McLaughlin and Clark, 2004). Along the southern flank of the La Honda basin, Paleogene strata rest unconformably on Salinian basement rocks, with no intervening Cretaceous strata present, within only 5 km of the San Gregorio–Hosgri fault trace (Brabb, 1989). Abrupt juxtaposition of this stratal succession against thick Cretaceous strata of the Gualala block is difficult to envisage.

Lithostratigraphic and chronostratigraphic contrasts between Paleogene successions of the Gualala block and the La Honda basin are also severe (Wentworth et al., 1998). In addition, detachment faults which place the Cretaceous succession of the Gualala block against structurally underlying spilite of an ophiolitic assemblage, and Paleogene strata against the Cretaceous succession, are reminiscent of structural relations in the California Coast Ranges east of the San Andreas fault where the Franciscan Complex is exposed. Deposition of the Gualala stratal succession on the Salinian block seems questionable (fig. 10 of Loomis and

Ingle, 1994). If the Gualala block is not part of the Salinian block, the apparently close correlation of aeromagnetic anomalies on our tectonic reconstruction (Fig. 10) juxtaposing the Gualala block with the La Honda basin of the Salinian block may be fortuitous and spurious. Neither an ophiolitic basement nor detachment faulting are known from the La Honda basin (Wentworth et al., 1998), although the substratum beneath the thickest sedimentary accumulation along the axis of the basin has never been penetrated by drilling.

Gualala Fault Sliver

A revealing outcrop of distinctive mafic conglomerate in the Anchor Bay Member of the Gualala Formation occurs within a fault sliver adjacent to the Pilarcitos fault on the San Francisco Peninsula (Fig. 4). The occurrence has been used as argument for 180 ± 5 km of net dextral strike slip across the San Gregorio–Hosgri fault at least as far south as the Monterey Peninsula (Burnham, 1998, 1999) by assuming displacement of the Gualala block northward from an initial position west of the San Francisco Peninsula. With the Gualala block so restored, depositional continuity between the offset conglomerate outcrop and the type Anchor Bay Member is difficult to postulate, however, because the granitic massif of Montara Mountain in the Salinian block would intervene between the two exposures (Fig. 10). No analogous or even correlative strata are present on the Salinian block either north of Montara Mountain near San Pedro Point or south of Montara Mountain within the La Honda basin. As Wentworth et al. (1998) noted, the outcrop of the Anchor Bay Member on the San Francisco Peninsula can be understood more readily as a fault sliver left behind during northward transit of the Gualala block along the Pilarcitos fault, an ancestral San Andreas strand, before the Salinian block had moved into position to the west.

Dextral offsets as great as 180 km across the San Gregorio–Hosgri fault are additionally disfavored by the modifications that would be required to the tectonic reconstruction of Figure 10 depicting only 155 km of net slip. The greater slip magnitude of 180 km would place the granodiorite of Inverness Ridge and the tonalite of Tomales Point (Fig. 10) athwart the northwest-southeast trend of the lithologically dissimilar porphyritic granodiorite of Monterey, and would introduce a local discrepancy of >0.0015 into the restored pattern of initial Sr isotopic ratios for Salinian granitic plutons.

Alternate Gualala Restoration

The similar initial positions of the Gualala block depicted by Figure 10, Jachens et al. (1998), and Burnham (1998, 1999) all place the granitic mass of Montara Mountain abruptly against spilitic basement of the Gualala block. This tectonic juxtaposition seems unlikely and stratal contrasts between the Gualala block and the La Honda basin further highlight the difficulty of postulating a close relationship between the Gualala block and

the San Francisco Peninsula. Fault kinematics permit tectonic reconstructions that do not require an initial position for the Gualala block west of the San Francisco Peninsula.

Acceptance of 156 km of net San Gregorio–Hosgri slip, to offset the Point Reyes Peninsula from the vicinity of the Monterey Peninsula (Fig. 10), requires transfer of San Gregorio–Hosgri slip to the San Andreas fault north of their juncture near Bolinas Lagoon (Figs. 1, 3A, and 4). Avoiding an initial position for the Gualala block west of the San Francisco Peninsula requires a fault to decouple the Gualala block from the adjacent offshore portion of the Salinian block during part of the time interval during which San Gregorio–Hosgri displacements occurred. With such a structural break along the western side of the Gualala block (Wentworth et al., 1998), restoration of the Gualala block by 156 km along the San Gregorio–Hosgri trend is not required.

Presumptive aeromagnetic evidence against a fault along the western flank of the Gualala block (Jachens et al., 1998) is not conclusive in the face of geologic mismatches between the Gualala block and the La Honda basin for tectonic restorations that do not allow for such a fault (Fig. 10). A compound fault trace has been mapped in the correct position offshore parallel to the coast of the Gualala block by McCulloch (1989c), and is here termed the Gualala fault (Fig. 13). The Gualala fault merges southward with the San Andreas fault near Bodega Head, but cannot be traced beyond the Navarro structural discontinuity to the north.


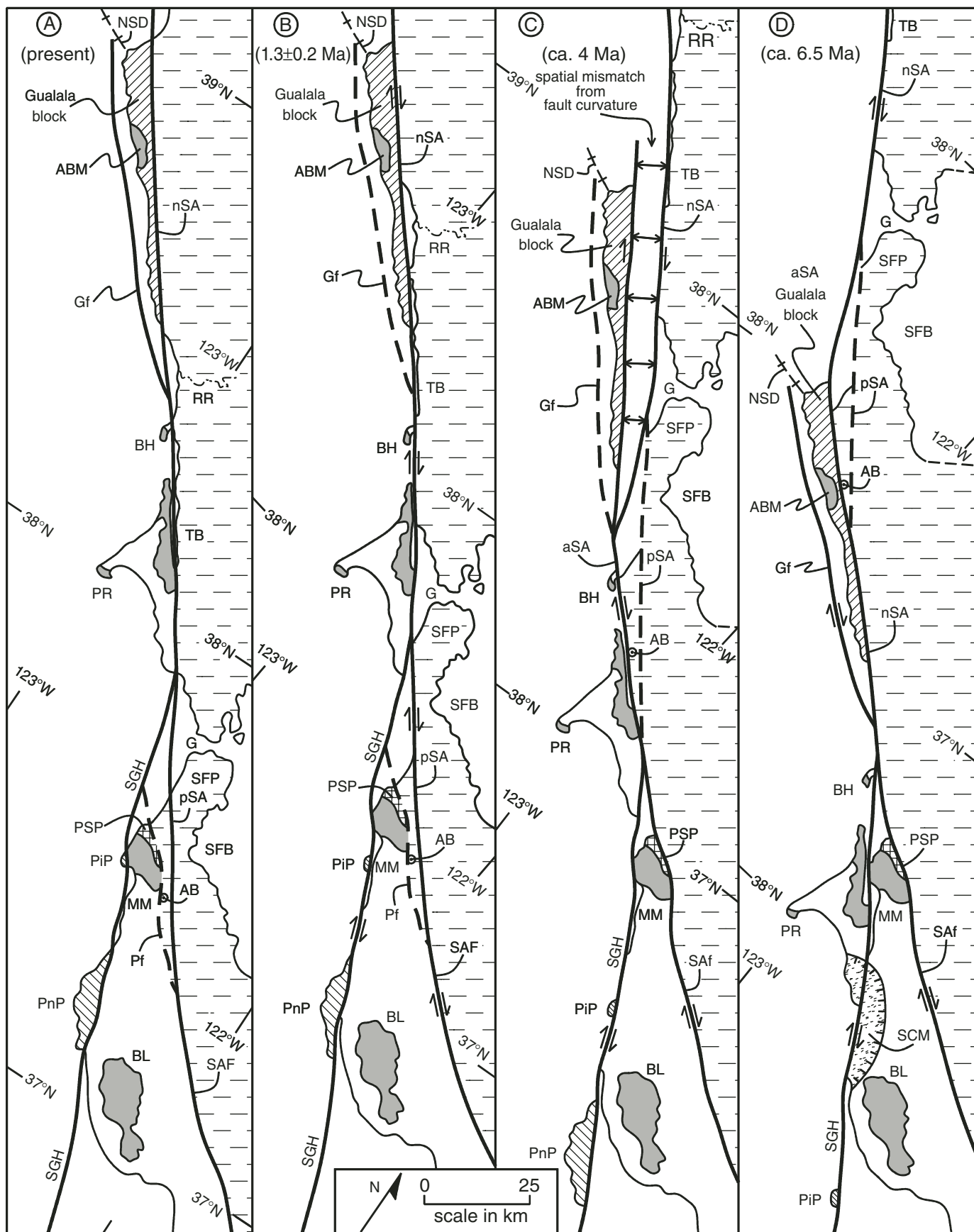


Figure 13. Sequential post-latest Miocene displacements on San Gregorio–Hosgri fault (SGH), San Andreas fault (SAf) south of SGH junction (including peninsular San Andreas fault, pSA, for A and B), northern San Andreas fault (nSA) north of SGH junction (including ancestral San Andreas fault, aSA = Pf, Pilarcitos fault, for C and D) illustrating the effect of decoupling the Gualala and Salinian blocks along the offshore Gualala fault (Gf) during early phases of San Gregorio–Hosgri dextral slip. (A) Present day. (B) Initiation of pSA slip (1.3 ± 0.2 Ma) (C) Alignment of Pilarcitos and Gualala fault traces (ca. 4 Ma) (D) Restoration of Santa Cruz Mudstone depositional system (ca. 6.5+ Ma). Position of Gualala fault adapted from McCulloch (1989c) after Graham and Dickinson (1978a, 1978b) and Figures 1 and 6 of Wentworth et al. (1998). Assumed dextral slip rates for A to B and B to C (estimated current rates): SGH, 6–9 (~7.5) mm/yr (Weber, 1990); SAf (= pSA for A to B), 17–24 (~20.5) mm/yr (Bruns et al., 2002); nSA (SGH + SAf), 28 ± 5 mm/yr (7.5 + 20.5) Assumed dextral slip rates for C to D (speculative): SGH, 15 mm/yr; SAf, 15 mm/yr; nSA (= aSA for B to D), 30 mm/yr (15 + 15). Geographic and geologic features (Salinian basement exposures shaded; dashed pattern denotes areas underlain by Franciscan substratum east of San Andreas and Pilarcitos faults): ABM, principal exposures of Anchor Bay Member of Gualala Formation (point AB, fault sliver of Anchor Bay Member east of Pilarcitos fault); BH, Bodega Head; BL, Ben Lomond Mountain; MM, Montara Mountain; NSD, Navarro structural discontinuity (northwest end of Salinian block); PiP, Pillar Point; PnP, Pigeon Point; PR, Point Reyes; PSP, Paleocene strata of San Pedro Point; RR, Russian River; SCM (on D only), Santa Cruz Mudstone after Clark et al. (1984); SFB, San Francisco Bay; SFP, San Francisco Peninsula; TB, Tomales Bay.



Pilarcitos Fault Relations

Appraising the tectonic significance of the Gualala fault calls attention to the Pilarcitos fault, a local strand of the San Andreas fault system on the San Francisco Peninsula (Figs. 1, 3A, and 4). The active master trace of the San Andreas fault on the San Francisco Peninsula has accommodated only 26 ± 4 km of net strike slip, as recorded by offsets of distinctive rock assemblages within the Franciscan Complex (Griscom and Jachens, 1989; Wakabayashi, 1999), Pleistocene nonmarine beds containing distinctive clast assemblages (Cummings, 1968), and a prominent linear aeromagnetic anomaly (Jachens and Zoback, 1999; Jachens et al., 2002). At current rates of San Andreas motion (17–24 mm/yr after Bruns et al., 2002), the total indicated San Andreas slip on the San Francisco Peninsula could have occurred entirely within the past 1.0–1.75 m.y., suggesting that earlier San Andreas strike slip occurred along the branching Pilarcitos fault, which marks the local contact between Salinian basement and Franciscan substratum (Figs. 3A and 4). Arguments for severely limited strike slip along the Pilarcitos fault (Wakabayashi, 1999) are unpersuasive, because the juxtaposition of Salinian basement and Franciscan substratum across the Pilarcitos fault could not have been achieved without a minimum aggregate strike slip of 200–225 km. Less displacement along the Pilarcitos (ancestral San Andreas) fault would not allow the initial position of the Navarro tectonic discontinuity at the northern end of the Salinian block to lie south of the juncture of the Pilarcitos fault with the San Andreas fault (Fig. 13A–B).

Graham and Dickinson (1978a, 1978b) suggested that the Gualala fault along the western flank of the Gualala block could be a segment of the Pilarcitos fault offset to the northwest by slip along the San Gregorio–Hosgri fault. That interpretation now seems unsatisfactory (Powell, 1993, p. 53) because the Pilarcitos fault was apparently the active strand of the San Andreas fault during a major fraction of net San Gregorio–Hosgri slip. The offshore juncture where the San Gregorio–Hosgri fault merges with the Pilarcitos fault is a pre-Quaternary analogue of the juncture where the San Gregorio–Hosgri and San Andreas faults now merge near Bolinas Lagoon (Powell, 1993, p. 53; Jachens et al., 2002). Tectonic overprinting by the offshore San Pedro reverse fault (Fig. 4) has obscured the position of the pre-Quaternary fault juncture, which probably lay along the San Gregorio–Hosgri fault trace in line with the offshore projection of the Pilarcitos fault (Fig. 4). The fault juncture lay near where the present Potato Patch fault branches from the main San Gregorio–Hosgri trace (fig. 4 of Bruns et al., 2002).

Although the Gualala fault cannot be an offset segment of the Pilarcitos fault offset across the San Gregorio–Hosgri fault, the Gualala fault could well be an inactive northern strand of the Pilarcitos (= ancestral San Andreas) fault. The ophiolitic basement of the Gualala block suggests close affinity with the Franciscan Complex rather than the Salinian block, and supports the presence of a tectonic dislocation between the Gualala block and Salinian basement lying both along tectonic strike to the

southeast and across tectonic strike to the southwest. Petrochemical evidence for probable derivation of detritus in Cretaceous and Paleogene strata of the Gualala block from the Salinian or Mojave blocks (Schott and Johnson, 1998a, 1998b, 2001; Schott, 2004; Schott et al., 2004) does not require deposition of those strata on the Salinian block itself.

Gualala Block Slip

Figure 13 illustrates a history of fault kinematics that allows for separation of the Gualala block from the Salinian block along the offshore Gualala fault during early phases of displacement along the San Gregorio–Hosgri fault. Reconstructing the pattern of fault movements through time is complicated because of the fact that the juncture of the San Gregorio–Hosgri fault slips progressively to the northwest along the San Andreas fault as displacements on the two faults proceed (Fig. 13A).

Reconstructions for early Pleistocene (Fig. 13B) and early Pliocene (Fig. 13C) time were derived by assuming that current slip rates on the San Gregorio–Hosgri and San Andreas faults have remained constant over the indicated time spans, with the Pilarcitos fault assumed to be the active pre-early Pleistocene strand of the San Andreas fault. Indicated motion rates are ~ 7.5 (6–9) mm/yr for the San Gregorio–Hosgri fault and ~ 20.5 mm/yr (17–24 mm/yr) for the San Andreas (or Pilarcitos) fault south of the San Gregorio–Hosgri juncture. The resultant slip rate of 28 ± 5 mm/yr on the San Andreas fault north of the San Gregorio–Hosgri juncture is compatible with average post-6 Ma Pacific–North America plate motion of ~ 50 mm/yr (table 1 of Dickinson and Wernicke, 1997; table 2 of Atwater and Stock, 1998a, 1998b) when combined with a post-6 Ma slip rate of ~ 12 mm/yr on the Hayward–Calaveras fault system east of San Francisco Bay (McLaughlin et al., 1996), and with a calculated vector of ~ 12 mm/yr imparted to the plate boundary by inland crustal extension within the Basin and Range province (table 1 of Dickinson and Wernicke, 1997). The implied net post-4 Ma slip of ~ 30 km along the San Gregorio–Hosgri fault is also compatible with an inferred post-3 Ma offset of Pliocene sedimentary facies by ~ 20 km on the San Francisco Peninsula (Clark, 1998).

The reconstruction for late Miocene time (Fig. 13D), which juxtaposes exposures of Santa Cruz Mudstone (Clark et al., 1984) across the San Gregorio–Hosgri fault, requires a hypothetical Miocene–Pliocene slip rate of ~ 15 mm/yr (pre-4 Ma, post-7 Ma) on the San Gregorio–Hosgri fault. The inference of an enhanced earlier slip rate agrees with indications that the San Gregorio–Hosgri slip rate has declined gradually over time, but is constrained only by the apparent offset of Santa Cruz Mudstone (ca. 7.0–8.4 Ma) in relation to the reconstruction for 4 Ma (Fig. 13C). For Figure 13D as well, a slip rate of ~ 15 mm/yr was assumed arbitrarily for the interval 7–4 Ma for the San Andreas (= Pilarcitos) fault south of the San Gregorio–Hosgri juncture in order to align outcrops of Anchor Bay Member of the Gualala Formation as exposed now on the Gualala block and east of the Pilarcitos fault. A combined 7–4 Ma slip rate of ~ 30 mm/yr was accordingly applied to the

northern San Andreas fault for reconstructing Figure 13D from Figure 13C. Because the actual time of separation of the two offset exposures of Anchor Bay Member is unknown, the late Miocene reconstruction (Fig. 13D) may be invalid in detail.

In any case, however, the tectonic reconstructions of Figure 13C–D show that the offshore Gualala fault, as a strand of the San Andreas transform system, could have offset the northern end of the Salinian block with respect to the Gualala block. The northern end of the Salinian block might have slipped past the Gualala block at any time during late Miocene time when some fraction of San Andreas transform displacement was partitioned westward from the master fault trace lying east of the Gualala block to the offshore Gualala strand of the San Andreas system lying west of the Gualala block (Fig. 13A–B). To avoid restoration of the Gualala block to an unattractive position west of the segment of the Salinian block exposed on the San Francisco Peninsula, essentially all net San Gregorio–Hosgri slip not incorporated into the restorations of Figure 13 must have continued northward as Gualala fault slip. The resultant minimum slip along the Gualala strand of the San Andreas system is ~70 km (155 km – 85 km), approximately the onshore length of the Gualala block.

As the initial position of the Gualala block along the continental margin remains uncertain (Wentworth et al., 1998), partitioning of slip through time between branches of the San Andreas transform lying east and west, respectively, of the Gualala block cannot be constrained. For example, if significant post-7 Ma slip occurred along the offshore Gualala fault, close juxtaposition of the Anchor Bay exposures (ABM and AB of Fig. 13D) may actually pertain to a much earlier time frame than shown.

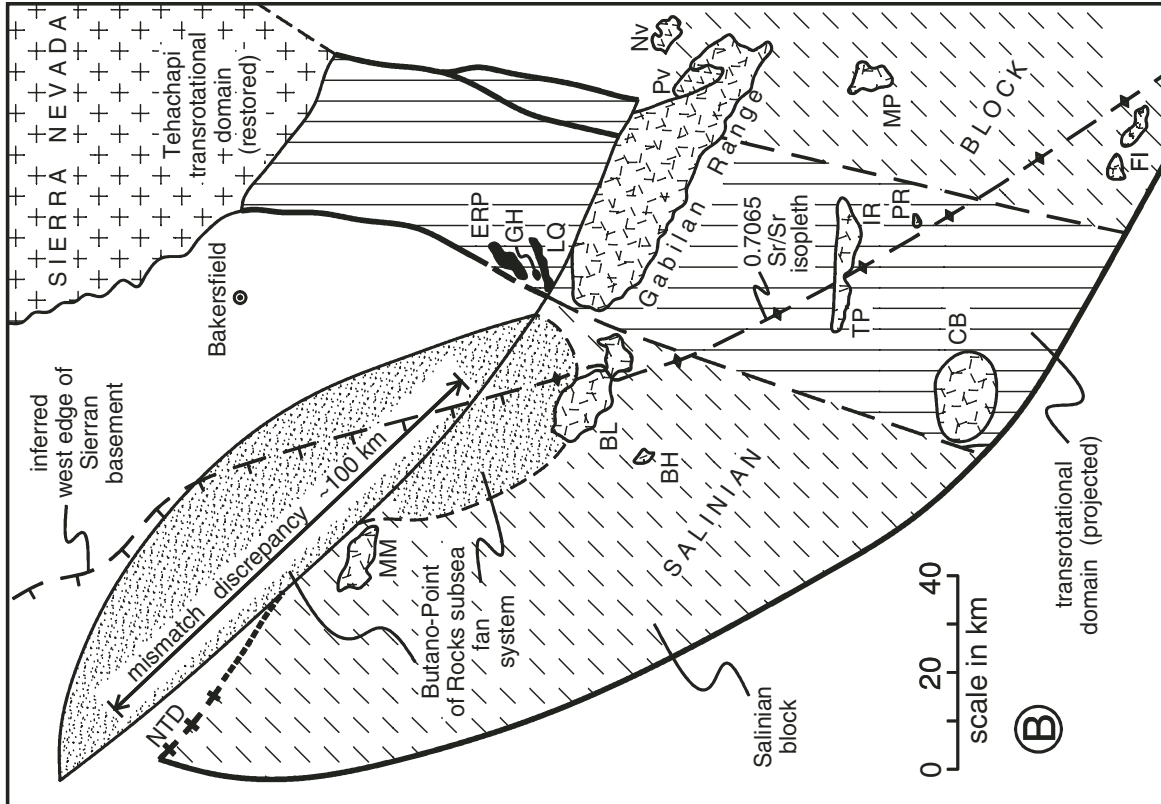
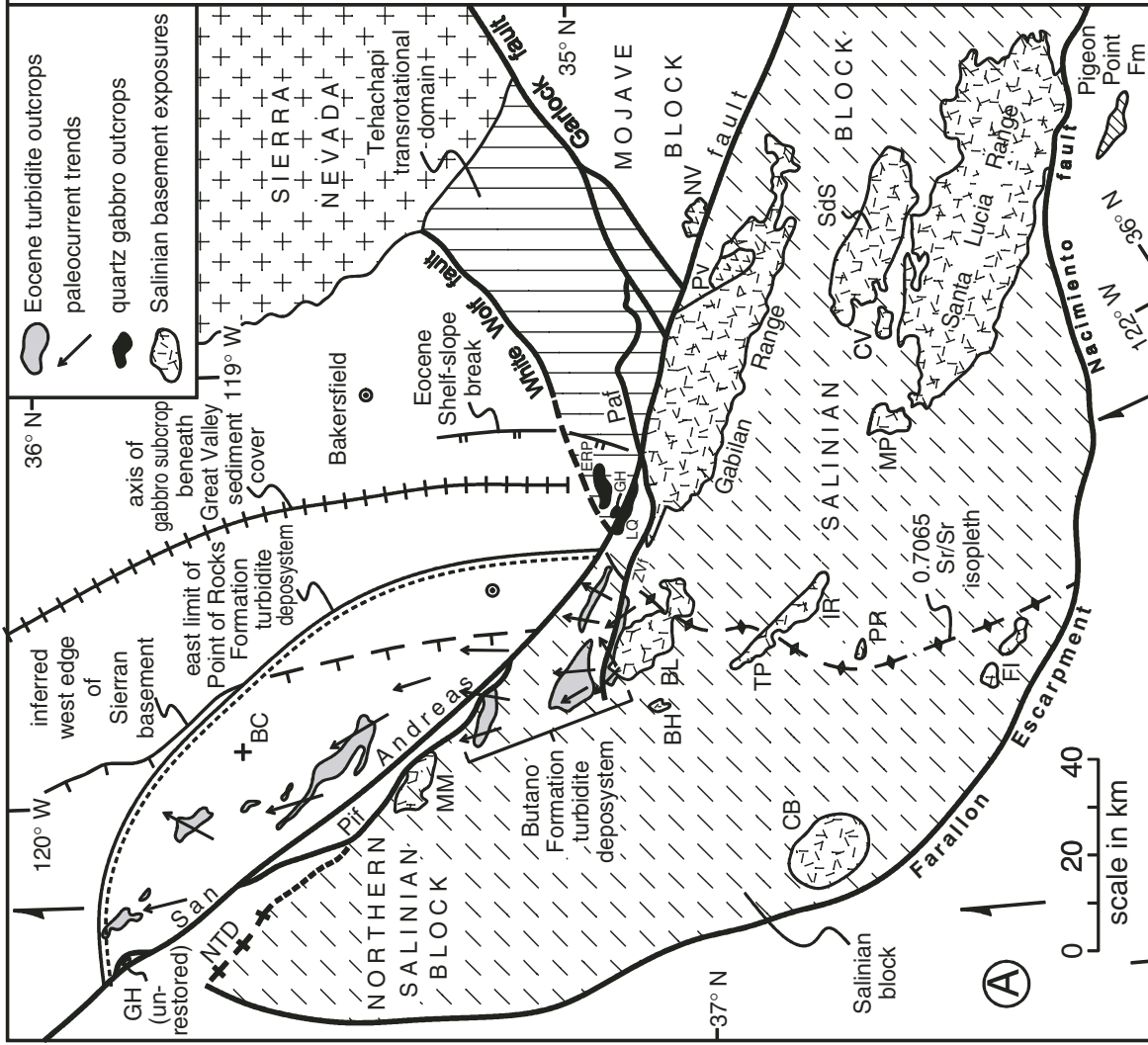
Paleocene strata resting unconformably (Morgan, 1981; Nilsen and Yount, 1981; Champion et al., 1984; Wakabayashi, 1999) on Salinian basement at San Pedro Point on the San Francisco Peninsula (Fig. 9) have been related provisionally to the partly correlative Paleogene strata of the much thicker German Rancho Formation in the Gualala block (Graham and Dickinson, 1978b, p. 17; Wentworth et al., 1998, p. 14). Paleocurrent indicators of northwesterly sediment transport at San Pedro Point (Chipping, 1972; Nilsen and Yount, 1981) are permissive of a depositional system linked northward with strata of the Gualala block, but this potential cross-fault tie seems unlikely for two reasons. First, sandstone petrofacies in the German Rancho Formation and the Paleocene strata of San Pedro Point are quite different, with almost no compositional overlap on published QFL and QKP diagrams (fig. 6 of Graham and Berry, 1979; fig. 4 of Morgan, 1981). Second, although reversal of linked dextral slip along the San Gregorio–Hosgri and northern San Andreas faults brings San Pedro Point and the Gualala block closer together (Fig. 13D vs. Fig. 13A), reversal of any preceding dextral slip along the Gualala fault would carry the two localities farther apart. There is as yet no fully satisfactory resolution of the initial position of the Gualala block along the California continental margin, but the sequential tectonic reconstructions of Figure 13 point the way toward a more satisfactory restoration of the Gualala block than the position adjacent to the San Francisco Peninsula shown by Figure 10.

Proto–San Andreas Question

To reconcile the total apparent post-Cretaceous offset of the northern end of the Salinian block from the southern extent of Sierran–Tehachapi granitic basement with the lesser displacement of Baja California with respect to mainland Mexico, Suppe (1970) proposed a two-stage history for the San Andreas fault system. By his hypothesis, Neogene San Andreas slip was preceded by Paleogene proto–San Andreas displacements, which formed a distended Paleogene continental borderland off central California (Nilsen and Clarke, 1975). Recognition that slip along the San Gregorio–Hosgri fault lengthened the Salinian block during Neogene San Andreas movement greatly reduces, but does not eliminate, the apparent slip discrepancy (Graham, 1978; Graham and Dickinson, 1978a, 1978b; Dickinson, 1983).

Figure 14 is a reappraisal of the proto–San Andreas question, with our analysis of San Gregorio–Hosgri slip as a constraint, and indicates that ~100 km of pre–San Andreas northwestward transport of the northern end of the Salinian block is still required to reconcile Eocene–Oligocene paleogeographic relationships. On Figure 14A, pre–San Andreas restoration of the Salinian block against the Tehachapi tail of the Sierra Nevada, and against the Mojave block, is guided by linkage of the Zayante–Vergeles and Pastoria fault trends across the course of the San Andreas fault (Ross, 1984; Dickinson, 1996). The resulting reconstruction juxtaposes the following offset pairs: (1) Paleogene depositional systems exposed immediately to the north of those two faults (Nilsen, 1984b; Graham et al., 1989), (2) the early Miocene Pinnacles and Neenach volcanic fields farther south (Matthews, 1976), (3) quartz gabbro bodies now dispersed on both sides of the San Andreas fault (fig. 4 of Dickinson, 1997) but aligned on the reconstruction with gabbro subcrop along the Great Valley gravity and magnetic anomaly, and (4) turbidite depositional systems of Eocene age now exposed as the Butano Sandstone of the Santa Cruz Mountains west of the San Andreas fault and the Point of Rocks Sandstone in the Temblor and Diablo Ranges east of the San Andreas fault (Clarke and Nilsen, 1973). The correlation of Butano and Point of Rocks turbidites has been challenged on the basis of contrasting clast assemblages in rare conglomerates within the two units (Seiders and Cox, 1992, p. 8, 15, 40), but the detrital modes of much more abundant sandstones in the two units are similar (Clarke, 1973; Nelson and Nilsen, 1974) and no alternate cross-fault correlation of either unit has been proposed to date.

Back-rotation of the Tehachapi structural panel (Fig. 14B), to recover the effects of early Miocene transrotational tectonism, shifts the relative positions of segments of the Salinian block with respect to the Sierra Nevada, but does not remedy the mismatch (by ~100 km) of the northern end of the Salinian block with the Tehachapi tail of the Sierra Nevada. Confirmation of the mismatch is provided by alignment (on the reconstruction of Fig. 14B) of the 0.7065 $^{87}\text{Sr}/^{86}\text{Sr}$ isopleth for plutons of the Salinian block with the western extremity of Sierran basement beneath the Great Valley. This alignment is unacceptable as the



initial (pre-Cenozoic) position of the Salinian block because the western part of the Sierra Nevada Batholith is known to display $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of <0.705 (Kistler and Ross, 1990), and comparably low ratios presumably pertain to buried Sierran basement extending westward beneath the Great Valley.

The nature and tectonic relations of the pre-Neogene rupture that displaced the Salinian block with respect to the Tehachapi tail of the Sierra Nevada remain uncertain. Nevertheless, the pre-San Andreas geologic relations depicted by Figure 14 document that a proto-San Andreas fault, or a combination of structures achieving the same net offset of the Salinian block, remains a necessary facet of California tectonic evolution.

INTRA-SALINIAN DEFORMATION

Dextral offsets of middle Miocene (ca. 15 Ma) depositional systems and basin margins document 44 ± 4 km of Neogene strike slip across the intra-Salinian Rinconada fault (Figs. 5 and 7) along the eastern flank of the Santa Lucia Range (Graham,

1978). Its buried continuation north of the Arroyo Seco beneath Quaternary deposits along the steep northeastern front of the Sierra de Salinas is commonly termed the Reliz fault (Fig. 5). The timing of Rinconada slip is not closely constrained, but evidence for only ~18 km offset of Upper Miocene to Lower Pliocene facies (fig. 2 of Durham, 1965) implies that fault movement continued over the same general time frame as slip along the San Gregorio–Hosgri fault.

To reconcile a valid estimate of 156 ± 8 km of strike slip on the San Gregorio–Hosgri fault north of Monterey Bay with an invalid estimate of only 110 ± 5 km of strike slip on the San Gregorio–Hosgri fault south of Monterey Bay, Dickinson (1996, p. 24) proposed that 46 ± 6 km of strike slip along the Rinconada fault was circuited around or through the northeastern Santa Lucia Range and across Monterey Bay, via the Monterey Bay fault zone (Fig. 2), to join the San Gregorio–Hosgri fault where it crosses the mouth of Monterey Bay (Powell and Weldon, 1992; Powell, p. 52). By that postulate, Rinconada and southern San Gregorio–Hosgri slip were treated as additive, summing to northern San Gregorio–Hosgri slip ($110 \text{ km} + 46 \text{ km} = 156 \text{ km}$). Powell (1993, p. 53) used the same kinematic logic, but with lesser inferred displacements ($105 \text{ km} + 45 \text{ km} = 150 \text{ km}$). From our analysis, however, addition of Rinconada slip to San Gregorio–Hosgri slip is unnecessary in the absence of any discrepancy between estimates for dextral slip along northern and southern segments of the San Gregorio–Hosgri fault at least as far south as its San Simeon segment (Fig. 3).

The buried continuation of the Reliz segment of the Rinconada fault beneath Quaternary cover underlying coastal lowlands near Salinas and the mouth of the Salinas River has long been uncertain (Figs. 3B and 5). Available gravity data can be interpreted to infer that the Reliz fault trends into Monterey Bay toward the northeastern edge of the Monterey Bay fault zone (Figs. 3B and 4). The most thoroughgoing strand (Navy fault) of the Monterey Bay fault zone lies, however, along the southwestern edge of the zone, and connects with the Tularcitos fault (Figs. 5 and 15) southwest of the Sierra de Salinas, rather than with the Reliz fault northeast of the Sierra de Salinas. We conclude that Rinconada displacement has been absorbed by deformation within the Salinian block without transfer of significant Rinconada slip to the offshore San Gregorio–Hosgri fault trend. The nature of the implied internal deformation within the Salinian block cannot be ascertained in the area east of Monterey Bay, because of unfaulted sediment cover over the Zayante–Vergeles fault trend (Fig. 4).

Tularcitos Saddle

Another potential avenue for circuiting Rinconada dextral slip to the San Gregorio–Hosgri fault is the Tularcitos saddle, the term used here to designate the structural depression spanning the Carmel River–Arroyo Seco drainage divide between the main Santa Lucia Range and its Sierra de Salinas spur (Fig. 15). Local facies discrepancies across various segments of the Tularcitos

Figure 14. Provisional reconstructions of Salinian block (NSD is Navarro structural discontinuity at its northern extremity) against Tehachapi Mountains (southern appendage of Sierra Nevada): (A) Middle Miocene (ca. 15 Ma) just prior to inception of San Andreas fault; (B) Oligocene–Miocene boundary (ca. 24 Ma) before dextral rotation of Tehachapi Mountains by $44^\circ \pm 4^\circ$ between 23–22 Ma and 18–16 Ma (Dickinson, 1996, p. 21). Salinian basement exposures: CB, Cordell Bank; CV, Carmel Valley; BH, Bodega Head; BL, Ben Lomond Mountain; FI, Farallon Islands; IR, Inverness Ridge; MM, Montara Mountain; MP, Monterey Peninsula; PR, Point Reyes; SdS, Sierra de Salinas; TP, Tomales Point. Early Miocene volcanic fields: Nv, Neenach Volcanics; Pv, Pinnacles Volcanics. Quartz gabbro bodies: ERP, Eagle Rest Peak; GH, Gold Hill; LQ, Logan Quarry. Faults: Paf, Pastoria; Pif, Pilarcitos (restored); ZVf, Zayante–Vergeles. Guides for restored position A of Salinian block before San Andreas and San Gregorio–Hosgri displacements: linkage of Zayante–Vergeles and Pastoria faults across San Andreas trend (fig. 14 of Ross, 1984; fig. 11 of Dickinson, 1996); internal configuration of Salinian block adapted from Figure 10; Salinian block flexed arbitrarily to fit around bend in San Andreas trend; axis of gabbro subcrop (general locus of Great Valley gravity and magnetic anomaly) after Cady (1975); west edge of Sierran basement inferred along east limbs of Kettleman Hills and Lost Hills anticlines (Dickinson, 2002), then projected southward (dashed line) parallel to axis of gabbro subcrop; paleocurrent trends for Butano Sandstone west of San Andreas fault from measured paleocurrent indicators (Nilsen and Simoni, 1973), but largely inferred for correlative Point of Rocks Sandstone east of San Andreas fault (Nilsen, 1984a, 1985; Graham et al., 1989); limit of Point of Rocks turbidite deposystem and location of correlative shelf-slope break after Graham et al. (1989). Guides for restored position B of Salinian block before rotation of Tehachapi Mountains and contiguous segment of Salinian block as a transrotational tectonic panel (Dickinson, 1996): crustal segments north and south of rotated Tehachapi structural panel (and its Salinian projection to the southwest) restored parallel to the San Andreas trend to maintain contact with the rotating crustal panel; widths of Great Valley and Salinian block shown less in B than in A because Tehachapi rotation induced crustal transtension to the north and south of the rotating crustal panel (Dickinson, 1996).

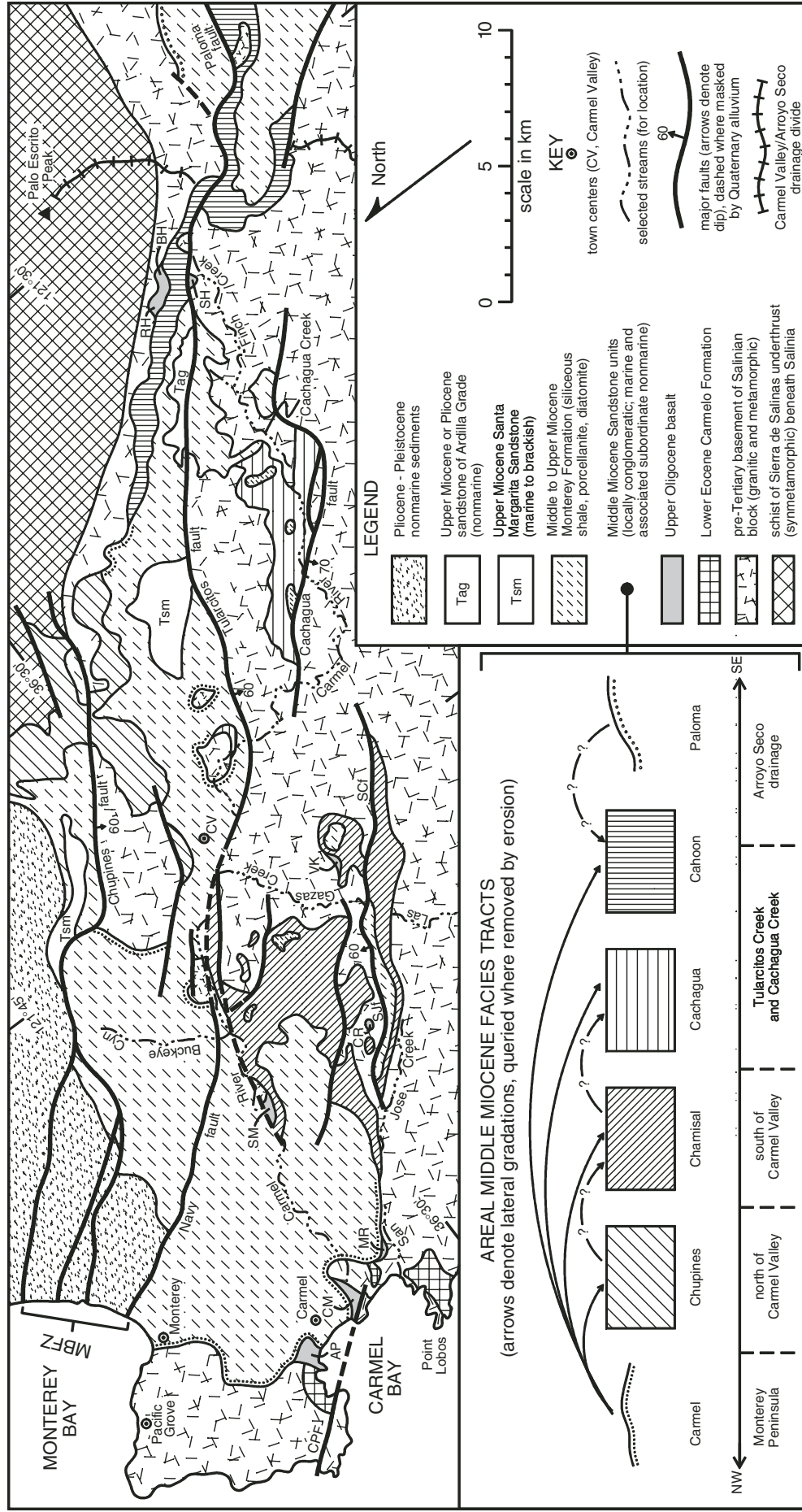


Figure 15. Structural and stratigraphic relations of pre-late Quaternary strata exposed from the Monterey Peninsula through the Tularcitos saddle (Carmel River-Arroyo Seco divide) between the main Santa Lucia Range and its Sierra de Salinas spur (see Fig. 3B for location) adapted after Brown (1962), Neel (1963), Wiedmann (1964), Bowen (1965), Hickman (1968), Graham (1976a), Clark et al. (1997, 2000), Dibblee (1999), Rosenberg (2001), and Wagner et al. (2003). See Table 2 for previous stratigraphic nomenclature of presently unnamed (Clark et al., 1997, 2000) Middle Miocene sandstone units (sub-Monterey) in various informally designated facies tracts (Carmel and Paloma facies depicted within base of Monterey Formation for reasons of scale). Oligocene basalt (to basaltic andesite) exposures dated as 27.0 ± 0.8 Ma at locality AP by Clark et al. (1984, 1997): AP, Arrowhead Point; BH, Buckeye Hill; CM, Carmel Mission; CR, Chamisal Ridge; MR, Monastery Ridge; RH, Red Hill; SH, School Hill; SM, Saddle Mountain; VK, Vasquez Knob. Faults: CPf, Cypress Point; MBFZ, Monterey Bay fault zone; SJF-SCf, San Jose-San Clemente. Symbol for Carmel River-Arroyo Seco drainage divide shown as discontinuous through Tularcitos Saddle to avoid overprinting lithologic symbols

fault trending through the saddle suggest strike slip (Graham, 1976a, 1978). The Tularcitos fault was once thought to continue westward down Carmel Valley to the mouth of the Carmel River (Bowen, 1965), but is now known to link with the Navy fault of the Monterey Bay fault zone (Fig. 15).

The facies contrasts across the Tularcitos fault are displayed by heterogeneous but sandstone-dominated Middle Miocene marine and locally nonmarine strata gradationally underlying the Middle to Upper Miocene Monterey Formation of fine-grained siliceous strata (Fig. 15, Table 2). Facies differences pertain primarily to thickness, and secondarily to texture, but detrital modes are comparable for all the facies tracts (Hall et al., 1995), and no consistent petrofacies contrasts are discernible. The diverse sandstone units were deposited within multiple depocenters of uncertain origin defining a complex Middle Miocene paleogeography for the Salinian block (Wiedmann, 1964; Graham, 1976a, 1978). Miocene onlap of basement sills and highs by the Monterey Formation eventually covered all the depocenters to link Late Miocene depositional systems through the Tularcitos saddle (Fig. 15). Among the informal Middle Miocene facies tracts of Figure 15 and Table 2, thin Carmel and Paloma facies tracts at opposite ends of the Tularcitos saddle are comparable in lithology (Graham, 1976a, p. 92), and no mappable sub-Monterey sandstone units are present beneath

the Monterey onlap within a restricted area between Cachagua and Cahoon facies tracts (Fig. 15).

The local Miocene facies contrasts are not confined to the trace of the Tularcitos fault (Fig. 15), and two observations argue against throughgoing strike slip along the fault to link Rinconada and San Gregorio–Hosgri displacements. First, the Paloma fault at the southeastern end of the Tularcitos trend splays into multiple strands within the Arroyo Seco synclorium (Graham, 1976a, p. 151), and no discrete fault surface can be mapped as far as the Rinconada fault (Fig. 5). Second, the southeastern outliers of an Oligocene volcanic field (localities RH, BH, SH of Fig. 15), more prominent to the northwest, appear to lie athwart the trend of the Tularcitos fault (Dickinson, 1972; Dibblee, 1999) and represent a distal segment of the volcanic province apparently disrupted mainly by dip slip across the fault.

Modest strike slip can be inferred for segments of the Tularcitos fault, its splays, and nearby subparallel faults from internal transpressive deformation of the Salinian block. Structural shortening across folded Tertiary strata of the Arroyo Seco synclorium (Fig. 5) implies transfer of as much as 5 km of dextral slip to the trend of the Tularcitos fault (Graham, 1976a, p. 148–150). If concentrated near the linkage of the Navy fault with the Tularcitos fault, in an area where the fault trace is locally masked by alluvium along the Carmel River (Fig. 15), dextral slip of ~5 km

TABLE 2. THICKNESS AND DOMINANT LITHOLOGY OF MIDDLE MIOCENE SANDSTONE FACIES, MONTEREY PENINSULA TO TULARCITOS SADDLE, SANTA LUCIA RANGE

| Facies tract | Thickness (m) | Lithology | Stratigraphic nomenclature |
|--------------|---------------|---|---|
| Carmel | <100 | buff to yellowish sandstone and siltstone | Laureles Sandstone (TI) of Neel (1963) and Weidmann (1964); Los Laureles Sandstone Member (Tml) of Monterey Formation (Bowen, 1965); upper marine sandstone (Tus/Tts) of Dibblee (1999) |
| Chupines | ~200 | gray to buff sandstone (with basal conglomerate) | Laureles Sandstone (TI) of Neel (1963); marine sandstone (Tts) of Dibblee (1999) |
| Chamisal | (c) <50 m | massive yellowish sandstone (phosphatic) | Laureles Sandstone Member (Tml) of Monterey Formation (Brown, 1962); Los Laureles Sandstone Member (Tml) of Monterey Formation (Bowen, 1965); upper marine sandstone (Tus) of Dibblee (1999) |
| | (b) 150–175 | gray to brown sandstone (locally pebbly) | Intermediate and upper marine members of Chamisal Formation (Tc) of Brown (1962); Los Tularcitos Member (Tct) of Chamisal Formation (Bowen, 1965); lower marine sandstone (Tls/Tts) of Dibblee (1999) |
| | (a) 75–150 | red to green and gray sandstone and conglomerate | Robinson Canyon Member of Chamisal Formation (Tcrb of Brown, 1962; Tcr of Bowen, 1965); redbeds of Robinson Canyon (Dibblee, 1999) |
| Cachagua | 125–200 | gray or white to green or buff coarse sandstone | Cachagua Member (Tcc) of Chamisal Formation (Neel, 1963; Weidmann, 1964); marine sandstone (Tts) of Dibblee (1999); includes nonmarine debris-flow and braided-stream deposits (Graham, 1976a, p. 86) |
| Cahoon | 125–225 | white to gray sandstone (with basal conglomerate) | Vaqueros Formation (Tvq) of Weidmann (1964) including basal continental unit (Tc); Los Tularcitos Member (Tct) of Chamisal Formation (Hickman, 1968); marine sandstone (Tts) of Dibblee (1999) |
| Paloma | <50 | buff to gray fine sandstone | Vaqueros Formation (Tvq) of Hickman (1968); “Tierra Redonda Formation” of Graham (1976a, p. 81) |

Note: Past nomenclature (formal and informal) tabulated for presently unnamed (Clark et al., 1997, 2000) sandstone-dominated Middle Miocene stratigraphic units gradationally underlying finer grained siliceous strata of Monterey Formation within multiple informally designated facies tracts (Fig. 13).

would remove much of the disjuncture between contrasting Carmel and Chamisal facies tracts (Table 2), and would place similar Chupines and Chamisal facies tracts (Table 2) into close juxtaposition (Fig. 15). In general, however, restoration of dextral displacement of <5 km along the trend of the Tularcitos fault would not reconcile contrasts among the various local facies tracts (Graham, 1976a; Fig. 15), which largely reflect initial depositional variability.

Santa Lucia Transpression

Tectonic treatment of the Santa Lucia Range as a rigid block between the Rinconada and San Gregorio–Hosgri faults is unsatisfactory because intense Pliocene–Pleistocene deformation of the range interior involved shortening by basement-cored or Franciscan-cored folds and associated reverse faults (Compton, 1966; Namson and Davis, 1990). The trends of folds and faults within the Santa Lucia Range lie oblique to the trend of the Rinconada fault (Figs. 5 and 7) in an orientation allowing transpressive transfer of a component of strike slip to the Rinconada fault from shortening of the Santa Lucia Range between the San Gregorio–Hosgri and Rinconada faults. The geometry of deformation suggests, however, that transpressive strike slip is inadequate to explain more than a minor fraction of known Rinconada slip.

Net Neogene crustal shortening across the northern Santa Lucia Range underlain by Salinian basement rocks has been <15%, from combined folding and faulting (e.g., Compton, 1966), across a belt ~40 km in width perpendicular to the fold-fault trend (Fig. 5). Greater shortening in the southern Santa Lucia Range underlain by Franciscan substratum has approached ~33% (fig. 7 of Namson and Davis, 1990) across a belt of comparable width (Fig. 7). Applying the estimated percentages of shortening to the full width (~80 km) of the fold-fault field measured normal to fold axes and fault trends within the range, shortening has not exceeded 25–30 km across structures oriented ~20° to the strike of the Rinconada fault. The resultant component of transpressive strike slip oriented parallel to the Rinconada fault is only ~9 km, a minor fraction of the inferred net strike slip of 44 ± 4 km. Oblique slip on faults within the Santa Lucia Range may have contributed to its internal deformation, but could not have imparted a component of strike slip to the external Rinconada fault.

For the Late Miocene reconstruction of Figure 10, we reduced inferred Rinconada slip northward by 9 km from 44 km near Paso Robles to 35 km near Monterey Bay to allow for transpression within the Santa Lucia Range. The present positions of various outcrops and subcrops of the schist of Sierra de Salinas (Fig. 10) are compatible with the offsets inferred (Ross, 1984), but not with much more or much less.

Distributive Strike Slip

Internal strain reflected by distributive strike slip may have deformed the Santa Lucia Range internally without kinematic linkage to either the San Gregorio–Hosgri or Rinconada faults.

For example, the Monterey Bay fault zone of multiple parallel and en echelon faults may reflect a style of internal dislocation of the Salinian block more widespread than onshore mapping has yet revealed. Minor faults are more readily detected by offshore seismic reflection profiling of largely flat-lying marine sediment layers than from onshore mapping of soil-covered outcrops. Onshore extensions of various strands of the Monterey Bay fault zone east of Monterey (Fig. 15) can be traced only by consulting water well logs to detect subtle offsets of subsurface strata (Greene, 1990; Clark et al., 1997). Where comparable subsurface data are unavailable in the less populated and topographically more rugged parts of the Santa Lucia Range, faults of similar magnitude may well have gone undetected during areal mapping.

Possible strike-slip components along major reverse faults of the Santa Lucia Range are also difficult to estimate, but the faults either die out along strike within Salinian basement or terminate against transverse structures (Fig. 5). In either case, significant throughgoing strike slip is precluded, and none of the reverse faults juxtapose contrasting Cretaceous or Tertiary sedimentary facies. Where minor strike slip has occurred, as along the Navy–Tularcitos and Palo Colorado faults (see previous discussions), we infer that the resulting strain has been absorbed within the Salinian block without significant transfer of strike slip to either the San Gregorio–Hosgri or Rinconada faults.

GENERAL CONCLUSIONS

Analysis of regional geologic mapping indicates that dextral Neogene slip of 156 ± 4 km was continuous southward along the San Gregorio–Hosgri fault near the California coast from its juncture with the San Andreas fault on the north to the Santa Maria basin on the south. Previous estimates of lesser or greater displacement are not supported by geologic relations. On-land coastal segments of the San Gregorio–Hosgri fault zone include the Seal Cove fault and the type San Gregorio fault of the San Francisco Peninsula, the Sur fault zone of the northern Santa Lucia Range, and the San Simeon fault zone of the southern Santa Lucia Range. Net slip is recorded by offset of the Nacimiento fault delineating the western flank of the Salinian block, and by offset of geologic features both within the Salinian block northeast of the Nacimiento fault and within the belt of Franciscan Complex southwest of the Nacimiento fault. No significant San Gregorio–Hosgri slip was diverted inland to the Rinconada fault or other structures of the central Coast Ranges, with the exception of ~15 km along the Oceanic–West Huasna fault along the coastal flank of the southern Santa Lucia Range. Transpressional strain within the Santa Lucia Range accompanied San Gregorio–Hosgri and Rinconada fault movements, but, apart from minor strike slip transmitted to the Rinconada fault, was absorbed by internal deformation of the block between the two fault traces.

San Gregorio–Hosgri slip extended northward along the San Andreas fault system from their common juncture, and was additive to the well-established net slip of ~315 km on the central San Andreas fault. The northern San Andreas system includes the

offshore Gualala fault west of the Gualala block as well as the master trace of the present San Andreas fault east of the Gualala block. On the south, dextral San Gregorio–Hosgri slip is transposed into crustal shortening within the rotating western Transverse Ranges and kinematically linked deformation within the Santa Maria basin north of the western Transverse Ranges. From a regional perspective, the San Gregorio–Hosgri fault provides the principal structural linkage between transrotational tectonism (to the south) and simple strike slip (to the north) within the San Andreas transform system of central California. Recovery of both San Andreas and San Gregorio–Hosgri Neogene displacements still leaves a mismatch of ~100 km between the northern end of the Salinian block and the Tehachapi tail of the Sierra Nevada block as the record of enigmatic proto–San Andreas deformation of the continental margin.

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