

Salinia revisited: a crystalline nappe sequence lying above the Nacimiento fault and dispersed along the San Andreas fault system, central California

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Salinia, as originally defined, is a fault-bounded terrane in westcentral California. As defined, Salinia lies between the Nacimiento fault on the west, and the Northern San Andreas fault (NSAF) and the main trace of the dextral SAF system on the east. This allochthonous terrane was translated from the southern part of the Sierra Nevada batholith and adjacent western Mojave Desert region by Neogene-Quaternary displacement along the SAF system. The Salina crystalline basement formed a westward promontory in the SW Cordilleran Cretaceous batholithic belt, relative to the Sierra Nevada batholith to the north and the Peninsular Ranges batholith to the south, making Salinia batholithic rocks susceptible to capture by the Pacific plate when the San Andreas transform system developed. Proper restoration of offsets on all branches of the San Andreas system is a critical factor in understanding the Salinia problem. When cumulative dextral slip of 171 km (106 mi) along the Hosgri–San Simeon–San Gregorio–Pilarcitos fault zone (S–N), or dextral slip of 200 km (124 mi) along the Hosgri–San Simeon–San Gregorio–Pilarcitos–northern San Andreas fault system, is added to the cumulative dextral slip of 315–322 km (196–200 mi) along the main trace of the SAF north of the San Emigdio–Tehachapi mountains, central California, there is a minimum amount of cumulative dextral slip of 486 km (302 mi) or a maximum amount of cumulative dextral slip of 522 km (324 mi) along the entire SAF system north of the Tehachapi Mountains. When these sums are compared with the offset distance (610–675 km or 379–420 mi) between the batholithic rocks associated with the Navarro structural discontinuity (NSD) in northern California, and those in the ‘tail’ of the southern Sierra Nevada granitic rocks in the San Emigdio–Tehachapi mountains, central California, a minimum deficit of from ~100 km (~62 mi) to a maximum deficit of ~189 km (~118 mi) is needed to restore the crystalline rocks associated with the NSD with the crystalline terranes within the San Emigdio and Tehachapi mountains – the enigma of Salinia. Two principal geologic models compete to explain the enigma (i.e. the discrepancy between measured dextral slip along traces of the SAF system and the amount of separation between the Sierra Nevada batholithic rocks near Point Arena in northern California and the Mesozoic and older crystalline rocks in the San Emigdio and Tehachapi mountains in southern California). (i) One model proposes pre-Neogene (>23 Ma), Late Cretaceous or Maastrichtian (<ca. 71 Ma) to early Palaeocene or Danian (ca. 66 Ma) sinistral slip of 500–600 km (311–373 mi) along the Nacimiento fault and of the western flank of Salinia from the eastern flank of the Peninsular Ranges (sinistral slip but in the opposite sense to later Neogene (<23 Ma) dextral slip along and within the SAF system. (ii) A second model proposes that the crystalline rocks of Salinia comprise a series of 100 km- (60 mi-) scale allochthonous (extensional) nappes that rode southwestward above the Rand schist–Sierra de Salinas (SdS) shear zone subduction extrusion channels. The allochthonous nappes are from NW–SE: (i) Farallon Islands–Santa Cruz Mountains–Montara Mountain, and adjacent batholithic fragments that appear to have been derived from the top of the deep-level Sierra Nevada batholith of the western San Emigdio–Tehachapi mountains; (ii) the Logan Quarry–Loma Prieta Peak fragments that appear to have been derived from the top of a buried detachment fault that forms the basement surface beneath the Maricopa sub-basin of the southernmost Great Valley; (iii) The Pastoria plate–Gabilan Range massif that appears to have been derived from the top of the deep-level SE Sierra Nevada batholith; and (iv) the Santa Lucia–SdS massif, which appears to be lower batholithic crust and underlying extruded schist that were breached westwards from the central to western Mojave Desert region. In this model, lower crustal batholithic blocks underwent ductile stretching above the extrusion channel schists, while mid- to upper-crustal level rocks rode southwestwards and westwards along trenchward dipping detachment faults. Salinian basement rocks of the Santa Lucia Range and the Big Sur area record the most complete geologic history of the displaced terrane. The oldest rocks consist of screens of Palaeozoic marine metasedimentary rocks (the Sur Series), including biotite gneiss and schist, quartzite, granulite gneiss, granofels, and marble. The Sur Series was intruded during Cretaceous high-flux batholithic magmatism by granodiorite, diorite, quartz diorite, and at deepest levels, charnockitic tonalite. Local nonconformable remnants of Campanian–Maastrichtian marine strata lie on the deep-level Salinia basement, and record deposition in an extensional setting. These Cretaceous strata are

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The word ‘nappe’ in the article title refers generically to detachment and transport along either major thrust or low-angle normal fault systems.

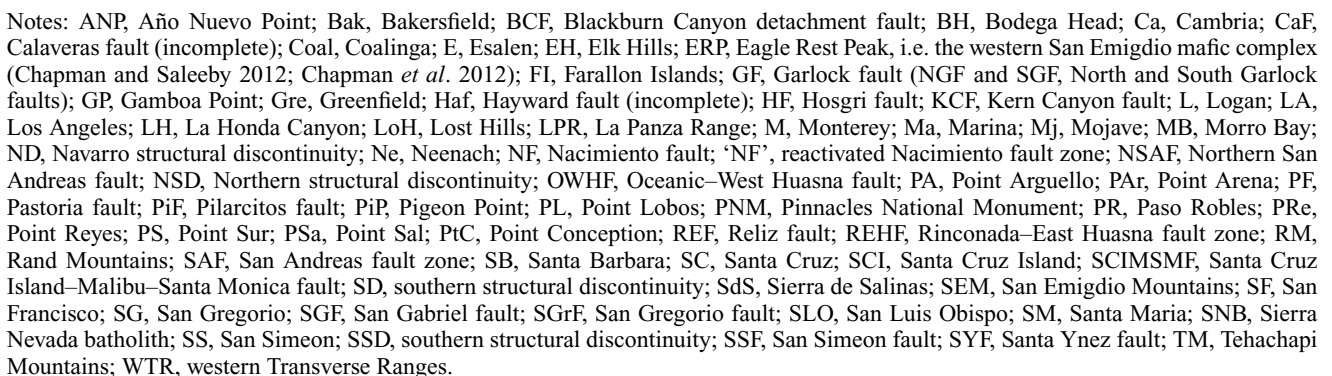
correlated with the middle to upper Campanian Pigeon Point (PiP) Formation south of San Francisco. The Upper Cretaceous strata, belonging to the Great Valley Sequence, include clasts of the basement rocks and felsic volcanic clasts that in Late Cretaceous time were brought to a coastal region by streams and rivers from Mesozoic felsic volcanic rocks in the Mojave Desert. The Rand and SdS schists of southern California were underplated beneath the southern Sierra Nevada batholith and the adjacent Salinia-Mojave region along a shallow segment of the subducting Farallon plate during Late Cretaceous time. The subduction trajectory of these schists concluded with an abrupt extrusion phase. During extrusion, the schists were transported to the SW from deep- to shallow-crustal levels as the low-angle subduction megathrust surface was transformed into a mylonitic low-angle normal fault system (i.e. Rand fault and Salinas shear zone). The upper batholithic plate(s) was(ere) partially coupled to the extrusion flow pattern, which resulted in 100 km-scale westward displacements of the upper plate(s). Structural stacking, temporal and metamorphic facies relations suggest that the Nacimiento (subduction megathrust) fault formed beneath the Rand-SdS extrusion channel. Metamorphic and structural relations in lower plate Franciscan rocks beneath the Nacimiento fault suggest a terminal phase of extrusion as well, during which the overlying Salinia underwent extension and subsidence to marine conditions. Westward extrusion of the subduction-underplated rocks and their upper batholithic plates rendered these Salinia rocks susceptible to subsequent capture by the SAF system. Evidence supporting the conclusion that the Nacimiento fault is principally a megathrust includes: (i) shear planes of the Nacimiento fault zone in the westcentral Coast Ranges locally dip NE at low angles. (ii) Klippen and/or faulted klippen are locally present along the trace of the Nacimiento fault zone from the Big Creek–Vicente Creek region south of Point Sur near Monterey, to east of San Simeon near San Luis Obispo in central California. Allochthonous detachment sheets and windows into their underplated schists comprise a composite Salinia terrane. The nappe complex forming the allochthon of Salinia was translated westward and northwestward ~100 km (~62 mi) above the Nacimiento megathrust or Franciscan subduction megathrust from SE California between ca. 66 and ca. 61 Ma (i.e. latest Cretaceous–earliest Palaeocene time). Much, or all, of the westward breaching of the Salinia batholithic rocks likely occurred above the extrusion channels of the Rand-SdS schists; following this event, the Franciscan Sur-Obispo terrane was thrust beneath the schists, perhaps during the final stages of extrusion in the upper channel. Later, the Sur-Obispo terrane was partially extruded from beneath the Salinia nappe terrane, during which time the upper plate(s) underwent extension and subsidence to marine conditions. Attenuation of the Salinia nappe sequence during the extrusion of the Franciscan Complex thinned the upper crust, making the upper plates susceptible to erosion from the top of the Franciscan Complex near San Simeon, where it is now exposed. In the San Emigdio Mountains, the relatively thin structural thickness of the upper batholithic plates made them susceptible to late Cenozoic flexural folding and disruption by high-angle dip-slip faults. The ~100 km (~62 mi) of westward and northwestward breaching of the Salinia batholithic rocks above the Rand-SdS channels, and the underlying Nacimiento fault followed by ~510 km (~320 mi) of dextral slip from ~23 Ma to Holocene time along the SAF system, allow for the palinspastic restoration of Salinia with the crystalline rocks of the San Emigdio–Tehachapi mountains and the Mojave terrane, resolving the enigma of Salinia.

Keywords: great valley sequence; Hosgri fault; Nacimiento fault; Pastoria fault; Pilarcitos fault; Salinia; San Gregorio fault; San Simeon fault; Sur Series

Introduction

Salinia, first defined by Reed and Hollister (1936), as a region and a structural and regional unit, is present largely in the Coast Ranges of central California, north of the Big Pine fault and western Transverse Ranges (WTRs), west of the San Andreas fault (SAF), east of the Nacimiento fault, and west-northwest of the San Emigdio (SEM) and Tehachapi mountains (TM) (Figure 1) (Reed and Hollister 1936; Hill and Dibblee 1953). The Salinian terrane consists of Palaeozoic and Mesozoic rocks that have been intruded by Mesozoic plutons that have compositions, isotopic signatures, and ages similar to plutons present in the southern Sierra Nevada (Kidder *et al.* 2003; Chapman *et al.* 2010, 2011, 2012; Saleeby *et al.* 2010; Chapman and Saleeby 2012). Upper Cretaceous and Cenozoic rocks rest nonconformably on the crystalline basement of Salinia. The Monterey terrane of Ducea *et al.* (2009, figure 2) is in part equivalent to Salinia. Granitoid rocks (see Ducea *et al.* 2009, p. 6 for detailed descriptions), similar in composition and ages (ca. 100–75 Ma or ca. 110–79 Ma) to plutons in the southern part of the Sierra Nevada and regions to the east, characterize the Salinia or Salinian terrane within the Monterey terrane (Ducea

et al. 2009). The Nacimiento terrane, also referred to as the Nacimiento block or Sur–Obispo terrane (Gilbert 1973; Ducea *et al.* 2009), lies in fault contact on the west flank of Salinia. West of the Nacimiento fault, the Franciscan Complex and sedimentary sequences within the Nacimiento terrane are equivalent to the distal, seaward, or sheets of Cretaceous sedimentary rocks that lie structurally beneath the Nacimiento fault (Kidder *et al.* 2003; Ducea *et al.* 2009). The depositional age of the Franciscan Complex in the Nacimiento terrane (Santa Lucia Mountains) is younger than ca. 79 Ma based on zircon dating (Alvarado *et al.* 2003). The metamorphic age or ages of the Franciscan mélange west of the Nacimiento fault is 88–70 Ma (Suppe 1972) or as young as 70 ± 5 Ma (Suppe and Armstrong 1975). Wakabayashi (1999) suggested that initial underplating of the Franciscan Complex was from 160 to 70 Ma and that subduction accretion of the Franciscan Complex was from 150 to 65 Ma. The Nacimiento terrane (which includes the Jurassic–Cretaceous Franciscan Complex) is in tectonic contact with and structurally overlain by Salinia (alternative interpretations are discussed below). The Sur Series within Salinia consists of granitoid plutons emplaced



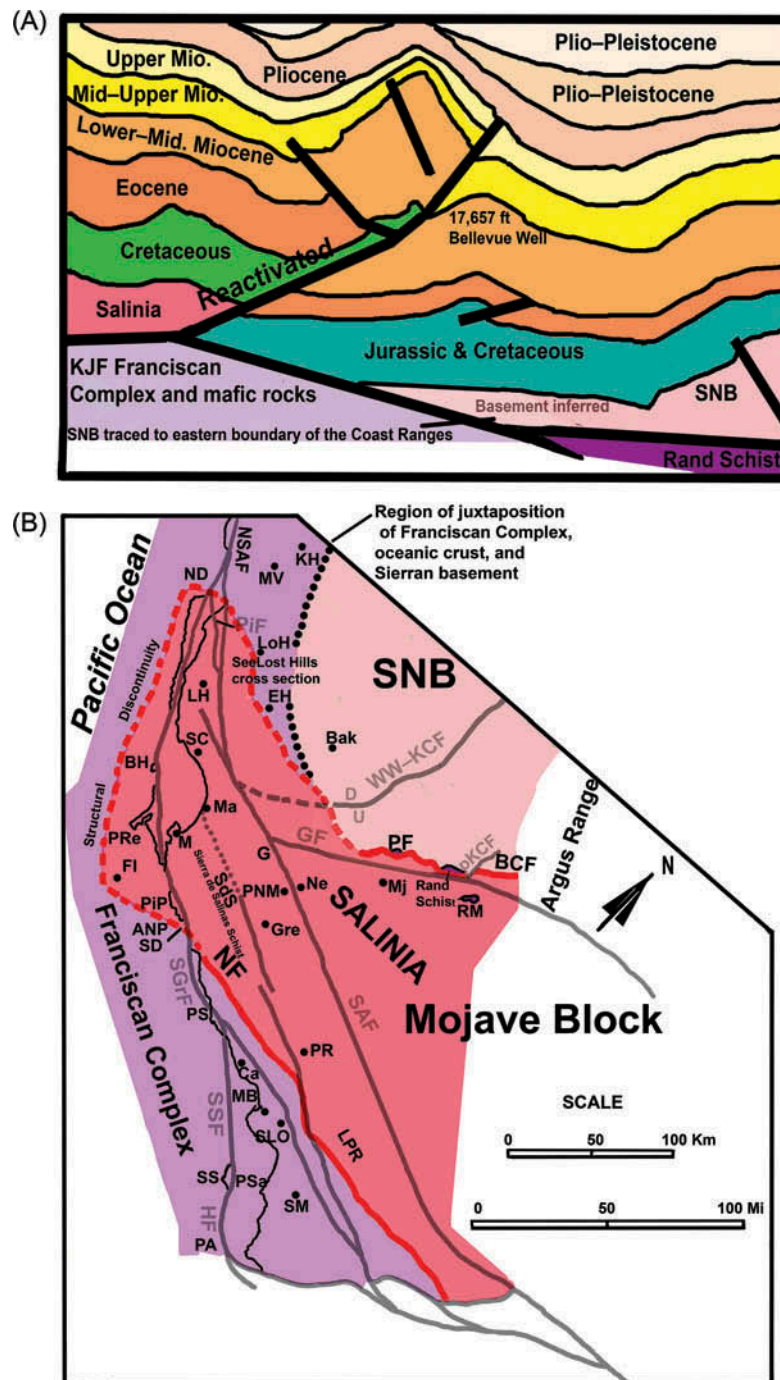


Figure 2. (A) A structural model at or near the eastern margin of Salinian basement rocks is based on a composite cross-section of the Lost Hills oil field (LoH, Figure 2A), inferred and reinterpreted from information in the San Joaquin Geological Society's web page (Famous Gushers of California, Lost Hills – The Bellevue Resources Bellevue No. 1 (17-26S-21E), (<http://www.sjvgeology.org/history/gushers.html>) and Ducea *et al.* (2009). Plio-Pleistocene, Tulare Formation, and underlying San Joaquin Formation; Pliocene, Etchegoin Formation; mid-upper Miocene, Reef Ridge, and Monterey formations; lower and mid-Miocene, Temblor formation; Eocene, Kreyenhagen formation; Upper Cretaceous Great Valley formations; Salinia, allochthonous terrane; Jurassic and Cretaceous rocks not part of the Franciscan Complex; KJf, Jurassic and Cretaceous Franciscan Complex. SNB, Sierra Nevada Batholith underplated by the Rand Schist. (B) Palinspastic map depicting the position of Salinia prior to offsets along the San Andreas fault system. Salinia, an allochthon that moved approximately 100 km (~62 mi) westward and northward from the Mojave block during latest Cretaceous to earliest Palaeogene time (~66 to ~62 Ma), and before being offset northward along the San Andreas fault system during Neogene time. We have not restored active blind thrusts (e.g. Figure 2A). At the eastern margin (Figure 2B), there are only in-place, but ductilely stretched, lower Sierra Nevada batholithic rocks (Saleeby *et al.* 1987, 2007; Chapman *et al.* 2010, 2012). See the caption for Figure 1 for the location and explanation of the abbreviations.

at both shallow crustal levels (see Ducea *et al.* 2009, figure 4) (e.g. 6–15 km or 4–9 mi) and at greater depths (e.g. 25–33 km or 16–21 mi), and a crystalline basement complex of high-grade Precambrian and Palaeozoic rocks (e.g. 2.9–2.5, 1.9–1.6, 1.5–0.9, 0.8–0.65 Ga, and 450–250 Ma). The metasedimentary rocks are interlayered with Late Cretaceous orthogneiss (Kidder *et al.* 2003). The rocks of the Sur Series are reportedly of similar ages and lithologies to rocks in the eastern Peninsular Ranges, and Mesozoic metamorphic and plutonic rocks (the latter with radiometric ages of 130–108, 120–83, 108–76, and 105–100 Ma) (Barbeau *et al.* 2005), in the Mojave terrane (Figure 2A). Nonconformably overlying the Sur Series are Upper Cretaceous turbidite deposits, deposited in a borderland environment (Grove 1993; Barbeau *et al.* 2005). Some of the depositional ages of aspects of the Sur Series are Late Devonian or Early Mississippian to early Permian (360–280 Ma). The depositional ages of the nonconformably overlying Cretaceous sedimentary strata are 90–78 Ma (Turonian to Maastrichtian ages) (Barbeau *et al.* 2005). Salinia plays a role in the history of much of California, when Salinia's western margin was a subduction zone during Late Jurassic to Late Cretaceous time, and California's history during the birth and the continuing development of the dextral slip San Andreas transform-fault system along the continental border of the western USA. Since the recognition and naming of Salinia by Reed and Hollister (1936), Salinia's geologic history and origin have been, and are a matter of controversy.

Associated with Salinia is a dispute regarding the amount of dextral slip on the (from S–N) Hosgri–San Simeon–San Gregorio fault zone (H–SS–SG) (HF, SSF, SGrF, Figure 1) (e.g. Hall 1975, 1991; Graham *et al.* 1978a, 1978b; Hall *et al.* 1995; Dickinson *et al.* 2005; Burnham 2009; and references in these references). This fault zone has included not only the offshore HF but also the largely offshore part of the Palo Colorado fault (PCF) depicted by Greene *et al.* (2002, figure 1). To understand the origin of Salinia requires an understanding of (i) the geology of northern, central, and southern California; (ii) the distribution of igneous and metamorphic rocks in those regions, and the Sierra Nevada and Mojave region; (iii) the history of the San Andreas transform and dextral fault system, a system that includes, from north to south, for example, the northern San Andreas, Pilarcitos (PiF or PF), San Gregorio–San Simeon–Hosgri (SG–SS–H), Reliz, Rinconada, and San Gabriel faults; (iv) the Nacimiento fault, e.g. the history of movement and, whether it is a right-slip, left-slip, or reverse fault, and (v) the mechanism and timing of the underplating of Mesozoic sedimentary and metasedimentary rocks within the subduction zone beneath western California.

In order to unravel the geologic history of Salinia, first it is necessary to palinspastically restore what is now much

of western California to a time prior to the development of the SAF system, i.e. to a time prior to 26–23 Ma, by restoring terranes or regional geologic terranes to their pre-slip locations. However, there is not a universal agreement as to the amount of slip on faults within the SAF system, which has created different scenarios for the pre-San Andreas geologic history of western California (e.g. Hall 1975, 1991; Graham *et al.* 1978a, 1978b; Hall *et al.* 1995; Dickinson *et al.* 2005; Burnham 2009; and references in these references).

Along the northern San Andreas and San Gregorio faults, near Point Reyes (PR), south to near Monterey (M, Figure 1), there has been a dextral slip of (i) ~150–160 km (93–100 mi) [i.e. 50–60 km (30–37 mi)] between 10 and 8 Ma; another 81 km (50 mi) between 8 and 3 Ma, and 19 km or more (12 mi or more), between 3 Ma and the present] (Clark and Brabb 1978; Clark *et al.* 1984; Clark 1998); (ii) a maximum of 156 ± 4 km (97 ± 2.5 mi) of dextral slip (e.g. Dickinson *et al.* 2005), or (iii) 175–185 km (108–115 mi) along the northern part of the San Gregorio–San Simeon–Hosgri fault zone (e.g. Burnham 2009, p. 206). The, Northern San Andreas fault (NSAF) and PiF zones also play prominent roles to account for differences in the amount of proposed dextral slip within these zones.

SAF system

Hill and Dibblee (1953) proposed that there has been large dextral slip movement along the SAF. A key feature of their hypothesis is the distribution of granitoid and metamorphic rocks in what is now largely the western part of California. They concluded that the northern outcrops of these types of rocks are in 'Salinia' near PR, north of San Francisco (PR, SF, Figure 1). These authors concluded that the correlatives of these rocks are on the east side of the SAF 498 km (309 mi) to the south of PR in the San Emigdio (SEM) and TM, near the southern terminus of the Sierra Nevada, and south of the southern end of the San Joaquin Valley (SEM, TM, Figure 1). However, other geologists (Table 1) noted that some piercing points along the SAF showed much less displacement [i.e. only 315 km (196 mi)] of dextral slip in central California, based on offset of 65-million-year-old shorelines and younger volcanic rocks with the same geochemical and rock-age signatures] and, thus, a quest for finding faults along which the remainder [e.g. 183 km (114 mi) of the 498 km (309 mi)] displacement could have taken place and for better dating the time or times of displacement along the SAF began.

Granitic rocks of Salinia are present farther north than PR [i.e. near Point Arena (PAr, Figure 1), Mendocino County, and Bodega Head (BH, Figure 1)], Sonoma County (see Hall 2002, Plate 1A; Dickinson *et al.* 2005, figure 1; Burnham 2009, figure 1). The PAr basin lies

Table 1. Dextral slip: Northern San Andreas–Pilarcitos–San Gregorio–Reliz–San Simeon–Hosgri fault system.

Dextral slip (km)	Name of fault(s) ^a	Offset areas	Offset formation(s) or features	Comments and/or references
171–200	NSAF	NSD (ND and NSD), granitic rocks–Franciscan contact and PiF, granitic rocks–Franciscan contact	Northern end of Salinia block, i.e. NSD, i.e. Sierran granitic rocks, offset from similar rocks in the PiF–SAF zone	Graham and Dickinson (1978a, 1978b), McCulloch (1987, 1989a, 1989b), Hall <i>et al.</i> (1995), and Burnham (2009, p. 217) Note: the distance from NSD south to granitic rocks of TMs is 610–675 km (379–420 mi)
200	NSAF–SG	Iversen Basalt and Mindego volcanic rocks	23.8 Ma Iversen and 23.7 Ma Mindego volcanic rocks	Clark and Brabb (1978), Brabb <i>et al.</i> (1998a), Wentworth <i>et al.</i> (1998), and Springer (2002)
175–185	NSAF–PF	Anchor Bay (Gualala) and Skyline/Highway 92	Anchor Bay Member, Gualala Formation, and Anchor Bay Conglomerate	Seiders and Cox (1992), Loomis and Ingle (1994), Elder <i>et al.</i> (1998), McLaughlin <i>et al.</i> (2007), and Burnham (2009, Appendix A)
171	NSAF–P (43 km), R (13 ± 2 km), WH (15 km), SS–H (100 km)	Unconformity at Point Reyes (PR) and unconformity at PL	Late early Eocene (55–50 Ma) PR Conglomerate and conglomerate of Carmelo Formation nonconformably on Cretaceous granitic rocks	McLaughlin <i>et al.</i> (2007) and Burnham (2009), see above
128 ± 2	R (13 ± 2 km), WH (15 km), SG–SS–H (100 km)	Pigeon Point (PiP) and Dolan/Gamboa Point	Upper Cretaceous, i.e. Campanian–lower Maastrichtian (ca. 84 to 75 Ma) PiP Formation and Campanian–Maastrichtian (84–71 Ma) Ku sandstone, shale, and conglomerate, south of PS, east of SG–SS–HF	PiP Formation: Hall <i>et al.</i> (1959, 1995), Tyler (1972, p. 538), Elder and Saul (1993), Brabb <i>et al.</i> (1998a), Saul and Squires (2008), Sanquini (2010, p. 11), Jacobson <i>et al.</i> (2011, figure 6 B), and Ernst <i>et al.</i> (2011) Ku ss, sh, cg: Trask (1927, p. 142), Nomland and Schenck (1932), Saul and Popenoe (1962, p. 301), Sutherland (1990, p. 22–32), Hall (1991, p. 12–13, Plate 1a); and Hall <i>et al.</i> (1995, plate 1)
115	WH (15 km), SS–H (100 km)	Point Sur (PS) area and Cambria areas	PS: Cenomanian to Coniacian or Santonian to Campanian (ca. 95–90 or 85–75 Ma) Pfeiffer slab (Ks), tectonically in contact with Franciscan rocks (KJf). KJf correlated with similar stratigraphy and structure near Cambria	Correlation between PS and Cambria areas: Graham and Dickinson (1978a,b), Hall (1991, Plate 1a); Hall <i>et al.</i> (1995, plate 1, table 2)
100	SS–H	SS and PSa	Pliocene Careaga Sandstone, Sisquoc, Monterey, PSa, and Lospe formations, Upper Cretaceous sandstone and siltstone, Franciscan Complex, Toro Formation, Upper Jurassic chert and ophiolite, all are present in both areas.	Hall (1975), Hall <i>et al.</i> (1995, plate 1, table 4), Johnson and Stanley (1994), and McLean and Stanley (1994) The 100 km offset is the distance between the unconformity between the lower-middle Miocene Lospe Formation and the Jurassic ophiolite present in the two areas (Hall <i>et al.</i> 1995, plate 1)

Notes: ^aFaults N–S: NSAF, i.e. north of San Francisco (Burnham 2009), PF or PiF, branch of the main trace of the San Andreas fault (SAF) near and south of San Francisco (McLaughlin *et al.* 2007). SG, SG fault zone, present on land near SG, Pescadero, and Punta Año Nuevo (ANP), largely south of San Francisco, intersects NSAF to the north, and is part of the SG–SS–H fault system to the south (Chapman *et al.* 1990; Brabb *et al.* 1998a). SS, on land at SS, near Hearst Castle (Hall 1975, 1991; Hall *et al.* 1995). H, Hosgri fault zone, in the offshore south of SS and south to near PSa (Hoskin and Griffiths 1971; Chapman *et al.* 1990; Langenheim, 2010). Reliz fault zone (R or ReF) Rosenberg and Clark (2009 as modified). WH, West Huasna fault zone, western SLO County (Hall, 1995, p. 87; Langenheim, 2010).

~121 km (75 mi) north of PR. Mesozoic granitic rocks and Franciscan mélangé floor the sedimentary basin, and the Navarro structural discontinuity (NSD, Figure 1) or boundary is a seismic structural anomaly that separates these rock units (Foland 1998). Wentworth *et al.* (1998) (see also Brabb *et al.* 1998b; Jones *et al.* 1998) suggested that Cretaceous sedimentary strata beneath the PAR basin, with a 'basal ophiolite,' could not be part of Salinia (i.e. a part of the displaced Sierra Nevada batholith and older rocks). However, the Cretaceous sedimentary strata near PAR are separated from the Jurassic ophiolite by a fault; they are not in depositional contact with the ophiolite (Table 1). Elsewhere in the Coast Ranges (e.g. Hall *et al.* 1995, Plate 1), the Coast Range ophiolite is less than 1 km (< 1 mi) from Salinia; it is tectonically in contact with Franciscan mélangé, and both the ophiolite and the Franciscan mélangé are in fault contact with Cretaceous strata within Salinia (Hall *et al.* 1995, plate 1). The NSD or northern structural discontinuity is here considered to be equivalent to the Nacimiento fault (i.e. it is the fault that separates Cretaceous strata near PAR from the ophiolite, and granite from Franciscan mélangé) (Hall 2002) (Figures 1 and 2). The granitic rocks associated with the NSD (Figure 2B), offshore from Mendocino County (Figure 1), are on the west side of the SAF system and 610–675 km (379–420 mi) north of granitic rocks within the southern part of the Sierra Nevada batholith and the granitic rocks in the SEM–TM (Kern County, Figure 1), which are east of the main trace of the SAF with which they are correlated, not the 498 km (309 mi) of offset of the batholithic rocks suggested by Hill and Dibblee (1953). Based on numerous piercing points (Burnham 2009), it is not possible to completely restore these offset granitoid rocks to their pre-slip positions along faults in the San Andreas system (see Burnham 2009, appendix A1 for a list of piercing points associated with the fault system). For example, Jurassic (ca. 150 Ma) gabbroic rocks of limited distribution at Logan (L, San Benito County, Figure 1), along the SW side of the main trace of the SAF, have been offset only 322 km (200 mi) from gabbroic rocks of limited distribution and of the same age and lithology on the NE side of the main trace of the SAF near Eagle Rest Peak (ERP, Figure 1), SEMs, Kern County, to the SE (Ross 1970; Ross *et al.* 1973; Dibblee 2005a, 2005b); and western San Emigdio mafic complex of Chapman *et al.* (2012). Another commonly cited offset pair of rocks with the same lithology and age, and limited distribution on opposite sides of the main trace of the SAF, are the 23.5-million-year-old volcanic rocks in Pinnacles National Monument (PNM, San Benito County, Figure 1), on the SW side of the SAF and the Neenach Volcanic Rocks 315 ± 3 km (196 ± 1.9 mi) to the SE at Neenach (Ne, Figure 1) on the NE side of the main trace of the SAF (Matthews 1976).

Thus, there is a discrepancy between the amount of separation measured between the Mesozoic granitic rocks on

opposite sides of the SAF (i.e. 610–675 km or 379–420 mi) and the amount of slip measured between piercing points (e.g. 315–322 km or 196–200 mi) on the main trace of SAF in central California. This discrepancy can, in part, be accounted for by faults within the SAF system. Candidate faults within this system are the PiF (Figure 1), SG–SS–H zone (Figure 1), the ReF (Figure 1), and the Oceanic–West Huasna fault zone (OWHF, Figure 1), all north of the WTRs (Figure 1). Models to explain competing amounts of slip measured within the SAF system are discussed below.

The enigma of Salinia

The total cumulative dextral slip along the entire SAF system outlined above, does not palinspastically restore granitoids of Salinia near Mendocino (NSD, Figure 1) with granitic rocks in the southern part of the Sierra Nevada batholith in the SEM and TM (Figure 1). This problem is referred to as the 'enigma of Salinia'. The answer to this enigma lies with the latest Cretaceous–earliest Palaeocene Nacimiento fault zone and megathrust faults discussed below; however, the nature and amount of movement along these faults are disputed. In order to discuss the disputes and resolve the enigma of Salinia, western California must first be palinspastically restored to its pre-San Andreas configuration.

Palo Colorado fault

Note that the onshore Palo Colorado–Coast Ridge fault zone (Ross 1984, figure 5) or onshore PCF (Dickinson *et al.* 2005, figure 5) are not part of the SG–SS–H fault zone nor is this fault zone a part of the Nacimiento fault in this region. The onshore PCF, as figured by Dickinson *et al.* (2005), is subparallel to the SG–SS–H fault zone, because it is not part of the system the fault does not contribute to the cumulative slip of the SG–SS–H fault zone or SAF system (Hall 1991; Hall *et al.* 1995; Dickinson *et al.* 2005, p. 9).

The Nacimiento fault

To the south of the offshore PCF and south of, but near, Point Sur (PS, Figure 1), there is confusion regarding differentiation and recognition of the SG–SS–H fault zone and the Nacimiento fault. For example, the 'Sur fault' depicted by Ross (1984, figure 5), the faults labelled 'Sur Thrust' and 'Sierra Hill Fault' compiled by R. G. Coleman in Zarkin (2000), and the reference to the Sur–SS–HF system in Wilson *et al.* (2005, p. 16) are the SG–SS–H fault zone or part of the zone (Hall 1991, geologic map 1a; Hall *et al.* 1995) (Figure 3).

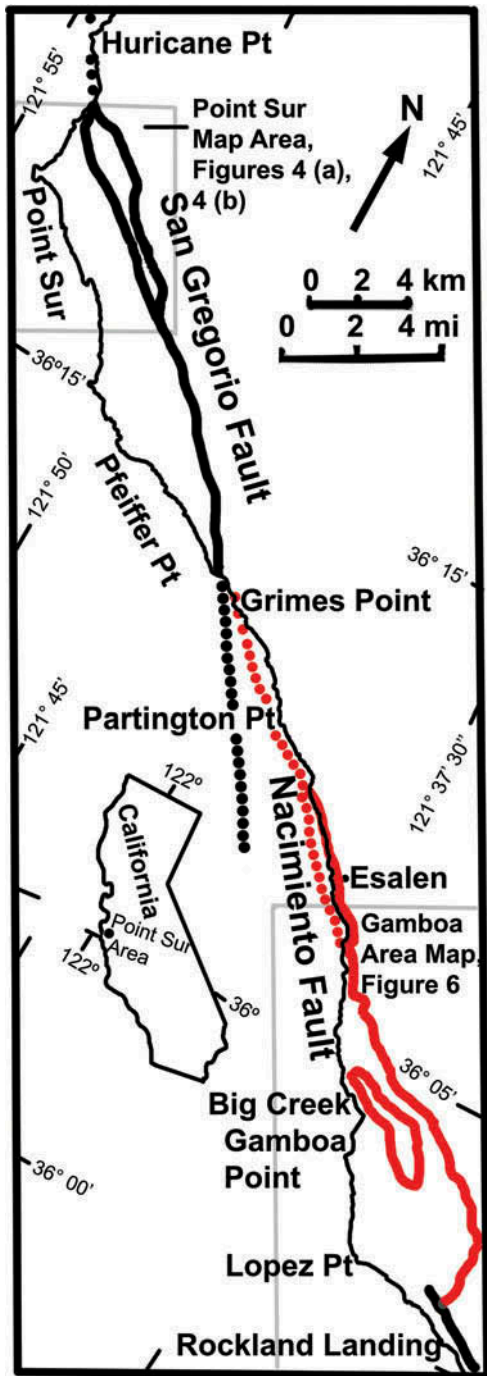


Figure 3. The truncation of the Nacimiento fault near Grimes Point, north of Esalen and south of Point Sur, Monterey County, by the dextral, strike-slip San Gregorio fault, a segment of the San Gregorio–San Simeon–Hosgri fault. The Nacimiento fault is offset ~ 128 km (80 mi) to the north from Grimes Point to near Año Nuevo Point (ANP, Figure 1), south of Pigeon Point (PiP, Figure 1), and west of the trace of the San Gregorio fault in San Mateo County. After Hall (1991). Figure 3 is an index map for the location of Figures 4A, 4B, near Point Sur, and Figure 6, near Gamboa and Lopez points (Monterey County), (see Figure 5 for the locations and titles of quadrangle maps of Figures 3, 4, 6, 7, and 8).

The role of the northern San Andreas–San Gregorio–San Simeon–Hosgri fault zone offsetting Salinia

The SG–SS–H fault zone, part of the SAF system, is present from near the entrance to San Francisco Bay (SF, Figure 1), south to about 34° N lat., i.e. near Point Conception (PtC, Figure 1) and west of Santa Barbara, along the coast of central California (Figure 1). The San Gregorio part of the SG–SS–H fault zone merges to the north with the NSAF (Figure 1) system. The length of this right-slip fault zone is 427 km (265 mi). Initial movement on the SG–SS–H fault zone began after 10 Ma, or possibly after 12 Ma (Clark *et al.* 1984; Clark 1998). The SG–SS–H fault zone is an active fault zone whose traces pass within ~ 4 km (2.5 mi) and 0.5 km (0.3 mi) of two Diablo Canyon nuclear reactors (west of SLO, Figure 1). An approximately 25 km- (16 mi-) long linear trend of seismicity runs 0.5 km (0.3 mi) offshore parallel to the coastline in the region of Point Buchon and the Diablo Canyon Nuclear facilities (west of San Luis Obispo, SLO, Figure 1) (Hardebeck 2010). This strand of the SG–SS–H fault zone has been named the Shoreline fault (Hardebeck 2010). This seismicity trend of the Shoreline fault is accompanied by a linear magnetic anomaly. Both the seismicity and the magnetic anomaly end where they obliquely merge with the main trace of the San Simeon–Hosgri fault zone. Focal mechanisms indicate that the Shoreline fault is a vertical strike-slip fault (Hardebeck 2010). Nishenko *et al.* (2010) suggested that the fault is not associated with near-surface faulting, implying that the fault is not active and not a danger to the nuclear plant even though it joins the active trace of the SG–SS–H fault zone.

The fault or faults in the SG–SS–H fault zone locally offset the lowest marine terraces and Holocene soil horizons (i.e. the most recent movement along the fault is younger than 10,000 years) (Hall 1991). Beheaded streams, springs, sag ponds, and pressure ridges locally define the trace of the fault, e.g. near Nepenthe on the Sur coast south of Monterey (Hall 1991), between Point Lobos (PL) and PS (Figure 1).

Dextral Slip on the northern San Andreas–Pilarcitos–San Gregorio–San Simeon–Hosgri Fault Zone

The amount of dextral slip or offset along the northern San Andreas–Pilarcitos–San Gregorio–San Simeon–Hosgri fault zone is summarized in Table 1, which lists segments of this fault zone from NW–SE. However, in order to best illustrate the cumulative dextral slip that has taken place along faults within the zone, segments of the fault zone are described below from S–N, i.e. from along the southern part of the fault or fault zones with the least measurable offset to the northern part of the system with the most cumulative offset. The following

topics are discussed, with a conclusion presented at the end of each numbered topic listed below: (i) offset along the Hosgri–San Simeon fault zone (i.e. Point Sal (PSa) stratigraphy, Santa Barbara County, [Figure 1](#)), offset to the SS area (SLO County, [Figure 1](#)). (ii) Cretaceous Cambria terrane (Ca, SLO County, [Figure 1](#)), offset to similar rocks in the vicinity of PS (Monterey County, [Figure 1](#)). (iii) PS–Big Sur terrane (PS, Monterey County, [Figure 1](#)), offset to a similar stratigraphy at Año Nuevo–Pigeon Point–Pescadero Point (Punta Año Nuevo (ANP), PiP, San Mateo County, [Figure 1](#)). (iv) Mesozoic granodiorite, nonconformity and Palaeogene PL conglomerate near Carmel (PL, Monterey County, [Figure 1](#)), offset to these types of rocks and geologic features on the PR Peninsula and near PR and Tomales Point, Marin County (PRe, [Figure 1](#)). (v) Strata of Anchor Bay stratigraphy near San Francisco, intersection of Skyline Boulevard and State Highway 92, San Mateo County (Wakabayashi 1999, [figure 3](#); Burnham 2009, no. 3 in [figures 4 and 9](#)), offset to similar stratigraphy near Anchor Bay and Gualala, Mendocino County ([Figure 1](#)). (vi) Mindego Basalt or volcanic rocks, type locality of La Honda Canyon, 2.2 km (1.4 mi) south of La Honda, near the Pescadero Road, San Mateo County (LH, [Figure 1](#)), offset as the Iversen Basalt (Iversen village was located 8 km or 5 mi south of PAr (PAr, Mendocino County, [Figure 1](#)). (vii) Granitic and Franciscan rocks in the PiF–NSAF zone near San Francisco (SF, [Figure 1](#)) (Wakabayashi 1999, [figure 3](#)), offset to similar rocks and structures in Mendocino County, i.e. the offshore NSD ([Figure 1](#)), west of Ukiah and near Navarro River Redwoods State Park (Burnham 2009, [figure 1](#)).

(1) PSa stratigraphy, Santa Barbara County, offset to SS, SLO County

Hall (1975) estimated the amount of dextral slip on the San Simeon–Hosgri fault zone to be ‘80 km or more (that is, more than 100 km between PSa and SS Point, minus the estimated maximum 20 km diameter of the area of the stratigraphic packages at SS and PSa)’. Hall *et al.* (1995) estimated dextral slip on the HF–SS fault zone to be 95–87 km (59–54 mi). The estimate of 95–87 km (59–54 mi) or more of dextral slip along the central part of the HF–SS fault zone south of PS was based on: (i) geophysical studies (Silver 1974; Chapman *et al.* 1990); (ii) offset pairs of stratigraphic sequences, and narrowly geographically distributed pairs of uncommon lithologic types across the H–SS–SG fault zone; (iii) offset submarine geology; (iv) geochemical studies across the fault zone; (v) provenance studies of sedimentary strata across the fault, and (vi) palinspastic shoreline reconstructions.

A 100 km (62 mi) offset can be measured between Jurassic ophiolite, and nonconformably overlying lower Miocene nonmarine rocks and tuff within the Lospe Formation that crop out and are known from exploratory

oil wells at or near PSa ([Figure 1](#)) (Woodring and Bramlette 1950; Hall 1975; Hopson *et al.* 1975, 2008; Webster and Yenne 1987, figure 13; Johnson and Stanley 1994; McLean and Stanley 1994), and an identical stratigraphic section and nonconformity near and north of the hamlet of SS (Hall 1975, [figure 2](#), 1991; Hall *et al.* 1979, 1995; Hopson *et al.* 2008; Mattinson and Hopson 2008). The piercing points at PSa and SS are mapped and unique, not ‘speculative,’ as suggested by Dickinson *et al.* (2005, p. 25).

Offset along the H–SS segment of the H–SS–SG fault zone that is less than the offset to the north of SS (see other segments discussed below) and south of Point Arguello (PA, [Figure 1](#)) is either owing to: (i) strike–slip being taken up in thrust faulting and folding at the southern end of the Hosgri segment (Steritz and Luyendyk 1994; Sorlien *et al.* 1999a, 1999b), (ii) crustal shortening within the rotating Transverse Ranges (Dickinson *et al.* 2005), (iii) slip along yet-to-be-identified faults in the offshore or Santa Maria basin, also ruling out crustal shortening (Graymer *et al.* 2010; Langenheim *et al.* 2010), (iv) ~15 km (9 mi) of slip inland from near Point Buchon and the Diablo Canyon nuclear reactor along the onshore OWHF zone (Hall *et al.* 1995), or (v) 23 km (14 mi) of dextral slip on the OWHF zone (Langenheim *et al.* 2010) (OWHF, [Figure 1](#)).

Conclusion for point 1

Dextral slip of ~100 km (62 mi) is present along the Hosgri segment of the Hosgri–SS fault zone between PSa and SS, based on offset of a unique stratigraphic section and an unconformity at those two localities.

(2) Cambria terrane, SLO County, offset to similar rocks in the vicinity of PS, Monterey County

Unnamed Upper Cretaceous sandstone and siltstone form the Cambria slab (Ca, [Figure 1](#)) or terrane that crops out between Point Estero, north of Cayucos, to Pico Creek, near SS ([Figure 1](#)), SLO County. These rocks structurally and stratigraphically overlie the Jurassic–Cretaceous Franciscan Complex (Hall *et al.* 1979, sheet 2; Smith *et al.* 1979) and they are east of the trace of the H–SS fault zone. Similar rocks and structures are present ~115–123 km (72–76 mi) to the north, and west of the H–SS fault zone near PS (Hall 1991; Hall *et al.* 1995) (PS, [Figure 1](#)).

The ~115–123 km (72–76 mi) of cumulative dextral slip on the H–SS zone includes the 100 km (62 mi) of offset south of the SS area described above, and 15–23 km (9–14 mi) of dextral slip along the OWHF zone that merges northward with the H–SS fault zone near Cape San Martin (Hall *et al.* 1995; Langenheim *et al.* 2009, 2010) (near Gamboa Point, [Figure 1](#)). The Oceanic fault is considered to be a NW continuation of the West Huasna fault (Hall

1973a, 1973b, 1974; Hall and Prior 1975; Hall *et al.* 1995; Langenheim *et al.* 2009, 2010; also see Tennyson *et al.* 1991). The OWHF zone is, in general, an anastomosing bundle of faults.

Using the distribution of Miocene andesitic sills, McLean (1993, 1994) concluded that strike separation along the West Huasna fault is no more than 8 km (5 mi). However, the distribution of (i) lower Miocene nonmarine red beds, (ii) the Obispo Formation in the subsurface in the Huasna and Santa Maria basins, (iii) Obispo tuff in surface outcrops, and (iv) Mohnian stage nearshore sandstone units suggests dextral slip of ~15 km (9 mi). Langenheim *et al.* (2010) used alternate offset pairs to suggest 23 km (14 mi) of dextral slip on the OWHF zone.

Langenheim *et al.* (2010) suggested 90 km (56 mi) of dextral slip on the H–SS fault zone north of Point Arguello (PA, Figure 1); this geographic point is south of PSa (Figure 1) (offset is 100 km or 62 mi of offset between PSa and SS). If the offsets proposed by Langenheim *et al.* (2010) for the H–SS fault zone (i.e. 90 km or 56 mi of dextral slip) and OWHF (i.e. 23 km or 14 mi of dextral slip) zones are accepted, then the cumulative dextral slip on this pair of fault zones is 113 km (70 mi), which also supports a Cambria slab (SLO County)–PS or Big Sur (Monterey County) correlation.

Sutherland (1990, p. 113) studied the sandstone and conglomerate beds and clasts in the upper Miocene Miguelito and Edna members of the Pismo Formation that crop out west of the H–SS–SG fault zone near PS (Figures 3 and 4A and 4B), and equivalent units in the Morro Bay area (MB, Figure 1). Volcanic clasts are present in upper Miocene sandstone beds in both areas, contrary to the studies by Graham and Dickinson (1978a, 1978b), who suggested an absence of volcanic clasts. The clasts are felsic and seriate (i.e. typically porphyritic, in which the sizes of the grains vary gradually or in a continuous series) (rhyolite and dacite are examples of these types of rocks) (Sutherland 1990). A conglomerate within the Edna Member of the Pismo Formation, exposed in the sea cliff north of the Little Sur River and west of the H–SS–SG fault zone (Tmpp, Figure 1), contains pebbles of porphyritic rhyodacite and welded, devitrified rhyodacitic tuff, as well as granitic clasts, quartzite and sandstone. The likely source of these silicic volcanic clasts is the Cambria Felsite, a highly silicic and potassic rhyolite-dacite-crystalline felsite that is locally tuffaceous (Ernst and Hall 1974). The distribution of the Cambria Felsite and tuff is largely restricted to the area between Santa Rosa and SS creeks (i.e. near Cambria, Ca, Figure 1), east of the H–SS–SG fault zone and 115 km (72 mi) south of PS (Hall *et al.* 1979) (PS, Figure 1).

Dickinson *et al.* (2005, p. 23) preferred that the Franciscan Complex, PS slab, and Pismo Formation near PS, Monterey County and within the PS terrane were carried northward '155 km' from the Point San Luis area

near Avila Beach (west of SLO Figure 1). To be present in the Pismo Formation conglomerate in the PS terrane, the Cambria Felsite clasts present in the conglomerate would first have had to travel by currents a minimum of 48 km (30 mi) south and westward to be deposited on the Point San Luis terrane before being carried northward along the H–SS–SG fault zone. It is unlikely that the relatively soft tuff clasts could have survived as cohesive clasts during a journey of 48 km (30 mi). In addition, the Point San Luis terrane includes Mesozoic pillow basalt; whereas neither outcrops of this rock type nor clasts of Jurassic basalt are present in the PS terrane, further negating the suggested correlation between the Point San Luis terrane and the PS–Big Sur area proposed by Dickinson *et al.* (2005, p. 23).

To support their correlation between the PS (west of the H–SS–SG fault zone) and Point San Luis (east of the fault zone) terranes, Dickinson *et al.* (2005, p. 23, figure 11) provided vitrinite reflective values for the two areas. However, the PS terrane, from which their samples were taken, is primarily Franciscan *mélange* with only a few small slabs of Cretaceous sandstone and shale; in contrast, the Point San Luis terrane includes more than one large slab of Cretaceous sandstone and shale, Jurassic pillow basalt, and a thick Tertiary strata. Present in the PS terrane is a relatively thin stratigraphic section of Tertiary rocks (i.e. Vaqueros, Rincon, and Pismo formations) (Hall 1991, map sheet 1a; Hall *et al.* 1995, Plate 1) (Figures 4A and 4B). This thin Tertiary stratigraphic section is discussed below. The stratigraphic, sedimentologic, and petrologic contrasts between the Tertiary stratigraphic sections in the Point San Luis and PS regions preclude the Dickinson *et al.* (2005) correlation between PS and Point San Luis.

The Cambria slab (near Ca, Figure 1), from which vitrinite reflective samples were taken (Dickinson *et al.* 2005), is exclusively Cretaceous sandstone and shale; no Franciscan *mélange* is present onshore west of the slab. The slab rests tectonically and stratigraphically on the Franciscan Complex near Highway 1 to the east (Hall *et al.* 1979; Smith *et al.* 1979). The Cretaceous sandstone of the slab was deposited on an inner-trench slope (Smith *et al.* 1979; Page 1981, p. 350). Given that the vitrinite samples (Dickinson *et al.* 2005, p. 23, figure 11) from the rocks at PS and the Cambria slab are of different ages, different rock types, and from different sedimentary environments, correlation between the PS terrane and the Cambria slab is considered problematic by Dickinson *et al.* (2005, p. 23). However, within 0.2–0.8 km (0.1–0.5 mi) of the Cretaceous Cambria slab is a Tertiary stratigraphic section that includes the Cambria Felsite, and Vaqueros and Rincon formations (Ernst and Hall 1974; Hall *et al.* 1979, map sheet 2 of 3; Hall 1991, map sheet 1a) similar in lithology and thickness to the PS stratigraphic section. In addition, the Cambria Felsite clasts in the Pismo Formation, present near PS, are likely from outcrops of the Cambria Felsite near Cambria, thus supporting a Cambria–PS correlation.

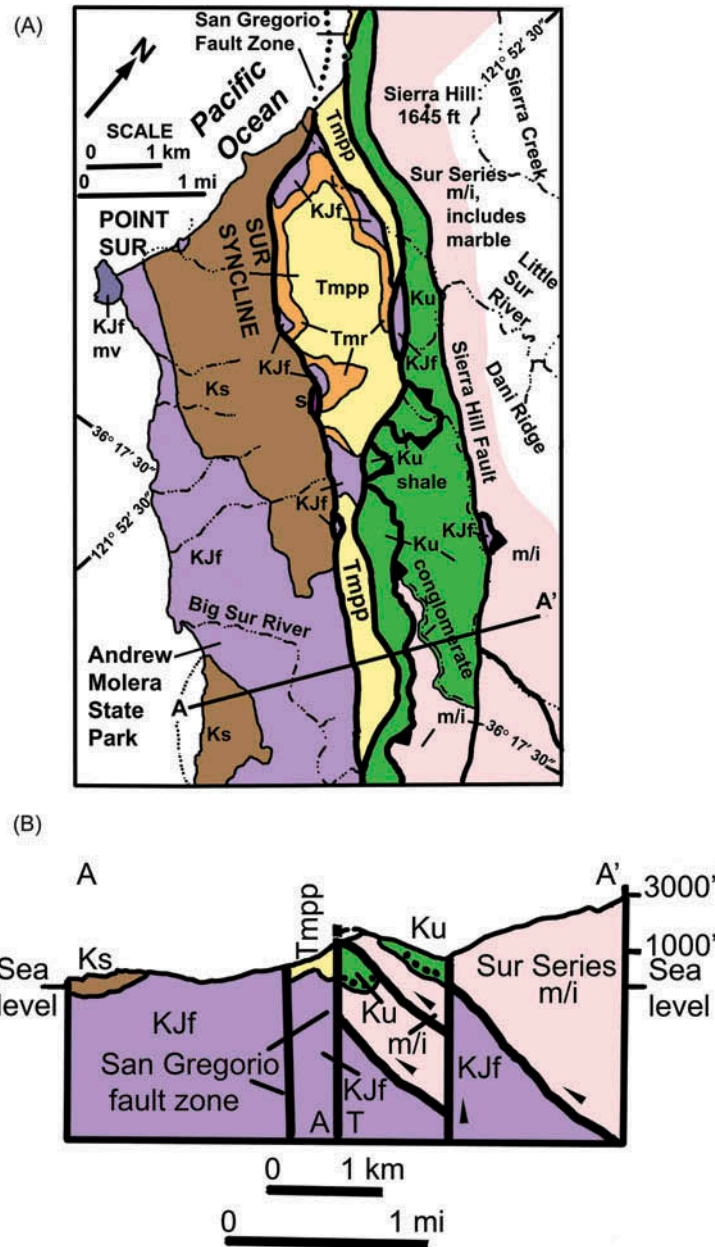


Figure 4. (A) Pre-Quaternary geologic map of the Point Sur region, Monterey County, depicting the Sur syncline and the trace of San Gregorio fault that bifurcates near Andrew Molera–Pfeiffer–Big Sur State parks, is bifurcated near Point Sur, and truncates the Sierra Hill fault near Hurricane Point (Figure 3). See Figure 1 for abbreviations for geographic and geologic features, and see Figures 4A, 4B, 6, and 7 abbreviations for geologic units: i/m, Sur Series, dominantly granitoid igneous rocks, with metamorphic rocks; m/i, Sur Series, dominantly metamorphic rocks (marble, gneiss, and schist), with granitoid igneous rocks; KJf, Cretaceous–Jurassic Franciscan Complex, a mélange of greywacke, chert, and metavolcanic rocks; KJmv and mv, Cretaceous–Jurassic metavolcanic rocks and metagabbro; Ks, dominantly Upper Cretaceous greywacke as tectonostratigraphic units or slabs within or tectonically on the Cretaceous–Jurassic Franciscan mélange (KJf); Ku, Upper Cretaceous, Campanian–Maastrichtian and middle and upper Campanian formations, dominantly sandstone (ss) and siltstone with minor conglomerate beds (cg) nonconformably upon the Sur Series and in fault contact with the Franciscan Complex; Kucg, Upper Cretaceous Campanian–Maastrichtian and middle and upper Campanian dominantly conglomerate (see Tables 2 and 3); s, Jurassic serpentinite and metagabbro; Tml, lower–middle Miocene Monterey Formation or Sandholdt Member of the Monterey Formation; Tmpp, upper Miocene–Pliocene Pismo Formation; Tod, Upper Oligocene dacite correlated with the Cambria Felsite and Morro–Islay volcanic rocks (27.6–23 Ma) [note that the Pescadero Felsite in San Mateo County, which was correlated with the Cambria Felsite (Dickinson *et al.* 2005), has a radiometric age of 90–86 Ma (Ernst *et al.* 2011)]; Tmr, early–middle Miocene Rincon Formation; Tvq, Oligocene–Miocene Vaqueros formation, stratigraphically beneath the Monterey or Rincon formations but commonly too thin to depict at the scale of the maps. After Hall (1991) and Hall *et al.* (1995), also see Gilbert (1971) and Sutherland (1990). (B) Cross-section A–A' depicting the San Gregorio–Sierra Hill fault zone near or bounding the Sur syncline and near Point Sur. See Figures 1 and 3 for locations. The Nacimiento fault is depicted in red.

The Point San Luis terrane, from which vitrinite reflective samples were taken (Dickinson *et al.* 2005), is principally Cretaceous sandstone resting on minor exposures of Jurassic pillow basalt or metavolcanic rocks. Significantly, the Point San Luis terrane includes a section of 290 m (950 ft) of the middle Miocene (16.3–15.5 Ma) Obispo Formation (e.g. tuff, perlite, and basalt) and 916 m (3005 ft) of middle Miocene (Relizian–Luisian stages) Monterey Formation (dolomitic shale, shale, and cherty shale). The upper Miocene–Pliocene Pismo Formation unconformably overlies these units (Hall *et al.* 1979, map sheet 1; Hall 1991, map sheet 1a). The Obispo Formation and other rocks within the Point San Luis region are not present at, or near, PS, nor are the lithologies of the Obispo Formation present as clasts in the upper Miocene conglomerate beds of the Pismo Formation in the PS region (Sutherland 1990). These relationships further preclude a correlation between the PS and Point San Luis terranes, as proposed by Dickinson *et al.* (2005).

Conclusion for point 2, Cambria terrane, SLO County, offset to similar rocks in the vicinity of PS, Monterey County

There has been cumulative dextral slip on the SH–SS fault zone (100 km or 62 mi) and the OWHF zone (15 or 23 km; 9 or 14 mi) of either 115 or 123 km (72 or 76 mi), offsetting inner-trench-slope Upper Cretaceous sedimentary rocks near Cambria (Ca, Figure 1) from inner-trench-slope Upper Cretaceous rocks near PS (Figure 1), and offsetting Tertiary rocks that include the Vaqueros, Rincon, and Pismo formations, the latter with clasts of Cambria Felsite from the Cambria region.

(3) PS–Big Sur terrane, Monterey County, offset to a similar stratigraphy at ANP–PiP–Pescadero Point, San Mateo County

A high percentage of felsic volcanic rock clasts and intermediate, dark, and light-coloured volcanic rock clasts are present in conglomerate strata in the PiP Formation (Table 2). Although Sutherland (1990) and Seiders and Cox (1992) reported 72% rhyodacite, tuff/felsite (Sutherland 1990) and 82% felsic volcanic rock clasts (Seiders and Cox 1992) from Upper Cretaceous rocks at a few localities in the PS and Big Sur region (Sutherland 1990) and conglomerate clasts in the Big Sur area (Seiders and Cox 1992) (Table 3), there is a relatively high percentage (e.g. 76%, Grove 1989) of felsic plutonic-rock clasts in the PS–Big Sur region that are not present in the PiP Formation (Tables 2 and 3) near Pescadero and PiP.

Although the PS–Big Sur conglomerate beds are locally made up solely, or with a high percentage, of clasts of felsic plutonic or granitic rocks, and these lithologies are known from the basement rocks locally and immediately beneath the conglomerate beds, volcanic clasts in the

PS–Big Sur conglomerate beds are not reported from the immediately underlying basement (Table 4).

Grove (1989, p. 157) commented on these types of relations:

An observation common to the sections (excluding Pigeon Point and Gualala, Mendocino County) is that basal clast populations are dominated by a variety of lithologies compatible with basement rock types, whereas younger populations are dominated by felsic volcanic lithologies that are unknown from within the basement complex.

Grove (1989, p. 158) proposed a model to account for the distribution and presence of clasts of felsic volcanic rocks, e.g. in the Upper Cretaceous PiP Formation. In her five-point model [our comments and additions are in square brackets]: (i) first a sedimentary basin [e.g. a basin of latest Cretaceous age] forms following the uplift of basement rocks [e.g. Sur Series or Complex–Coast Ridge belt rocks (see Ducea *et al.* 2003, 2009; Kidder *et al.* 2003)]. [Exhumation of Salinia from depths of 25 km (16 mi) occurred between cessation of high- and mid-temperature metamorphism around 80 Ma and deposition of Campanian and Maastrichtian marine rocks at ca. 75–65 Ma (Barbeau *et al.* 2005)]. (ii) A narrow shelf and short drainages typify the sedimentologic setting and turbidity current deposited sediments derived from the local basement rocks [e.g. Esalen (Figure 3) conglomerate beds from the nearby Sur Series–Coast Ridge belt basement terrane, Monterey County]. (iii) The basin fills, subsidence continues and a thick [3300 m or 10,800 ft of PiP Formation, San Mateo County; PiP, Figure 1] and shallow-marine sedimentary section is deposited. (iv) As tectonic activity continues, subsidence increases, drainages become better integrated and rivers carry more sediment from distant sources to the basin [and coastward in this case]. (v) As subsidence increases, deep-sea turbidites [e.g. submerged gravity-driven turbid suspensions of water and sediment; present within the PiP Formation (Howell and Joyce 1981)] are deposited and felsic volcanic clasts are brought to the coastal region from distant terranes [e.g. from Mesozoic felsic volcanic rocks in the Mojave Desert, San Bernardino and Riverside counties, and Peninsular Ranges, San Diego County] by an integrated river system.

The Grove (1989) model not only accounts for the distribution of felsic volcanic clasts in the PiP Formation, but also allows for the proposed correlation between the PiP Formation west of the H–SS–SG fault zone and Upper Cretaceous strata in the PS–Big Sur region east of that right-slip fault zone, now separated by a distance of 128 ± 2 km (80 ± 1.2 mi); in other words, cumulative slip of 100 km (62 mi) on the H–SG fault zone, 15–23 km (9–14 mi) on the OWHF zone merged with the H–SS fault zone, and 13 ± 2 km (8 ± 1.2 mi) of dextral slip on the ReF merged with the H–SS–SG fault zone (see discussion of the ReF segment below).

Table 2. Conglomerate clasts, Upper Cretaceous Pigeon Point Formation.

84–71 Ma percentage	PiP Fm. Type of clast	Reference	84–71 Ma percentage	PiP Fm. Type of clast	Reference
69.0	Felsic volcanic rocks	Tyler (1972)	63.0	Intermediate, dark, and light volcanic rocks	Grove (1989)
24.0	Plutonic rocks				
5.0	Quartzite		20.0	Plutonic rocks	
2.0	Chert		10.0	Metasedimentary rocks	
100.0			1.0	Quartzite	
			6.0	Miscellaneous rocks	
			100.0		
54.0	Intermediate, dark, and light volcanic rocks	Grove (1989)	76.0	Intermediate, dark, and light volcanic rocks	Grove (1989)
24.0	Plutonic rocks		15.0	Plutonic rocks	
17.0	Metasedimentary rocks		2.0	Metasedimentary rocks	
3.0	Miscellaneous rocks		7.0	Miscellaneous rocks	
2.0	Quartzite		100.0		
100.0					
75.0	Intermediate, dark and light volcanic rocks	Grove (1989)	80.7	Felsic volcanic rocks	Seiders and Cox (1992)
15.0	Plutonic rocks		1.7	Other volcanic rocks	
10.0	Metasedimentary rocks		11.7	Granitic rocks	
100.0			1.5	Quartz sandstone	
			1.6	Other sandstone	
63.0	Intermediate, dark and light volcanic rocks	Grove (1989) Member G	1.5	Argillite (Sutherland 1990)	
20.0	Plutonic rocks		0.9	Miscellaneous rocks	
6.0	Quartzite		0.4	Mudstone	
5.0	Metasedimentary rocks		100.0		
6.0	Miscellaneous rocks				
100.0					
63.0	Intermediate, dark, and light volcanic rocks	Grove (1989)	72.0	Felsic and intermediate volcanic rocks	Sanquini (2010)
20.0	Plutonic rocks		16.0	Plutonic rocks, including tonalite	
10.0	Metasedimentary rocks		5.0	Quartzite	
1.0	Quartzite		7.0	Sedimentary, other	
6.0	Miscellaneous rocks		100.0		
100.0					

Notes: The PiP Formation nonconformably overlies the Pescadero Felsite, an altered sodic diabase with quartz. The age of the felsite (90–86 Ma) is comparable to some ages of rocks in the Coast Ridge Belt, Monterey County (see Ernst *et al.* 2011, p. 1510)

The lower middle Campanian to upper Campanian (ca. 79 to ca. 71 Ma) PiP Formation (Hall *et al.* 1959; Saul and Squires 2008; Ward *et al.* 2012, figure 12) also has been correlated with Upper Cretaceous strata west of the Nacimiento fault zone and east of the H–SG fault zone by Graham and Dickinson (1978a) (also see Tyler 1972; Grove 1989, p. 156; Sanquini 2010; Sanquini *et al.* 2010). The correlation suggested to Graham and Dickinson (1978a) was between 115 and 150 km (~72–93 mi) of dextral slip along that zone. However, Dickinson *et al.* (2005) correlated the Atascadero Formation in the southern Santa Lucia Range with the PiP Formation. Sanquini (2010, p. 38–39) discussed four reasons that the Dickinson *et al.* (2005) correlation is problematic: (i) the molluscs in the PiP Formation are primarily warm-temperate or tropical forms, whereas the molluscs from the Atascadero

Formation (south of PiP) are temperate-water forms, (ii) the Jurassic Toro Formation (primarily dark shale) underlies [it is in thrust fault contact (Seiders 1989)] the Upper Cretaceous Atascadero Formation north of SLO [however in tectonic contact]. The Toro Formation is not present below the PiP Formation onshore or offshore (Heck *et al.* 1990, p. 146–149; Ernst *et al.* 2011), (iii) Dickinson *et al.* (2005, p. 21) supported their correlation between the PiP and Atascadero formations by correlation of the Pescadero felsite beneath the PiP Formation (near Pescadero Point and north of PiP) with the 27 Ma Cambria Felsite. However, Ernst *et al.* (2011) dated the Pescadero felsite at 90–80 Ma, thus negating the postulated correlation of the felsite near Pescadero Point with the felsite near Cambria proposed by Dickerson *et al.* (2005) [See Table 2 regarding Sanguini's third point]. In addition to Sanguini's

Table 3. Conglomerate clasts, Upper Cretaceous rocks (Kucg) near Point Sur.

84-71 Ma percentage	Sierra Hill-PS Type of clast	Reference	84-71 Ma percentage	Big Sur State Park Type of clast	Reference
45.0–50.0	Plutonic rocks (tonalite, diorite, granodiorite, and granite)	Norris (1985)	51.0	Meta-andesite	Sutherland
30.0	Metamorphic rocks (gneiss, schist, and amphibolite)	(Basal conglomerate, Dolan Ridge, and Boulders, >1 metre in diameter)	45.0	Quartzite	(1990)
10.0–20.0	Felsic volcanic rocks		3.0	Intermediate volcanic rocks	
100.0			1.0	Argillite	
72.0	Intermediate volcanic rocks	Sutherland (1990)	100.0		
7.0	Granitic rocks		56.0	Argillite	Sutherland
17.0	Quartzite		32.0	Granitic rocks	(1990)
4.0	Meta-rhyolite		12.0	Quartzite	
100.0			100.0		
55.0	Granitic rocks	Sutherland (1990)	79.0	Rhyolitic tuff/felsite	Sutherland
40.0	Meta-andesite		18.0	Meta-rhyolite	(1990)
5.0	Hypabyssal granite/rhyolite porphyry		3.0	Intermediate volcanic rocks	
100.0			100.0		
72.0	Rhyodacitic tuff/felsites	Sutherland (1990)	78.0	Rhyolite tuff/felsite	Sutherland
14.0	Granitic rocks, hypabyssal granite		15.0	Quartzite	(1990)
11.0	Rhyolite		7.0	Metavolcanic rocks	
3.0	Quartzite		100.0	Esalen (Kucg)	Grove (1989)
100.0				(south of Big Sur State Park Felsic plutonic rocks	Location 1
82.0	Felsic volcanic rocks	Seiders and Cox (1992)	76.0	Felsic plutonic rocks	Grove (1989)
12.5	Other volcanic rocks		8.0	Intermediate mafic plutonic rocks	Location 2
3.8	Quartz sandstone		5.0	Intermediate mafic volcanic rocks	
0.8	Miscellaneous rocks		8.0	Low-grade meta sedimentary rocks	
0.5	Chert (argillite)		2.0	Quartzite	
0.3	Mudstone		1.0	Light siliceous volcanic rocks	
99.9			100.0		
	Esalen (Kucg)	Seiders and Cox (1992)		North of PS (near Hurricane Point)	Grove (1989)
39.9	Granitic rocks	'basal Conglomerate'	43.0	Light siliceous volcanic rocks	Location 3
29.9	Metamorphic rocks		18.0	Felsic plutonic rocks	
13.4	Felsic volcanic rocks		14.0	Dark siliceous vols.	
5.0	Mudstone		13.0	Quartzite	
4.7	Chert (argillite)		7.0	Intermediate mafic volcanic rocks	
3.4	Quartz sandstone		5.0	Intermediate/mafic plutonic rocks	
0.6	Other sandstone		100.0		
0.3	Other volcanic rocks				
2.8	Other rocks				
100.0					

Note: Esalen sandstone, age-probability peaks at 135 and 95 Ma (Barbeau *et al.* 2005).

analysis, Ernst *et al.* (2011) attributed the wide scatter in their age data to a sedimentary or metasedimentary rather than a volcanic–plutonic arc source for the analysed Pescadero zircons, ‘Virtually all of the zircons were ultimately derived from pre-existing igneous rocks. Certainly, the Pescadero zircon source could have been a mixture of sedimentary and plutonic rocks’ (W.G. Ernst, written communication, November 2011). Thus, the source of the Pescadero zircons could have been the Sur Series–Coast Ridge belt in that the belt contains both Proterozoic and Palaeozoic zircons, and (iv) Sanguini’s fourth point is that Dickinson *et al.* (2005, p. 21) supported their correlation based on the distribution of 22.0 ± 0.7 Ma basalt in the Vaqueros (?) Formation or Mindego (?)

Volcanic Rocks at Pescadero Beach [unconformably overlying and locally in fault contact with the Campanian–Maastrichtian PiP Formation] and at ANP, with the Morro–Islay Complex (26.5–27 Ma) (Stanley *et al.* 2000; Wilson *et al.* 2005) to the south in SLO County, and on the opposite side of the H–SG fault zone. However, the lithologies of the correlated rocks (basalt of the syndepositional magmatism within the Vaqueros (?) Formation *versus* rhyodacite of the Morro–Islay Hill Complex) and their ages (22 Ma *versus* 27 Ma) are dissimilar, not supporting their correlation.

Dickinson *et al.* (2005) regarded Cretaceous strata that overlie Salinia as exclusively Maastrichtian (70.6–65.5 Ma) in age. However, Cretaceous sandstone and conglomerate,

Table 4. Salinia basement, Santa Lucia Range, Monterey Bay south to near Cape San Martin.

Location	Metamorphic rocks	Plutonic rocks	Age (e.g. radiometric, detrital zircon)	References and comments
Cone Peak, Monterey Co.	Amphibolite Biotite-feldspar quartzite Calcite marble Calc-silicate granofels Metadolomite Quartzo-feldspathic gneisses and granofels	Pyroxenite Quartz diorite	75–69 Ma	Compton (1960) Sur Series <50% granitic rocks. Coastal part largely foliated metamorphic rocks, quartz diorite, and granodiorite.
Junipero and Serra Peak, Monterey Co.		Adamellite Granodiorite		Compton (1960) Sur Series
Northern Santa Lucia Range, Monterey Co.	Aluminous rocks Amphibolites Calc-silicate rocks Quartzo-feldspathic Granofels	Biotite tonalite Granitic complex Granodiorite Hornblende gabbro Quartz monzonite		Wiebe (1970a, 1970b) Sur Series
Northern Santa Lucia Range, Monterey Co.	Hornfels Granofels Quartzite Quartzo-feldspathic Granofels Amphibolite Marble	Charnockitic tonalite Diorite Gabbro Granitic complex Quartz diorite Quartz monzonite	Quartzite: dominant ages: 130–96 and 130–80 Ma	Ross (1976) Sur Series-Coast Ridge belt Average composition of Salinia arc is one of granodiorite (Barbeau <i>et al.</i> 2005)
Partington Ridge, Monterey Co.		Charnockitic tonalite Granodiorite Quartz diorite Tonalite	100 Ma 117 ± 12 Ma 100–83.8 Ma	Kistler <i>et al.</i> (2001)
Sur Series Coast Ridge belt, Monterey Co.	Amphibolite Granofels Marble Quartz biotite schist Quartzite Quartzo-feldspathic Gneiss Biotite gneiss	Diorite Fine-grained mafic rocks Gabbro Quartz diorite	Magmatism began between 110 and 100 Ma, ended between 81 and 76 Ma 93 Ma	Kidder <i>et al.</i> (2003) Brought to surface in 8 Ma. Mojave source. Inherited ages: Proterozoic–Cambrian, e.g. from Wood Canyon Formation
Coast Ridge belt, Monterey Co.		Mafic to intermediate magmas Ductile deformation	93–80 Ma At 93–80 Ma	Ducea <i>et al.</i> (2003)
Salinia Coast Ridge belt-Sur Series Monterey Co.	Marble Pelitic mica schists Quartzite Amphibolite to granulite facies	Quartz diorite Tonalite Mafic rocks Granodiorite	At 25–33 km crustal levels At 6–15 km crustal levels	Ducea <i>et al.</i> (2009) (Crustal levels for plutonic rocks)

present structurally above the Nacimiento fault and east of the H–SS–SG fault zone in the PS area, contain Campanian (83.5–70.6 Ma) and Maastrichtian (70.6–65.5 Ma) fossils (Sutherland 1990; Hall 1991; Hall *et al.* 1995). In addition, the PiP Formation that crops out to the north and west of the H–SS–SG fault near Pescadero is possibly early medial to late Campanian in age (Saul and Squires 2008) (ca. 79 to ca. 71 Ma; Ward *et al.* 2012). The Upper Cretaceous pebble and cobble conglomerate and biotite-rich quartzofeldspathic sandstone of the PS area, east of the H–SS–SG fault contains conglomerate clasts of

granite, granodiorite, metasedimentary and metavolcanic rocks derived from the Sur Series (metamorphic ages of 130–108 Ma and 108–76 Ma). Trask (1926) reported a megafaunal assemblage from these strata that is considered to be Campanian to Maastrichtian in age (Saul and Popenoe 1962; Elder and Saul 1993; Grove 1993; Elder *et al.* 1998). Associated with the pebble and conglomerate beds are green and dark shale beds. The shale beds are interbedded with the conglomerate (Hall 1991, plate 1a). The shale units locally contain microfossils of Campanian age (Sutherland 1990, appendix E). Therefore, the

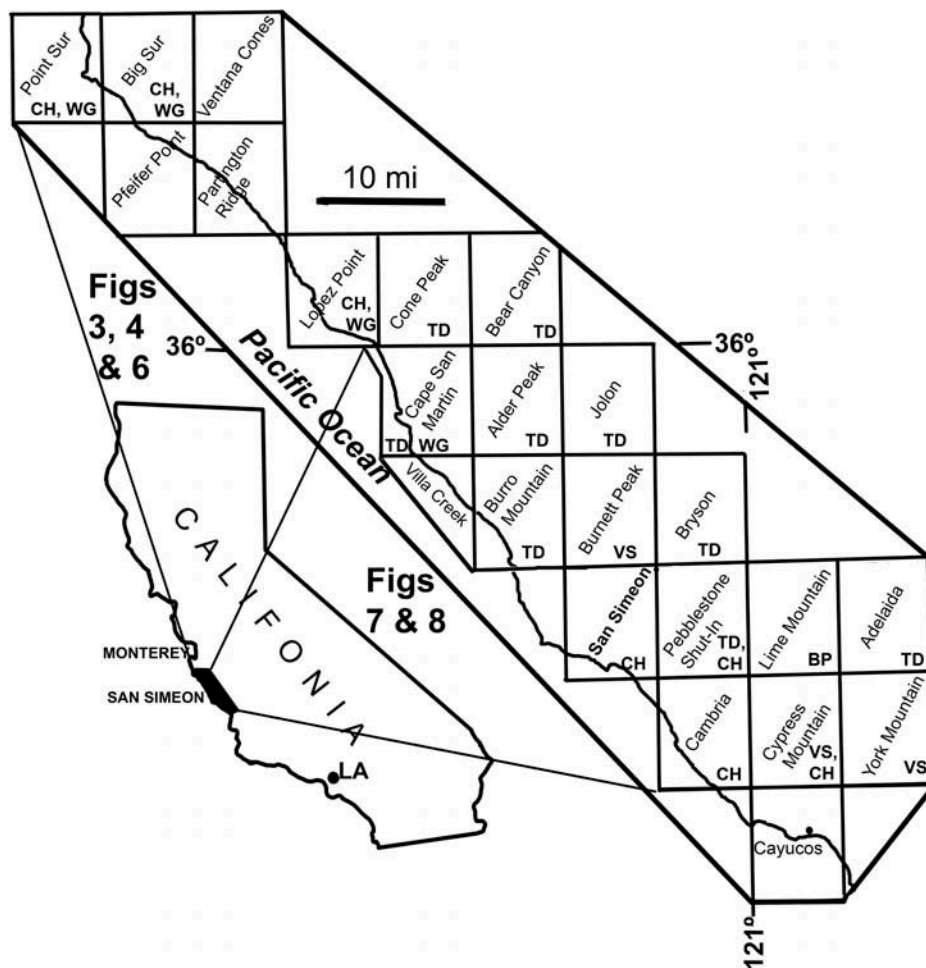


Figure 5. Index map for quadrangle and geologic mapping associated with Figures 3, 4, 6, 7, and 8 from Point Sur to near Cambria, Monterey, and San Luis Obispo counties. Abbreviations are: BP, Ben Page, Page (1970a, 1970b, 1972); CH, Clarence Hall, Hall (1974, 1991); Hall *et al.* (1979, 1995); TD, Tom Dibblee, Dibblee (2006a, 2006b, 2006c, 2007a, 2007b, 2007c, 2007d, 2007e); VS, Victor Seiders, Seiders (1982, 1989); WG, Wyatt Gilbert, Gilbert (1971).

supra-Salinian strata are not restricted to the Maastrichtian stage, but are ca. 79 to ca. 71 Ma or to 65.5 Ma, Late Cretaceous Campanian to Maastrichtian in age, or from Turonian to Maastrichtian ages according to Barbeau *et al.* (2005).

Dickinson *et al.* (2005, p. 11, figure 6) assigned the Kuss and Kucg (Hall 1991, maps 1A and B) (Figures 4A and 4B), which crop out in the Pfeiffer-Big Sur State Park, to the upper Miocene Santa Margarita Formation (Oakeshott 1951), Miocene Big Sur Sandstone (Gilbert 1971, 1973), or unnamed Miocene sandstone (Dibblee 1999). There are no chert clasts in these rocks, as suggested by Oakeshott (1951); the clasts are siliceous argillite (Sutherland 1990). It is not clear why the palaeontologic data provided by Sutherland (1990) and Hall (1991) from rocks in the fault sliver referred to by Dickinson *et al.* (2005, p. 11, figure 6) were not

considered by them. Microfossils in the shale of the Upper Cretaceous interbedded sandstone and shale in these rocks include Late Cretaceous '*Planulina* sp. cf. *P. constricta*, *Gyrodidina* sp.?, *Cribratomoides* sp., and other less diagnostic Cretaceous forms (M.L. Cotton Thornton, 1990, written communication)' (Sutherland 1990, p. 27). These Campanian–Maastrichtian strata in the region east of the SG fault, PS and Andrew Molera State Park (the latter immediately adjoining Pfeiffer-Big Sur State Park) (Hall 1991, geologic maps 1a and b), are correlated here with the PiP Formation (e.g. Hall *et al.* 1959; Figure 1). The Upper Cretaceous rocks near PS in Monterey County crop out discontinuously from near Hurricane Point to near Grimes Point (Figure 3), from McWay Canyon to east of Dolan Point (Hall 1991, geologic maps 1a and b) and southward from near Gamboa and Lopez points (Figures 4–6) into SLO County. The Dickinson *et al.*

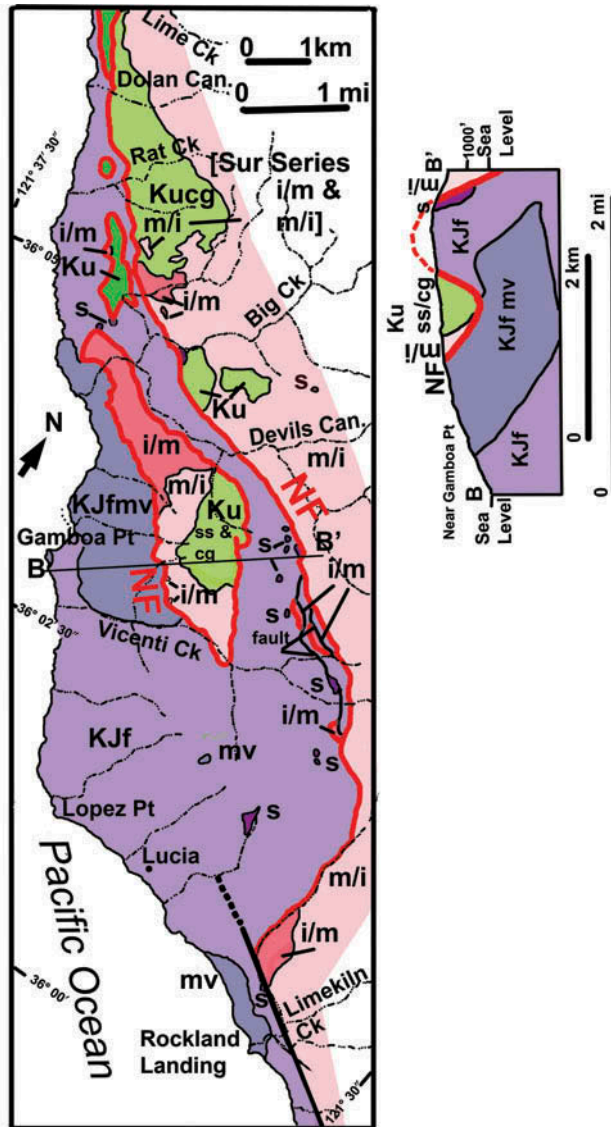


Figure 6. Pre-Quaternary geologic map of the Big Creek–Gamboa–Lopez Point region, Monterey County, depicting klippen near Gamboa Point. For abbreviations, see Figure 4A; for location, see Figure 3. After Hall (1991).

(2005) correlation of the Upper Cretaceous PiP Formation (PiP, Figure 1), west of the SG fault, with the Upper Cretaceous Atascadero Formation, SLO County east of the fault, is not unique.

Conclusion to point 3, PS–Big Sur terrane, Monterey County, offset to a similar stratigraphy at ANP–PiP–Pescadero Point, San Mateo County

Cumulative slip of 128 ± 2 km (80 ± 1.2 mi) on the H–SS–OWHF zone (i.e. 115–123 km or 72–76 mi) and the ReF (13 ± 2 km, 8 ± 1.2 mi) (see discussion of the ReF below), offset Upper Cretaceous strata in the PS–Esalen

region (Figure 3) in Monterey County to the PiP region (Figure 1) in San Mateo County.

(4) Point Lobos (PL) conglomerate, nonconformity, and granodiorite, Monterey County, offset northward to these types of rocks and geologic features near Point Reyes (PRe), Marin County

The PL conglomerate (Carmelo Formation) at PL (Figure 1) and the PRe Conglomerate (PRe, Figure 1) are both assigned a Penutian age (i.e. the conglomerate is late Palaeocene to early Eocene in age) (ca. 56 Ma) (Bowen 1965; Galloway 1977; Clark *et al.* 1984).

There are identical suites of distinctive pairs of matching felsic volcanic and plutonic clasts in the Carmelo Formation and PRe Conglomerate that are of Late Jurassic Tithonian Age (151.6 ± 2.6 – 145.5 Ma) (Burnham 1999, 2005, 2009).

The two formations display similar sedimentary structures, matrices, and sandstone petrology (Burnham 2009).

Both formations nonconformably overlie Late Cretaceous granodiorite. At PL, the granodiorite is dated at 82 Ma and at PRe it is radiometrically dated at 79.5 Ma (Burnham 2009) (Figure 1).

The conglomerate and granodiorite at and near PL, east of the H–SS–SG fault zone, have been offset northward 150 to 185 km (93 to 115 mi) to PRe, west of the H–SS–SG fault zone according to Burnham (2005). Burnham (2009, p. 206) concluded:

The Point Reyes Conglomerate and the Carmelo Formation in the vicinity of Point Lobos ... are separated by 175–185 km, and due to uncertainties of channel configuration, the post-sedimentation offset distance could be as little as 150 km or as much as 185 km. The larger offset is preferred, because the smaller offset reduces the likelihood that the 2-meter boulders of porphyritic granodiorite of Monterey from the vicinity of Point Lobos could have been deposited at Point Reyes.

Dickinson *et al.* (2005, p. 28) rejected the Burnham (2009, p. 206) correlations (i.e. the 175–185 km of dextral slip along the northern San Andreas–San Gregorio fault zone). Burnham (2009, p. 218) countered the Dickinson *et al.* (2005, p. 28) arguments. Some arguments by Dickinson *et al.* (2005) require comment here, namely their following analysis:

Dextral offsets as great as 180 km across the San Gregorio–Hosgri fault are additionally disfavored by the modification that would be required to the tectonic reconstruction of figure 10 [their 2005 figure] depicting only 155 km of net slip. The greater slip magnitude of 180 km would place the granodiorite of the Inverness Ridge [near Point Reyes] and the tonalite of Tomales Point (fig. 10) [just north of Inverness] 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 strontium isotopic ratios for Salinian granitic plutons (Dickinson *et al.* 2005, p. 28, figure 10).

Dickinson *et al.* (2005, p. 28, figure 10) restored the granitic rocks of Inverness Ridge to a latitude near the middle of Monterey Bay, and the 'ridge' did not abut outcrops above sea level. They provided the following initial strontium isotopic ratios for the Inverness Ridge: '0.7062' and '0.7076'. Dickinson *et al.* (2005, figure 10) gave ratios for samples from Monterey Bay of: '0.7087' and '0.7072'. Thus, there are maximum and minimum discrepancies of 0.0025 and 0.0004, respectively between their 'ridge' and bay samples. The initial strontium isotopic ratio for two samples of granitic rocks from the Monterey Peninsula, shown in their figure 10, is 0.7079; thus maximum and minimum discrepancies between their 'ridge' samples and the peninsula sample are 0.0008 and 0.0007; these discrepancies are substantially less than the 0.0025 discrepancy between 'ridge' and bay samples. In addition, Dickinson *et al.* (2005, figure 10) showed initial strontium isotopic ratios for granitic rocks south of their bay and peninsula samples (i.e. in the Santa Lucia Range, Sur Series–Coast Ridge belt) as 0.7076, which are identical to their 'ridge' sample west of the Hosgri fault, thus suggesting offsets of greater than 155 or 156 km (~ 96 mi).

Tonalite at Tomales Point (100 Ma tonalite, Tomales Point, Hall 2002, map 1A), if back-slipped ~ 175 km (108 mi), would also place these rocks at the latitude of PL (south of Monterey Bay); thus, the Dickinson *et al.* (2005, p. 28) correlation of the PR granitic rocks and granitic rock of mid-Monterey Bay, using offset figures of 155–156 km (96–97 mi), is not unique. One-hundred-million-year-old tonalite is also present in the Sur Series–Coast Ridge belt south of Monterey (e.g. 16.5 km or ~ 10 mi south of PL, near Notley's Landing and at Partington Point, Figure 3) (Compton 1960; Ross 1976; Kistler and Champion 2001; Ducea *et al.* 2009). Neither petrology nor isotopic ratios rule out the ~ 175 km (~ 108 mi) correlation between PR and PL proposed by Burnham (2009, p. 206).

Even though Clark (1998) and Dickinson *et al.* (2005, p. 33) described the striking similarities between the geology at PL in the Monterey region and PR north of San Francisco, they concluded that these rocks are offset by 150–160 km (92–99 mi) (Clark 1998) and ~ 155 km (~ 96 mi) (Dickinson *et al.* 2005, p. 23) of dextral slip, not 175–185 km (108–115 mi) (Burnham 2009, p. 206), along the H–SS–SG fault zone.

In order to justify the ~ 155 km or $\sim 156 \pm 4$ km (96 ± 5 mi to 97 mi) (Dickinson *et al.* 2005, p. 33) offset of the PL and PR rocks, they reject including the 44 ± 4 km (27 ± 2.5 mi) (Graham 1976, 1978), 60 km (~ 40 mi) (Dibblee 1976), 46 ± 6 km (29 ± 4 mi) (Dickinson 1996), and 45 km (28 mi) (Powell 1993) offset of Upper Cretaceous–Palaeocene basal conglomerate and offset of

a twenty-million-year-old palaeo-shoreline along the NW trace of the Rinconada–ReF (ReF, REHF, Figure 1), into Monterey Bay, and converging with the SH–SS–SG fault zone.

The Reliz–Rinconada fault zone

The Rinconada–East Huasna fault zone (REHF, Figure 1) has been continued northwestward to the ReF zone (Figure 1) and into the Monterey Bay fault zone (M, Figure 1), as first suggested by Martin and Emery (1967) and Ross and Brabb (1973), and as shown on maps by McCulloch and Greene (1990, map 5A), Greene (1990, figures 5, 8, and 10), Greene and Hicks (1990, figures 5, 11, and 12, based on water wells; figure 14, p. 245, near Marina, Ma, Figure 1), Chapman *et al.* (1990), Greene *et al.* (2002, figure 1a and tip-in map), a fault activity map (Jennings and Saucedo revised by Topozada and Branum (2002), and Rosenberg and Clark (2009, map 3059).

Dickinson *et al.* (2005, p. 33) concluded: 'Rinconada displacement has been absorbed by deformation within the Salinian terrane without transfer of significant Rinconada slip to the offshore San Gregorio–Hosgri fault trend'. Dickinson *et al.* (2005) also reduced slip on the ReF–Rinconada fault zone by 9 km (~ 6 mi) (i.e. from 44 km (27 mi) near Paso Robles (PR, Figure 1) to 35 km (22 mi) near Monterey). Their basis for the reduction is based on offset outcrops and subcrops of schist (Dickinson *et al.* 2005, p. 36).

Rosenberg and Clark (2009, p. 24) concluded that there has been cumulative dextral slip of 38 km (24 mi) on the central Rinconada fault (i.e. dextral slip beginning in late Miocene time of 20 km (12 mi), and since early Pliocene time, another 18 km (11 mi).

Titus *et al.* (2011) studied aseismic deformation along the ReF–Rinconada fault from PR north to Greenfield (Gre, Figure 1). Greenfield is southeast of Monterey Bay, and it is located 53 km (33 mi) southeast of Salinas. Titus *et al.* (2011) determined clockwise rotations of strata of 15° – 25° near the northwest and central parts of the Rinconada fault, and that creep along this segment of the fault has been occurring for several million years, thus suggesting that the central part of the Rinconada fault is active.

Rosenberg and Clark (2009) noted that north of Arroyo Seco, the ReF zone steps right south of the Monterey Bay fault zone, nearly aligning with the Rinconada fault zone that is present to the southeast. However, they concluded that the ReF is mostly a reverse-slip fault that is independent of the Rinconada fault zone. They concluded that 'strike-slip along the ReF zone is lacking' and that 'there has been no more than 23 km, and possibly less' dextral slip along the fault (Rosenberg and Clark 2009, p. 24).

Rosenberg and Clark (2009, p. 24) concluded that dextral slip along the Rinconada fault is partitioned into the

Salina terrane and ‘some, if not all, of the strike-slip motion (16–40 km) along the Rinconada fault zone may have been partitioned northwestward into the Salinian terrane via the Tularcitos fault of upper Carmel Valley’. Dickinson *et al.* (2005, p. 35) concluded that there is a dextral slip of no more than 5 km (3 mi) along the Tularcitos fault that could be transferred to the Navy fault (Monterey Bay fault zone) and, thus, transferred to the offshore H–SS–SG fault zone through Monterey Bay. The conclusions of Rosenberg and Clark (2009) and Dickinson *et al.* (2005) regarding strike-slip along the Rinconada fault are adopted here.

The role of the distribution of the PiP Formation between Pescadero and ANPs in determining the amount of dextral slip along the H–SS–SG fault zone northward between Monterey Bay and the San Francisco Peninsula

Based, in part, on an offshore Shell exploratory well, an unnamed offshore fault, and a ‘northern structural discontinuity’, Dickinson *et al.* (2005, p. 20, figures 3 and 4) favoured 156 ± 4 km (97 ± 2.5 mi) of offset of the trace of Nacimiento fault along the H–SS–SG fault zone. These authors concluded that this fault zone offsets two piercing points. Their points are: (i) a structural discontinuity mapped in the offshore by Chapman *et al.* (1990), which is near Half Moon Bay, north of Pescadero Point and PiP (Figure 1), and south of the San Francisco Peninsula (Dickinson *et al.* 2005, figure 4, piercing point NPP₁) and (ii) near Esalen (Nomland and Schenck 1932) (Figure 3), south of Grimes Point, south of PS (Dickinson *et al.* 2005, figure 6) (Figure 3), and 156 km (97 mi) south of the NPP₁ structural discontinuity.

Two exploratory oil wells were drilled west of ANP (Figure 1) (Shell OCS P-035 # 1) (ANP, Figure 1) and generally west of Pescadero Point (Shell OSC P-036 #1), San Mateo County. These wells were drilled in 1967 as part of a lease sale in 1963. Shell OCS P-035 # 1 was drilled ~13 km (8 mi) W–SW of PiP (PiP, Figure 1) and Shell OSC P-036 #1 was drilled 23 km (14 mi) approximately due west of Pescadero Point (Heck *et al.* 1990, figures 1 and 2 for locations). The bottom 160 m (526 ft) of the well log for Shell OCS P-035 # 1 is the PiP Formation (Webster and Yenne 1987; Heck *et al.* 1990, p. 149). In Shell OSC P-036 #1, a lower part of the well log [at depths 2417–2073 m (7930–6800 ft), or a thickness of 344 m (1130 ft)] is taken to be the Oligocene–Miocene Mindego Formation (Webster and Yenne 1987; Heck *et al.* 1990, p. 148). Beneath the Mindego Formation are 1060 ft [at depths of 2530–2853 m (8300–9360 ft)] of the PiP Formation. The bottom 40 m (130 ft) of the well log for Shell OSC P-036 #1 is also taken to be the PiP Formation (Webster and Yenne 1987; Heck *et al.* 1990, p. 148). In addition, these authors noted on page 148:

A core at bottom hole recovered 17 ft of light gray medium gray, dense, hard, silica cemented sandstone with dark brown silt pods. This core was abundantly veined with calcite.

Dickinson *et al.* (2005, p. 19) examined the 5.18 m (17 ft) of core at the bottom of the drill hole, and in a detailed analysis, determined that the bottom 5.18 m (17 ft) of the well log/core was the Franciscan Complex and not the overlying PiP Formation. Thus, the Nacimiento fault was encountered at a well depth of either 9360 ft or 9473 ft (i.e. $130 - 17 \text{ ft} + 9360 \text{ ft}$) between the Franciscan Complex and the PiP Formation. This is the NPP₂ piercing point of Dickinson *et al.* (2005, figure 4) near ANP (Figure 1), south of PiP (Figure 1) (see Mullins and Nagel 1981; Nagel and Mullins 1983; McCulloch 1987, 1989a, 1989b; Chapman *et al.* 1990).

The Upper Cretaceous PiP Formation (Figure 1) and the ANP (Figure 1)–Nacimiento piercing point, San Mateo County, are here correlated with the Upper Cretaceous strata and Nacimiento piercing point near Grimes Point and Esalen (Figure 3), Monterey County, which is present 128 ± 2 km (80 ± 1.2 mi) to the south.

The discontinuity proposed by Chapman *et al.* (1990) and its piercing point with the H–SS–SG fault zone near Half Moon Bay, San Mateo County, i.e. NPP₁ of Dickinson *et al.* (2005, figure 4), represents the contact between the igneous and metamorphic rocks of the Sur Series–Coast Ridge belt and the SW-dipping contact of the nonconformably overlying Upper Cretaceous PiP Formation, not the Nacimiento fault.

Conclusion to point 4, PL conglomerate, unconformity, and granodiorite, Monterey County, offset northward to these types of rocks and geologic features near PR, Marin County

There has been cumulative dextral slip of 128 ± 2 km (80 ± 1.2 mi) [i.e. 100 km (62 mi) on the H–SS fault zone, 15 km (9 mi) on the OWHF zone that merges with the H–SS fault zone, and 13 ± 2 km (8 ± 1.2 mi) of dextral slip on the ReF zone (ReF, Figure 1)]. The reduction of the < 23 km (14 mi) of dextral slip suggested by Rosenberg and Clark (2009, p. 24) to 13 ± 2 km (8 ± 1.2 mi) (above) is based on the correlation of the 128 ± 2 km (80 ± 1.2 mi) offset between the southern structural discontinuity near ANP (SSD, ANP, Figure 1) and the Nacimiento fault near Grimes Point (Figure 3). To this 128 ± 2 km (80 ± 1.2 mi) of cumulative offset is added 43 km (27 mi) on the PiF (see discussion of the PiF below), for a total cumulative offset on the Hosgri–San Simeon–West Huasna–Reliz–Pilarcitos fault system of 171 ± 2 km (106 ± 1.2 mi), in general agreement with the 175–185 km (108–115 mi) offset of the

Carmelo Formation (at PL) and PR conglomerate proposed by Burnham (2009, p. 206).

(5) Strata near San Francisco offset to similar strata near Anchor Bay and Gualala, Mendocino County

Note that the conclusions regarding offsets associated with points 5–7 follow the discussion of offset piercing points of point 7.

Burnham (1998, 2009, e.g. figures 2, 3, and 4) reported more than 180 km (112 mi) of dextral offset of Upper Cretaceous strata along the combined traces of the northern San Gregorio and NSAFs between Anchor Bay, near Gualala in Mendocino County (Figure 1), on the west side of the NSAF, and strata of the same age near Skyline Highway–Highway 92 on the San Francisco Peninsula in San Mateo County (Figure 1), on the east side of the San Gregorio fault and west of the PiF (Figure 1). Her arguments further support interpretations of more dextral slip offset for the northern part of the Hosgri–San Simeon–San Gregorio–Pilarcitos fault zone than the ~156 km (97 mi) proposed by Dickinson *et al.* (2005).

Dickinson *et al.* (2005) regarded the rocks at PAR (Figure 1), in the Gualala terrane, as a fault sliver between their inferred offshore Gualala fault and the SAF. An inferred Gualala fault is required in their palinspastic reconstructions so as to limit the maximum total slip along the H–SS–SG fault zone to ~156 km (97 mi), and to account for the slip deficit between the northwestern boundary of Salinia, west of the SAF, and the granitic rocks in the SEM–TM (Figure 1) at the southern end of the Sierra Nevada and San Joaquin Valley, east of the SAF by about 125 km (78 mi). The inferred presence of the Gualala fault is also required by them to discount the notion that Salinian rocks have been underthrust by Jurassic ophiolite. However, these interpretations are in question owing to the following: (i) Jachens *et al.* (1998, figure 12) and McLaughlin *et al.* (1998) palinspastically restored the PAR region, or the Gualala terrane, with the Santa Cruz Mountains south of San Francisco, and they inferred that Salinian granitic rocks have been underthrust by mafic masses or ophiolite; (ii) Jachens *et al.* (1998) disputed the presence of the Gualala fault [as inferred by Dickinson *et al.* (2005)]; (iii) McCulloch (1989a) depicted a fault zone that is subparallel and 2 km (~1 mi) or more west of the main trace of the SAF zone and PAR. However, McCulloch's (1989a) fault zone in the offshore region west of PAR passes through BH (east of the granitic rocks at the headland) and into Tomales Bay and does not demonstrate lateral slip (McCulloch 1989a). Dickinson *et al.* (2005) did not project their inferred Gualala fault through BH (Figure 1) and offset granitic rocks, apparently to avoid their Gualala fault from being the northern extension of the H–SS–SG fault zone (see Dickinson *et al.* 2005, figure 14D).

(6) Mindego Basalt or volcanic rocks, San Mateo and Santa Cruz counties offset as the Iversen Basalt, Mendocino County

Not shown by Dickinson *et al.* (2005, p. 22, figure 10) is the distribution of the 23.8 Ma Iversen Basalt, Mendocino County, near the NSD (Burnham 2009, figure 5) and the correlated 20.2 ± 1.2 Ma Mindego basalt, San Mateo County [distribution from Stanley (1990, figure 15), near Montara Mountain, and Burnham (2009, figure 5)]. The units are separated by the San Gregorio–Pilarcitos–NSAF system by ~200 km (~124 mi) (Springer 2002). Dickinson *et al.* (2005, p. 27) mentioned the 'attractive correlation' between these units (the documentation for the correlation is summarized by Loomis and Ingle (1994, p. 927). However, Dickinson *et al.* (2005) concluded that the correlation is not 'unique', and therefore, rejected the correlation because it does not fit their model of 155 or 156 km (96 or 97 mi) of slip on the northern H–SS–SG fault zone. As a corollary, they rejected the documented offset of 180 ± 5 km (112 ± 3 mi) (Burnham 2009, p. 206) and the offset of ~200 km (~124 mi) proposed by Springer (2002) along the SG–PiF–NSAF zone.

(7) Granitoid and Franciscan rocks in the Pilarcitos–SAF zone, San Francisco and San Mateo counties, offset to similar rocks and structures in Mendocino County

As mentioned above, the NSD or northern structural discontinuity (Figure 1) is considered by some geologists to be equivalent to or include the Nacimiento fault zone (i.e. it is the fault that separates Cretaceous strata at PAR from the Jurassic ophiolite, and separates Mesozoic granitic rocks from the Mesozoic Franciscan mélange). The granitic rocks associated with the NSD, offshore from Mendocino in northern California, are on the west side of the SAF system and 610–675 km (379–420 mi) north of granitic rocks within the southern part of the SEM–TMs, east of the SAF. Thus, structural and stratigraphic relationships associated with the Nacimiento discontinuity are critical to understanding not only the amount of dextral slip on the Hosgri–San Simeon–San Gregorio–Pilarcitos–NSAF zone, but also the solution to the enigma of Salinia.

Burnham (2009, p. 218) and authors cited by her correlated: (i) the eastern part of the NSD, near Cape Mendocino, with the PiF zone in San Francisco and San Mateo counties; (ii) the conglomerate at Anchor Bay, Mendocino County, with the Skyline–Highway 92 conglomerate near San Francisco; and (iii) the magnetic anomalies at Black Point, Marin County, with a location south of the hamlet of SG, from which she concluded that the correlated pairs constrain offset on the northern San Gregorio–NSAF zone to greater than 175 km (109 mi).

Graham and Dickinson (1978a), McCulloch (1987, 1989a), Hall *et al.* (1995), Wakabayashi (1999, figure 4),

Hall (2002), and Burnham (2009, p. 218) supported correlation between the NSD and the splay of the PiF and main trace of the SAF. Burnham (2009) summarized her earlier correlations and conclusions; also, see the discussion of the Anchor Bay Gualala conglomerate and Iversen basalt correlations above. However, Dickinson *et al.* (2005, figure 10) did not consider that the NSD is a reflection of the Nacimiento fault.

Dickinson *et al.* (2005, p. 30) reviewed the tectonic history of the PiF (Figure 1) and accepted proposals that the active trace of the SAF near San Francisco has accommodated 26 ± 4 km (16 ± 2.5 mi) of net strike-slip. They proposed that this slip occurred in the past 1.0–1.75 million years on the main trace of the SAF, and that earlier SAF system strike-slip occurred along the branching PiF, also near San Francisco. They rejected the conclusion of Wakabayashi (1999, p. 1250, based largely on the research of K. Burnham and others) that: ‘post-Late Cretaceous dextral displacement along the PiF of >15 km is not permitted by the location of the conglomerate outcrops (i.e. at Gualala/Anchor Bay and Skyline–Highway 92), because such a displacement would restore the Gualala conglomerate (Mendocino County) and ‘Pilarcitos conglomerate,’ Skyline Drive–Highway 92 (San Mateo County), a key correlation of Burnham (2009, figure 5) to support her calculation of slip on the SAF system.

McLaughlin *et al.* (2007) concluded the following regarding the PiF:

... the distinctive Santa Clara Formation strata [3.3 Ma] west of the MSAF [modern San Andreas fault] are also underlain by 5.4–7.0 Ma marine Purisima Formation and by middle Miocene and older marine strata. Along the east side of the MSAF the northwesternmost exposures of the Purisima Formation underlain by Miocene marine strata are 74 km [46 mi] southeast of this pull-apart wedge, in the vicinity of the Sargent oil field northwest of Hollister. This relation requires 43 km [27 mi] of pre-MSAF slip to have been taken up by a segment of the PF [Pilarcitos fault] that we propose bounds the Miocene strata in the fault wedge between the main PF and MSAF.

Summary of cumulative dextral slip along faults in the SAF system west of the main trace of the SAF discussed in points 1–7

There has been approximately 171 km (106 mi) of cumulative, dextral slip on the Hosgri–San Simeon–West Huasna–Oceanic–Reliz–San Gregorio–Pilarcitos fault system. The amount of cumulative dextral slip on these faults plus the NSAF (i.e. north of San Francisco) is ~ 200 km (~ 124 mi) as follows: (i) ~ 100 km (~ 62 mi) on the H–SS fault zone; (ii) 15–23 km (9–14 mi) on the OWHF zone; (iii) 13 ± 2 km (8 ± 1.2 mi) on the ReF; (iv) 43 km (27 mi) on the PiF zone for a total of 171 ± 2 km (106 ± 1.2 mi) (Table 5). If the NSAF zone is included, then dextral slip on this system totals 200 km (124 mi). If the cumulative slip

of 171 km (106 mi) or the dextral slip of 200 km (124 mi) is added to the cumulative dextral slip of 315–322 km (196–200 mi) on the main trace of the SAF north of the TMs (Figure 1), then there is a minimum amount of cumulative dextral slip of 486 km (302 mi) or a maximum amount of cumulative dextral slip of 522 km (324 mi) along the entire SAF system north of the TMs. When these sums are compared with the separation between granitic rocks associated with the NSD (Mendocino County) and granitic and associated rocks in the SEM–TMs (Kern County) [i.e. 610–675 km (379–420 mi)], then there is a minimum deficit of 88 km (i.e. $610 - 522$ km) [55 mi ($379 - 324$ mi)] or a maximum deficit of 189 km (i.e. $675 - 486$ km) [118 mi ($420 - 302$ mi)] (see Table 5 for other alternative minimum and maximum deficits) needed to restore granitic rocks associated with the NSD with granitic rocks within the SEM–TMs – the enigma of Salinia.

Along the southern part of the main trace of the SAF system, south of the WTRs, dextral slip on the main trace of the SAF amounts to 210–245 km (130–152 mi). However by adding 75 km (47 mi) of slip from the San Gabriel–Canton fault system (Crowell 2003) (SGF, Figure 1) to the 210–245 km (130–152 mi) offset, there is a cumulative dextral slip of 320 km (199 mi), which is comparable to the 315 km (196 mi) of offset along the central part or main trace of the SAF.

Salinia’s place of origin and theories to account for the mismatch of palinspastically restored terranes

It is not possible to restore Salinia to its pre-Neogene location by simply removing the measured strike-slip between piercing points along faults within the SAF system in order to align the northern distal part of Salinia [i.e. the NSD ~ 125 km (78 mi) north of PR] with granitic and associated rocks in the southern tail of the Sierra Nevada batholith and SEM–TMs. Backslipping Mesozoic igneous rocks in Salinia, based on all offsets of piercing points within the SAF system, also juxtaposes somewhat younger igneous rocks of Salinia in the northwest with older igneous rocks in the southern Sierra Nevada, as well as not bringing the northwesternmost region of Salinia into alignment with the southern Sierra Nevada. We also add here that by study of Figure (2A), and as asserted in Saleeby (2007, 2012), Sierran batholithic rocks extend far to the west into the Great Valley subsurface. Considering that the SEM–western TMs are recently emergent from beneath the southern San Joaquin Basin above blind thrusts (Davis and Lagoe 1988; Chapman and Saleeby 2012), the term ‘Sierran tail’ is somewhat of a misnomer.

Western boundary of Salinia

Strongly associated with various models regarding the place of origin of Salinia are interpretations involving the

Table 5. Minimum and maximum right lateral strike-slip fault system, SAF system, and the separation between the NSD and the TMs.

Minimum right slip Km	Maximum right slip Km	Minimum right slip Mi	Maximum right slip Mi
Hosgri–San Simeon fault zone	Hosgri–San Simeon fault zone	Hosgri–San Simeon fault zone	Hosgri–San Simeon fault zone
100	100	62	62
OWHF	OWHF	OWHF	OWHF
15	23	9	14
ReF	ReF	ReF	ReF
13	<23	8	<14
PiFzone	PiFzone	PiF zone	PiF zone
43	43	27	27
Subtotal cumulative slip	Subtotal cumulative slip	Subtotal cumulative slip	Subtotal cumulative slip
171	189	106	117
Main trace SAF	Main trace SAF	Main trace SAF	Main trace SAF
315	322	196	200
Total cumulative right slip SAF system	Total cumulative right slip SAF system	Total cumulative right slip SAF system	Total cumulative right slip SAF system
486	511	302	317
Minimum separation between NSD and granite western TMs	Maximum separation between NSD and granite western TMs	Minimum separation between NSD and granite western TMs	Maximum separation between NSD and granite western TMs
610	675	379	420
Minimum difference between total cumulative slip and separation 610 – 511 = 99	Maximum difference between total cumulative slip and separation 675 – 486 = 189	Minimum difference between total cumulative slip and separation 379 – 317 = 62	Maximum difference between total cumulative slip and separation 420 – 302 = 118

nature and history of the western boundary of Salinia, a boundary between Salinian granitic rocks and the Franciscan Complex, along with the sense and history of movement along the Nacimiento fault (e.g. Gilbert 1971, 1973; Page 1981, 1982; Dickinson 1983; Hall 1991, 2002; Hall *et al.* 1995; Dickinson *et al.* 2005; Ducea *et al.* 2009; Jacobson *et al.* 2011).

Four interpretations of the nature of the boundary discussed in numbered topics below are: (i) dextral slip of (a) 2100–2500 km (1305–1554 mi) or more (Champion *et al.* 1984) along unnamed faults or (b) 90 km (56 mi) or more of dextral slip on the Nacimiento fault (Vedder *et al.* 1991, p. 951); (ii) sinistral strike slip of 500–600 km (311–373 mi) on the Nacimiento fault (Dickinson 1983; Seiders and Blome 1988; Dickinson *et al.* 2005; Jacobson *et al.* 2011, figure 10); (iii) thrusting along the K–T Nacimiento fault (Page 1967, 1969, 1970a, 1970b, 1972, 1982; Silver 1982, 1983; Hall 1991; Page and Brocher 1993; Hall *et al.* 1995; Barth and Schneiderman 1996; Saleeby 1997, 2003; Yin 2002; Barth *et al.* 2003; Kidder and Ducea 2006; Ducea *et al.* 2009; Namson and Davis 2012); and (iv) as a corollary to (iii) above, the Nacimiento

fault was a low-angle subduction megathrust surface along which the Sur-Obispo Franciscan belt was subducted, and then partially extruded back out along which promoted the observed upper plate (Salinia) extension and subsidence to marine conditions in Maastrichtian time (after Grove 1993).

In order to decipher the Late Cretaceous to Palaeogene geologic history of western and southern California, it is also necessary to understand (i) the origins and ages of the SdS (Figure 1) and Rand schists (Figure 2B); (ii) the role of the Nacimiento fault in the geologic history of the southern Coast Ranges of southern California (see references above); and (iii) how to account for the removal of arc and forearc terranes along the Nacimiento fault.

Dextral slip: (1a) 2100–2500 km (1305–1554 mi) or more (Champion *et al.* 1984) along unnamed faults in western California, or (1b) 90 km (56 mi) or more of dextral slip on the Nacimiento fault

(1a) The terrane-accretion model proposes that since Late Cretaceous time, much of western California, particularly

Salinia and the rocks west of it, was transported thousands of kilometres (2100 km or 1305 mi or more) northward from southern Mexico to their present position (Champion *et al.* 1984). After this lengthy trip, the proposed exotic terranes or regions of rocks that had been carried to the north were accreted to California prior to being sliced by movement along the SAF system. Proponents of accreted or exotic terranes in western California have argued that there is not a match between the northern part of Salinia and the granitic rocks in the southern Sierra Nevada after restoring offset along the SAF because the granitic and metamorphic rocks in Salinia are unrelated (i.e. in their view, the rocks at PAr and PR were never juxtaposed with those in the southern part of the Sierra Nevada batholith) (e.g. Champion *et al.* 1984).

Nilsen (1987) also inferred a palaeogeography in which such Mesozoic basins as the pre-Gualala, PiP, Santa Lucia, Santa Maria, and Santa Ynez basins of western California are all accreted terranes.

The hypothesis of accreted terranes fails on several accounts: (i) the age, chemistry, and stratigraphy of the metamorphic and granitic rocks in Salinia can be correlated with rocks in the southern Sierra Nevada and Mojave Desert regions on the east side of the SAF; (ii) there is no known source for the granitic rocks in Salinia thousands of kilometres to the south; (iii) the palaeomagnetic evidence, reported by members of the United States Geological Survey, which supported the notion that terranes of the coastal area of California are far-travelled, is considered by other geophysicists and geologists to be spurious (see Butler *et al.* 1991; Smith and Busby 1993; Dickinson and Butler 1998 for the history of the exotic, far-travelled-terranes theory, and the geophysical data that nullify the far-travelled-accreted-terranes model); and (iv) detrital-zircon age peaks identified in the metamorphic rocks within the Sur Series or the Santa Lucia basement rocks contain several Precambrian age peaks that indicate that detritus in the Sur Series and Salinia are from the Mojave Desert and Peninsular Ranges regions, not from southern Mexico (Barbeau *et al.* 2005).

(1b) Vedder *et al.* (1991, p. 951) concluded: ‘... a 5 km-wide belt of coarse-grained Eocene strata unlike the Eocene mudstone near upper Pine Creek persist for 90 km along the NE side of the Nacimiento fault zone between Garcia Ridge and Madulce Peak [‘NF’, Figure 1]. This difference implies that post-Eocene dextral slip along the fault has been 90 km or more’. Burnham (2009, figure 7, pp. 221–224 and p. 252) agreed with Vedder *et al.* (1991) that there has been dextral slip of 90 km (56 mi) or more on the Nacimiento fault between 36.6 and 23.7 Ma. However, Page (1970b), Graham (1978), and Dickinson *et al.* (2005, p. 15) noted that thrusting (Page 1970b) or ‘slip’ (Dickinson *et al.* 2005) along the Nacimiento fault occurred prior to latest Oligocene to early Miocene time (i.e. the fault is locally covered by the Vaqueros Formation

of this age range) (e.g. Hall *et al.* 1979). The Nacimiento fault is offset by the dextral Neogene Rinconada fault and its southern continuation, the East Huasna fault (Hall *et al.* 1995; Dickinson 1996), which passes to the west of Stanley Mountain (Hall and Corbató 1967).

Dickinson *et al.* (2005, p. 14) ruled out dextral slip along the Nacimiento fault because there is not a geologic setting similar to Salinia to the north to which an outboard displaced Salinia sliver could have been transported.

Conclusion for points 1a and 1b, the dextral-slip models. The Nacimiento fault of Vedder *et al.* (1991, figure 4) is a branch of the REHF zone, along which Oligocene or younger dextral slip occurred. A structurally weakened Nacimiento fault zone was reactivated along this zone, but the fault is not the Late Cretaceous–Palaeocene Nacimiento fault *sensu stricto*. Terminology for the fault cited by Vedder *et al.* (1991) was perpetuated by Rosenberg and Clark (2009, figure 2) (i.e. the latter’s ‘Nacimiento section’ of the Rinconada fault zone is not the Nacimiento fault *sensu stricto*). Langenheim *et al.* (2009, map) depicted the southern part of the Nacimiento fault zone as the REHF zone. Near its southeastern termination by the Big Pine fault, Kellogg *et al.* (2008) depicted the Nacimiento fault as a reverse fault with a relatively sinuous trace and a SW dip; this is the model adopted here.

(2) The western boundary of Salinia as a sinistral fault

Dickinson (1983, figure 10), Dickinson *et al.* (2005, figure 1), and Jacobson *et al.* (2011, figure 10, adapted from Dickinson 1983) concluded that the Nacimiento fault is a pre-Neogene, sinistral fault, along which the western Peninsular Ranges, west of the Nacimiento fault, moved southward from the San Andreas restored Salinia and Mojave regions during Late Cretaceous (Maastrichtian age) to Palaeocene time (earlier than 70.6 to 55.8 Ma). Dickinson *et al.* (2005, p. 14) ruled out Salinia being thrust over the Franciscan Complex or underplated by the complex because of: (i) the steep attitude of the Nacimiento fault; (ii) the absence of rock assemblages along the western flank of Salinia that are analogous to assemblages along the western flank of Sierra Nevada; and (iii) the distribution of detrital zircons, they conclude, suggests that the Franciscan Complex and SdS schist (Figure 2B) are of different ages and that the zircons are not from the continental interior.

Regionally, there are several points, which have been suggested by others, counter to the notion that the Nacimiento fault is a sinistral fault with 500–600 km (310–373 mi) of sinistral slip, as suggested by Dickinson *et al.* (2005). These arguments include the following.

- (1) Detrital zircon ages from the Franciscan mélange near SS, in the central coastal region of California, and the SdS schist, from Salinia, are similar

(A. Chapman, written communication, 2013). These detrital zircons, together with detrital zircons reported from the Upper Jurassic–Lower Cretaceous dominantly mudstone, with some sandstone and rare conglomerate of the Toro Formation present in Salinia, central California Coast Ranges, which are dominated by input from the continental interior and from the Medial and Late Jurassic southern Sierra-Mojave arc (Johnston 2013), suggest a southern provenance.

- (2) Removing the proposed sinistral slip of the Nacimiento terrane in order to palinspastically restore the Nacimiento terrane would leave the terrane from 150 to 250 km (93–155 mi) to the north of its present location and juxtapose the terrane against the Franciscan Complex and the Great Valley Mesozoic rocks east of the SAF, ruling out sinistral slip (Jacobson *et al.* 2011, p. 499).
- (3) Also as noted by Jacobson *et al.* (2011, p. 499):

Long and Wakabayashi (2009) argued that accretionary rocks of these two regions do not make a good match. In particular, distinctive sequences within the Franciscan Complex east of the San Andreas fault, such as the Marin Headlands and Permanente terranes and Skaggs Springs schist (Wakabayashi 1999), have not been recognized within the Nacimiento block. (Wakabayashi, pers. comm.)

- (4) Another regional problem with the Nacimiento fault being a sinistral fault is that relative motion between the Farallon and North American plates was approximately normal to dextral slip during Late Cretaceous to Palaeocene time, rather than sinistral slip (Engebretson *et al.* 1985; Stock and Molnar 1988).
- (5) Still another regional problem with the Nacimiento fault being a sinistral fault is that:

... if the original block-bounding fault had been a [left] strike slip and/or high angle-reverse-slip fault, the western arc and forearc of the subduction system should be present elsewhere along the margin, and it has not been identified ... (Ducea *et al.* 2009, p. 11)

Conclusion to point 2, rejecting the western boundary of Salinia as a sinistral strike-slip fault

Based on several points discussed above, regional sinistral slip along the Nacimiento fault in the PS region in Monterey County is discounted; see Page (1970a, p. 685–686) and the topics below for additional bases for negating regional sinistral slip along the Nacimiento fault.

(3) The western boundary of Salinia as a thrust fault

- (1) Page (1967, 1969, 1970a, 1970b) first suggested that the Nacimiento fault is a major fault system, noting that the fault zone includes an assemblage of different types of faults with different ages (Page 1982). He noted that the Nacimiento fault separates Salinian rocks from the Franciscan Complex and proposed conveyor-belt-like eastward movement of Cretaceous oceanic crust, bounded on the east by a trench filled with Franciscan deposits that was pushed against or partly beneath an Early to mid-Cretaceous granitic continental edge (Page 1970a, 1970b, 1981, 1982). In his model, the Nacimiento fault represents the contact between the trench deposits of a Sur–Obispo terrane or the Franciscan Complex of the Nacimiento terrane, and the granitic/metamorphic magmatic arc, or Salinian terrane. Page (1970b) noted that thrusting along the Nacimiento fault occurred prior to Oligocene time. The Nacimiento fault does not offset rocks as young as Oligocene in Monterey and SLO counties [e.g. the Oligocene to lower Miocene Vaqueros Formation covers the fault near SLO (Hall *et al.* 1979, Sheet 3), and similar evidence is cited in Dickinson *et al.* (2005, p. 15)], whereas, the H–SS–SG fault zone offsets middle Miocene and younger strata.
- (2) The Nacimiento fault zone everywhere separates Salinian rocks from the Franciscan Complex. Locally and regionally, the dip of the fault is shallow (i.e. $<45^{\circ}$ – 60°), and locally and regionally the fault has a steeper dip. Where the dip is shallow, the field relations indicate that the Nacimiento fault is a thrust fault (Page 1970b, figure 7; Gilbert 1971, Plate III, figure J; Dibblee 1976, figure 21; Hall *et al.* 1995, Plate 1) (Figures 3 and 5–8). Where the dip of the fault (i.e. the Nacimiento fault zone) is steep, the field relations and regional geology indicate that the pre-Neogene fault plane of the Nacimiento fault has been locally and regionally steepened during Neogene tectonism (Gilbert 1971, plate II, Rockland Landing locally) (Figure 6). This inference is also based on the folded Neogene rocks in the Sur syncline (Monterey County) (Figure 4A) and the projection of fold axes in the syncline immediately to the SE, into older rocks bounded by the Nacimiento fault (Hall 1991, Plate 1a).

Page (1970a, p. 684, figure 8) and Jacobson *et al.* (2011, figures 2 and 4), along the Nacimiento fault in Monterey and SLO counties, depicted the trace of the Nacimiento fault to be sinuous, which can imply a shallow dip for the fault plane.

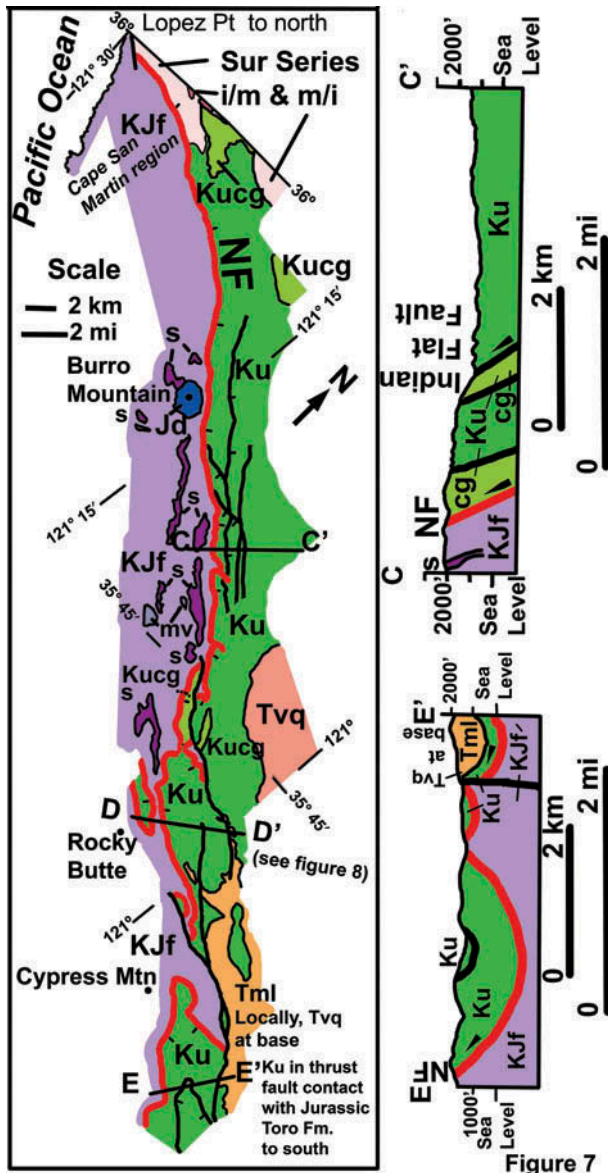


Figure 7. Trace of the Nacimiento fault (red), south of Lopez Point (Figure 6), from near Cape San Martin, Monterey County, to near Rocky Butte and Cypress Mountain, San Luis Obispo County. Upper Cretaceous rocks (Ku, Kucg) that nonconformably overlie the Sur Series north of the Cape San Martin region, see Figures 4 and 6, can be traced southward (this figure), where they have been correlated with the Upper Cretaceous Atascadero Formation (see index to geologic mapping, e.g. Figure 5, TD, Tom Dibblee and VS, Victor Seiders and others). See Figures 1 and 4 for abbreviations. Cross-section D–D' refers to the location of cross-section D–D' in Figure 8, the Lime Mountain region. The Nacimiento fault zone, as mapped by the authors, noted in Figure 5 and depicted here, continues to the southeast from Monterey County, near Grimes Point, Gamboa Point, Lopez Point, and Cape San Martin to near Atascadero and Paso Robles in San Luis Obispo County; it is not the Coast Range thrust fault.

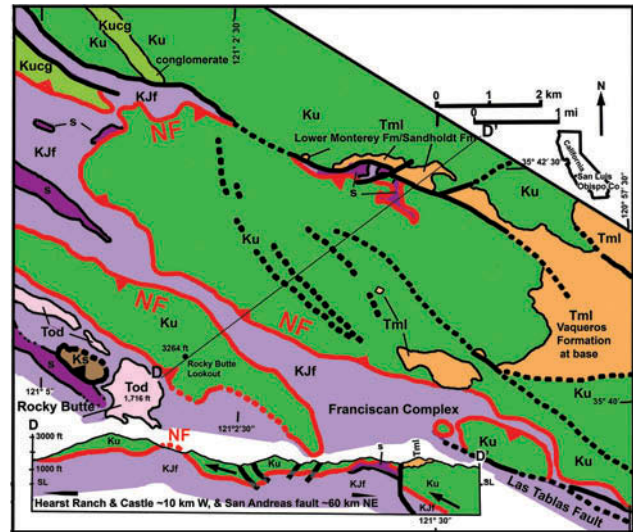


Figure 8. Pre-Quaternary geologic map and cross-section of the Lime Mountain area, San Luis Obispo County (see Figures 5 and 7 [D–D'] for location). See Figure 4 for abbreviations. Adapted from Page (1970a) and Hall *et al.* (1979).

- (3) Rock assemblages in the western Mojave region are similar to those along the western flank of Salinia. Such assemblages are present as klippen or faulted klippen in the Big Creek–Vicente Creek region south of PS in Monterey County (Gilbert 1971; Hall 1991) (Figures 5 and 6).
- (4) Jacobson *et al.* (2011, p. 498) note ‘that movement on the Nacimiento fault must have occurred during emplacement of the Pelona–Orocopia–Rand schists’, a statement that appears to be at odds with their conclusion that the Nacimiento fault is a sinistral fault.
- (5) The Sur (Gilbert 1971) or Sur–Nacimiento (Page 1970b) fault zone ~40 km (~25 mi) south of PS near Big Creek, Vicente Creek, and Gamboa Point, is one of several key regions in understanding the history of Salinia (Gilbert 1971; Norris 1985; Hall 1991, plate 1b; Hall 2002, plate 1A; Hall *et al.* 1995, plate 2) (Figures 5 and 6). Page (1970a, 1970b, 1972) describes other critical areas associated with interpreting the nature of the Nacimiento fault. One such area is the Big Creek–Vicente Creek region (Figure 6).
- (6) The Nacimiento fault in the Big and Vicente creeks area (Figure 6) is a thrust fault. Because the light-coloured Upper Cretaceous sandstone, granitic-cobble-rich beds, and older granitic and metamorphic rocks of the Sur Complex in the upper plate in the area of the klippen rest structurally on dark metavolcanic rocks and sheared, clastic units of the

Franciscan Complex, it is possible to locate the trace of the Nacimiento fault [i.e. within a distance of 2 to 6 m (5 to 20 ft)] where not covered by slope wash and dense vegetation along the eastern boundary. The Nacimiento fault circumscribing the largest klippe in this area is locally subparallel to the contour lines above Vicente Creek. The trace of the Nacimiento fault that bounds the largest klippe in the Big Creek–Vicente Creek area is sinuous along its western boundary (Hall 1991) and less so on the eastern boundary (Figure 6), which was mapped as a normal fault by Gilbert (1971). The Sur Series and well-bedded Upper Cretaceous sandstone and conglomerate rest in Nacimiento thrust-fault contact above the Franciscan Complex. The Sur Series and well-bedded Upper Cretaceous sandstone are present as klippen west of the main trace of the Nacimiento fault (Figure 6). The Franciscan Complex, structurally beneath the main trace of the Nacimiento fault and the klippen, consists of a mélangé of highly sheared greywacke, microgreywacke, chert, and metavolcanic rocks, or dark-coloured and sheared metavolcanic rocks (Figure 6). A landslide immediately northwest of Big Creek, in part, covers the northwestern end of the largest klippe and mass wasting does the same on the southwestern end (Figure 6).

The southern projection of his Gamboa fault (Gilbert 1971) is based primarily on a single, small outcrop of serpentinite near a Cenozoic high-angle fault that cuts the Nacimiento fault near Rockland Landing (Gilbert 1971) (Figure 6). Outcrops of serpentinite are ubiquitous in the Big Creek–Vicente Creek area (Gilbert 1971; Seiders *et al.* 1983; Hall 1991, Map 1b) (Figure 6); however, Gilbert (1971) mapped only one small outcrop of serpentinite that roughly aligns with a high-angle fault near Rockland Landing (Figure 6). Gilbert (1971) altered the trend of the high-angle fault near Limekiln Creek and Rockland Landing (Figure 5) from N55° W to N45° W in order to intersect the single, small outcrop of serpentinite and tie his high-angle fault near Rockland Landing with his Gamboa fault. Seiders *et al.* (1983) neither showed the small outcrop of serpentinite on their map nor provided any written or mapped bases for continuing the trace of the Gamboa fault of Gilbert (1971) to near the Rockland Landing.

The Nacimiento fault zone includes a smaller klippe northwest of Big Creek and north of the larger Big Creek–Vicente Creek area klippe (Hall 1991, Plate 1b) (Figure 6). The upper plate in that area consists of Upper Cretaceous sandstone and small slivers of granitic rocks from the Sur Complex. The sheared Franciscan Complex lies structurally beneath the Nacimiento fault plane and Salinia terrane. There is no field evidence for the inferred high-angle faults shown emerging from the northwestern

and southeastern ends of this structure, as depicted by Dickinson *et al.* (2005, figure 8). Gilbert (1971, cross-section J) clearly indicated that his Sur fault (regarded here as the Nacimiento fault) is a thrust fault.

- (7) The Nacimiento fault zone north of the two Big Creek–Vicente Creek klippen dips steeply ($\sim 60^\circ$) near Dolan Canyon (Figure 6), but the fault zone is nearly vertical near Esalen (Figure 3) owing to Neogene tectonism (Page 1970a, p. 685) (see Hall 1991, Plate 1b). The Upper Cretaceous quartzofeldspathic sandstone and pebble and cobble conglomerate in the same area rest nonconformably upon the Sur Series; immediately to the west, Upper Cretaceous strata lie structurally above the Franciscan Complex along the Nacimiento fault (Hall 1991, Plate 1a) (Figure 6). The Cretaceous sandstone and conglomerate and a basal conglomerate are locally tightly folded in overturned anticlines and synclines.
- (8) Furthermore, our studies in the Sur–Obispo belt of the Franciscan show that there are significant clusters of serpentinized wherlite (peridotite) mélangé blocks, which are more likely to have been derived from subducted fragments of the Coast Range ophiolite than Farallon plate mantle lithosphere [compare Hopson *et al.* (1981) and Luffi *et al.* (2009), and references therein]. In parallel, some mafic schist blocks in the Rand schist have boninitic geochemical signatures (A. Chapman and J. Saleeby, unpublished data), which are more likely to have been derived from the Coast Range ophiolite than Farallon mafic crust. Thus, even though not strongly represented, some remnants of the southwestern Cordilleran batholith's ophiolitic forearc are present in the subduction assemblages that were underplated beneath Salinia and its southernmost Sierra Nevada source land.
- (9) The geological and geophysical evidence that the boundary between the Sur–Obispo Franciscan belt and Salinia originated as a subduction megathrust [after Page (1967, 1969, 1970a, 1970b, 1972, 1981, 1982)] provides the best fit to the observations [Stewart (1968); Silver *et al.* (1971); Ross (1976); Ross and McCulloch (1979); Mullins and Nagel (1981); model 2 of Walter and Mooney (1982); Silver (1982, 1983); Silver and James (1989); Hall (1991); Page and Brocher (1993); Hall *et al.* (1995); Schott and Johnson (1998); Jachens *et al.* (1998); McLaughlin *et al.* (1998); Ducea *et al.* (2009); and Namson and Davis (2012), e.g. cross-sections 3 and 5].
- (10) The youngest Mesozoic rocks in Nacimiento fault contact with the Franciscan Complex near Dolan

Canyon and Lopez Point (Figure 6), south of PS (Hall 1991, Map 1b) (Figure 3) are Campanian and Maastrichtian (ca. 79 to ca. 66 Ma), suggesting that final movement on the Nacimiento fault is post-66 Ma.

Based on geologic relationships, such as the correlation of unconformities, and stratigraphic packages in Salinia from PAR, the Santa Cruz Mountains, and the San Joaquin Valley region (Nilsen and Clarke 1975; Graham and Berry 1979; Clark 1981), movement along the Nacimiento fault was taking place during Palaeocene Danian time (65.5–61.1 Ma) and before Eocene Ypresian time (58.8–48.6 Ma) (i.e. between ca. 66 and ca. 59 Ma), the upper limit being in agreement with the latest movement (late Palaeocene time) on the Nacimiento fault suggested by Jacobson *et al.* (2011, p. 497), but earlier than the age of ‘Termination of Nacimiento slip by latest Oligocene or earliest Miocene time’ suggested by Dickinson *et al.* (2005, p. 15).

Conclusions to point 3

The western boundary of Salinia is a megathrust fault. In a region about 50 km (30 mi) south of Monterey (M, Figures 1 and 2), there are klippen associated with a regional thrust fault in the Big Creek–Vicente Creek and Lime Mountain areas that are part of or within the Nacimiento thrust-fault zone (Figures 6–8). East of Rocky Butte, there is another klippe present along the Nacimiento fault zone. The presence of these structural features indicates that the Nacimiento fault is part of a megathrust fault that forms the sole of allochthonous Salinia (Figures 2A and 6–8). Ducea *et al.* (2009, p. 10, 11) also proposed such an interpretation.

(4) The Nacimiento fault was a low-angle subduction megathrust surface that transitioned into a low-angle normal fault along which the Sur-Obispo Franciscan belt was partly extruded (a corollary to the subduction megathrust model)

This interpretation for late-stage normal remobilization resulting from extrusion and structural ascent of underplated subduction assemblages is in parallel to the interpretation of other well-studied subduction megathrust faults of California [e.g. the Coast Range thrust (Jayko *et al.* 1987; Harms *et al.* 1992; Unruh *et al.* 2007)], the Rand fault and Salinas shear zone (Saleeby 2003; Chapman *et al.* 2010), and the Vincent thrust (Ehlig 1981). Several factors strongly support this interpretation: (i) neither the higher grade blueschist blocks nor the more widespread lower grade blueschist overprint formed in a position proximal to the upper plate Salinia rocks as evident from the thermal state of the upper plate Salinia batholithic rocks during

their low-angle subduction thrusting (Kidder and Ducea 2006), and its observed retrogression path, and it is highly unlikely that such Franciscan metamorphism formed up-dip to the west; (ii) upper plate Salinia rocks subsided to marine conditions in an extensional setting during the displacement history of Nacimiento fault (Grove 1993); (iii) upper plate Salinia basement rocks are everywhere highly shattered and retrograded, typical of extensional basement nappes; and (iv) Sur-Obispo Franciscan rocks structurally record late-stage extension (Platt 2013). In this model, the Sur-Obispo Franciscan Complex and SdS schist form an extensive E-dipping subduction duplex structurally beneath Salinia batholithic rocks, as implied by Ducea *et al.* (2009), with an inverted metamorphic gradient that resulted from the primary heat of the solidus to hot sub-solidus state of the batholithic upper plate during thrusting (after Saleeby *et al.* 2007; Chapman *et al.* 2011; Kidder *et al.* 2013). This model requires that the schist of SdS was tectonically eroded from the base of Salinia along the exposed trace of the Nacimiento fault either during low-angle subduction-related thrusting, or during the Franciscan-extrusion phase.

Conclusions to points 3 and 4. The western boundary of Salinia is principally a subduction megathrust fault, and the Nacimiento fault was a low-angle subduction megathrust surface that evolved into the upper (normal fault) boundary subduction extrusion channel.

The Eastern Flank of Salinia

The current eastern boundary of Salinia is the SAF, as first proposed by Reed and Hollister (1936). However, the resolution of unique piercing points in the basement is confounded by the fact that basement rocks of Salinia, as well as the southernmost Sierra Nevada and western Mojave regions are tectonically layered; thus, variations in structural relief and erosional level across the San Andreas have masked potential unique piercing points. In the most recent in-depth analysis of basement correlations between Salinia and the southern Sierra Nevada region, Chapman *et al.* (2012) used a number of criteria to interpret, at coarse scales, the structural stacking problem with establishing basement ties. These criteria include: (i) regional primary transverse zonation patterns in the age, bulk composition, and radiogenic isotopes (e.g. Nd, Pb, and Sr) of the southwestern Cordilleran batholithic belt, extending from the Sierra Nevada southwards through the Peninsular Ranges batholiths; (ii) in parallel with the zonation pattern of the batholith are distinct belts of pre-batholithic, metamorphic-framework rocks that typically are present as steeply dipping screens, or pendants, with distinct down-dip syn-batholith emplacement strain gradients; (iii) primary igneous pressure, or exhumation gradients in batholithic exposures; and (iv)

medium-to-low temperature thermochronometric patterns. Critical to this analysis is the resolution of the remnants of Late Cretaceous detachment faults. This is confounded, however, by Cenozoic structural and depositional overprints and overlaps. Discussed below are two examples of Late Cretaceous detachment faults in the southern Sierra Nevada that appear to extend into Salinia, these are the Pastoria fault and the Edison-Maricopa detachment.

The analysis of Chapman *et al.* (2012) recognized well-defined upper plate (extensional nappe)-tectonically exhumed lower-plate correlations. These include from northwest to southeast: (i) the Farallon Islands-Santa Cruz Mountains-Montara Mountain, and adjacent batholithic fragments that appear to have been derived off the top of the deep-level Sierra Nevada batholith of the SEM-western TMs; (ii) the Logan Quarry-Loma Prieta Peak fragments that appear to have been derived off the top of the now buried Edison-Maricopa detachment; (iii) the Pastoria plate-Gabilan Range massif that appears to have been derived off the top of the deep-level southeastern Sierra Nevada batholith, and (iv) the Santa Lucia-SdS massif, which appears to be lower batholithic crust and underlying extruded schist that were breached westwards from the central to western Mojave Desert region.

The region, depicted in Figure 2B as Salinia, consists of batholithic plates or nappes that are completely detached from their primary roots. The western boundary with the Franciscan Complex is the Nacimiento fault, which dips eastward beneath Salinia and further down-dip beneath the SdS shear zone and Rand schist. This subduction-accretion-duplex pattern continues into the mantle lithosphere beneath the Mojave Desert, where beneath the underplated Rand schist, and a possible underlying lower crustal layer of Sur-Obispo equivalent Franciscan rocks, Farallon plate mantle lithosphere nappes are underplated in a duplex pattern (Luffi *et al.* 2009). The mantle duplex has reconstructed the mantle lithosphere beneath the Mojave region, which lost its primary batholithic mantle lithosphere (or mantle wedge) at the onset of shallow flat subduction that progressed in time to Rand schist underplating (Saleeby 2003; Luffi *et al.* 2009).

The northern margin of Salinia, as shown in Figure 2B, corresponds to a well-mapped detachment system named the Jawbone Canyon-Blackburn Canyon faults (Wood and Saleeby 1997; Chapman *et al.* 2012). Southern Great Valley strata bury the northeastern margin of Salinia (Figure 2B), and Salinia is interpreted as the trailing edge of a single massive, or series, of detached extensional nappe(s). A relatively well-resolved member of this system is the Logan Quarry-Loma Prieta Peak-western San Emigdio mafic complex allochthon [near ERP (Figure 1)], at least in part derived from the Edison-Maricopa buried detachment.

In Figure 2B, we extend the eastern margin of the Salinian nappes diagonally across the southeastern end of

the San Joaquin Valley, and across the White Wolf fault in continuity with the Pastoria fault. These rocks presently do not exist across much of the western Tehachapi Range and adjacent Tejon Embayment area, although our studies show that conglomerate clast populations in Neogene strata of the Tejon Embayment area record erosion through the lithologically distinct Pastoria-Gabilan nappe(s), and down into its underlying deep-level batholithic plate.

The northeastern margin of restored Salinia on Figure 2B is shown to wrap around the northern end of the terrane as the NSD, with a continuing wrapping pattern to the southwest into the Nacimiento fault. This pattern suggests that the structural discontinuity is in some fashion related to both the trailing edge detachments that extend across the southeastern Great Valley, and into the southern Sierra Nevada, and the Nacimiento fault. One possibility is that the NSD represents the extensionally modified Nacimiento megathrust, with overprinting resulting from the extrusion phase of Sur-Obispo Franciscan underplating.

The eastern margin of Salinia shown in Figure 2B to pass through the central Mojave is conjectural, but not without some supporting data. In Chapman *et al.* (2012), the Santa Lucia-SdS massif is reconstructed (pre-schist extrusion and crustal extension) to the western Mojave region. Batholithic exposures of the Neenach (Ne, Figure 1) area are part of the Pastoria-Gabilan nappe(s). The extent of such detached batholithic rocks eastwards, beneath the West Antelope Basin is unknown, due to burial by Neogene-Quaternary strata. The next batholithic exposures to the east are the upper plates of the Rand thrust system (type Rand Mountains area), which are in part correlative to the Jawbone-Blackburn Canyon nappe(s). Immediately to the south lie the deep-level batholithic exposures of the Buttes area, or the central Mojave metamorphic core complex, having first formed in the Late Cretaceous (Chapman *et al.* 2010, 2012). Upper crustal basement seismic velocities beneath the West Antelope Basin are low, and suggestive of intense cataclasis and retrograding, as is typical of all basement extensional nappes of Salinia (Yan *et al.* 2005). This suggests that much of this region is underlain by Salinian extensional nappes, perhaps partly equivalent to the Pastoria-Gabilan nappe(s), and/or perhaps shed westwards from the central Mojave metamorphic core complex. We recognize a phase of Neogene detachment faulting in this region, but wide-temperature range thermochronometric data synthesized in Chapman *et al.* (2012) clearly show profound, near whole-crust scale exhumation of the basement of this region during Late Cretaceous time.

In summary, the eastern margin of the San Andreas-restored Salinia is interpreted as a complex zone consisting of the trailing edges of mid-to-upper crustal extensional nappes, with their profoundly exhumed deep-level root zones remaining to the north and east. These root-zone rocks form the upper plate to a Salinas-Rand

subduction megathrust, beneath which the Rand-SdS extrusion channel pulled the crust westwards at 100 km (62 mi) scale. Upper crustal extension was of such a magnitude that in places the upper crustal nappes cut down through the deep batholithic plate, and placed upper crustal rocks directly onto the extruded schists (Chapman *et al.* 2010, 2012; Chapman and Saleeby 2012).

The NSD and the northern Nacimiento megathrust (from a latitude near and east of PAR to near the latitude of Bakersfield)

As noted above, the northeastern margin of restored Salinia in Figure 2B is depicted to be the NSD, which wraps to the southwest into the Nacimiento fault. It is reasoned that the NSD represents the extensionally modified Nacimiento megathrust, with overprinting resulting from the extrusion phase of Sur-Obispo Franciscan underplating. The NSD is inferred to be transitional between the Nacimiento and upper crustal detachment faults.

The bases for the inferred location of the northern part of the Nacimiento megathrust are geologic maps, geologic cross-sections, and exploratory and producing oil wells. Cretaceous and Cenozoic strata are in fault contact with the Jurassic–Cretaceous Franciscan Complex in the San Joaquin Valley (Wentworth *et al.* 1983; Hall and Loomis 1992). Near Lost Hills, California Division of Oil and Gas oil well and exploratory well data, e.g. Los Hills Bellevue No. 1 (LoH, Figure 2A), are inferred and interpreted in order to create a model at or near the eastern margin of Salinian basement rocks and the western margin of the San Joaquin Valley.

Well and geophysical data also outline a discontinuity present near the eastern margin of the eastern foothills of the California Coast Ranges (Wentworth *et al.* 1995, revised 2012) (Figures 2B and 9A and 9B). Structure contour lines outline a possible western boundary of the Sierra Nevada batholith in the San Joaquin Valley from 38° N Lat. south to approximately 35° 45' Lat., i.e. south of Coalinga to north of Bakersfield) (Figures 1, 2B, and 9A). Alternatively, the abrupt termination of the structure contour lines in Wentworth *et al.* (1995, revised 2012, figure 1) and in Saleeby *et al.* (2013, figure 1), along the western side and near the southern end of the San Joaquin Valley, can be interpreted as the loss of resolution of basement. That alternative is not favoured here owing to the remarkable uniformity of the abrupt termination of the structure contour lines (Wentworth *et al.* 1995, revised 2012, figure 1; Saleeby *et al.* 2013). In addition, when the NSD is palinspastically restored along and within the SAF system (Table 1), the inferred discontinuity truncates the structure contour lines at the southern end of the San Joaquin Valley (Wentworth *et al.* 1995, revised 2012, figure 1, from near seismic line SJ6 to the southeast) (discontinuity, Figures 1 and 9A and 9B). The basement

complex between the SAF and the discontinuity depicted in Figures 1 and 9A and 9B is inferred to mark the boundary of several tectonostratigraphic units (i.e. a mélange of lithostratigraphic units that have resulted from tectonic deformation). The Salinian basement consists of highly shattered detachment sheets, a series of allochthonous sheets, or nappes (Wood and Saleeby 1997; Chapman *et al.* 2010, figure 2). It can be argued that the limit of resolution of the basement beneath the Maricopa embayment (Figure 9A) is owing to the structural and stratigraphic complexity of these shattered tectonostratigraphic units or detachment sheets – the structural and stratigraphic complexity of the mélange of these nappes largely defines the boundaries of the eastern boundary of Salinia. Analogues of the tectonostratigraphic units of Salinia are the Virgin Spring, Calico, and Jubilee tectonic phases of the Amargosa Chaos of Death Valley (Wright and Troxel 1984, 1993).

There are deep subsurface data for the southern San Joaquin Valley that are resolved. However, these data are for rock units beneath a complex mélange of overlying nappes and structure contours on the surface of the Rand fault, which lies beneath the Sierra Nevada batholith in the Tejon embayment (Figure 9A) (Malin *et al.* 1995; Chapman *et al.* 2010, 2012).

Structure contours, on the top of the Sierra Nevada batholith from 35° 45' N Lat. and west of Bakersfield to ~35° N Lat., and to near the White Wolf fault at the southern end of the San Joaquin Valley, are truncated west of an inferred discontinuity between the Franciscan Complex and associated metamorphic rocks and the Sierra Nevada batholith (Wentworth *et al.* 1995, revised 2012, figure 1; Namson and Davis 2012; Saleeby *et al.* 2013, figure 1) (Figures 2B, 9A and 9B). The inferred and dotted black contact in Figure 9B is in part based on the eastern outcrop limit of Franciscan mélange depicted by Saleeby *et al.* (2013), figure 1).

The southern Nacimiento fault (south of Bakersfield south to near Mojave)

The pre-SAF system–pre-Garlock fault inferred palinspastic reconstruction of the geologically complex southern Sierra Nevada batholith and the SEM and TMs (Figures 2, 9A and 9B) is based on the pioneering research of Crowell (1952), Burchfiel and Davis (1981), Silver (1982, 1983, 1986), and Ross (1984, 1988, 1989). Geologic mapping, for example of Dibblee and Chesterman (1953), Dibblee (2005a, 2005b, 2005c), Kellogg *et al.* (2008), and Chapman and Saleeby (2012) forms the underpinnings of any palinspastic reconstruction of the southern Sierra Nevada. The research of Busby-Spera and Saleeby (1990), Barbeau *et al.* (2005), Ducea *et al.* (2009), Chapman *et al.* (2010, 2011, 2012), Clark *et al.* (2005), Nadin and Saleeby (2008, 2010), Pickett and Saleeby (1993, 1994), Saleeby

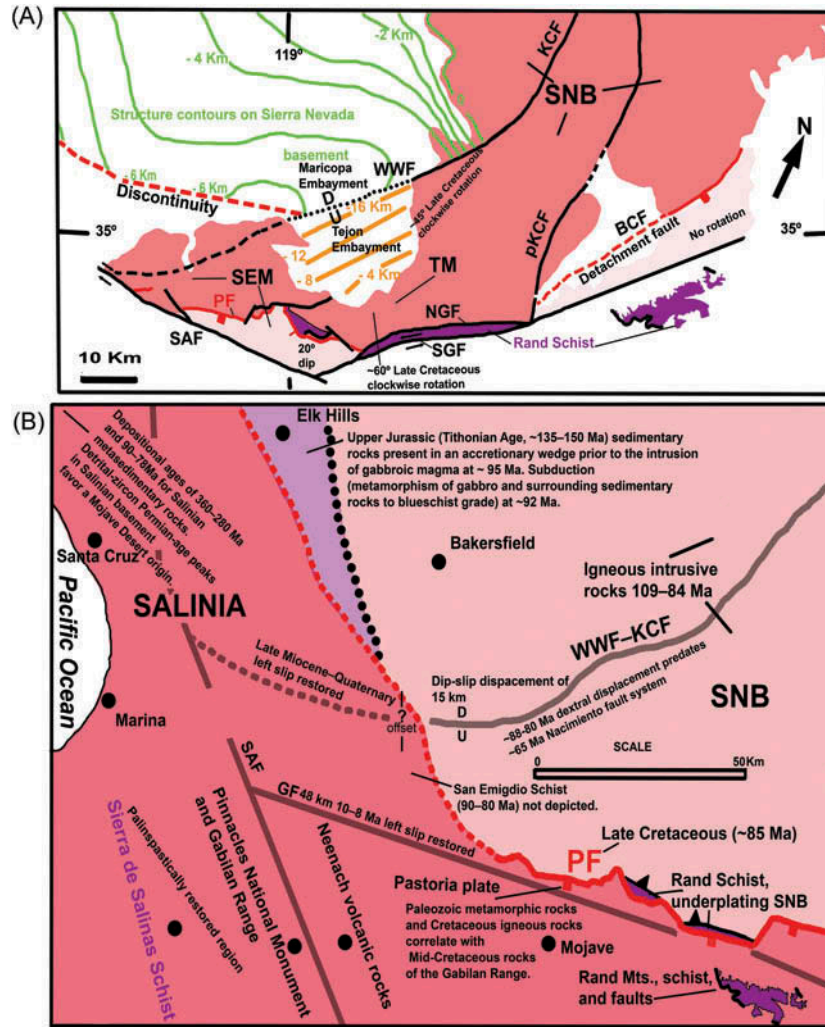


Figure 9. (A, B) A complex fault zone likely marks the eastern boundary of Salinia. This fault zone is in part correlated with the western boundary of Salinia, i.e. the Nacimiento fault, and to the north with the Navarro structural discontinuity (Figure 1). Figure 9A is adapted primarily from Wood and Saleeby (1998), Saleeby *et al.* (2007), Kellogg *et al.* (2008), Saleeby *et al.* (2010), and Chapman *et al.* (2012). The light-green structure contour lines, reflecting the nonconformity between the Sierra Nevada batholith and Cenozoic strata north of the White Wolf fault (WWF) in the southwestern part of the San Joaquin Valley, are adapted from Wentworth *et al.* (1995, revised 2012). The ‘discontinuity’ is inferred (see the text). The orange structure contour lines south of the WWF are on the Rand fault (Chapman *et al.* 2012, Figure 1). Late Cretaceous rotation from Chapman *et al.* (2010). Figure 9B is adapted from Wentworth *et al.* (1983), Hall and Loomis (1992), Wentworth *et al.* (1995, revised 2012), Saleeby *et al.* (2007, 2008), Nadin and Saleeby (2008), and the references cited for Figure 9A. In addition, the following references were considered in the development of this figure: Crowell (1952), Dibblee and Chesterman (1953), Burchfiel and Davis (1981), Silver (1982, 1983, 1986), Ross (1984, 1988, 1989), Saleeby *et al.* (1987, 2009a, 2009b, 2013), Busby-Spera and Saleeby (1990), Pickett and Saleeby (1993, 1994), Saleeby (1997, 2003), Barbeau *et al.* (2005), Clark *et al.* (2005), Ducea *et al.* (2009), and Chapman *et al.* (2010, 2011). For the locations of Figures 9A and 9B, see Figure 1.

(1997, 2003), and Saleeby *et al.* (1987, 2007, 2008, 2009a, 2009b, 2010, 2013) are paramount to understanding the region.

Factors associated with the Late Cretaceous–Palaeocene palinspastic reconstruction of the southern Sierra Nevada region (Figures 2 and 9A)

- (1) The age of slip on the low-angle Nacimiento fault or megathrust beneath Salinia is the latest Cretaceous to Palaeogene (Page 1970a, 1970b,

1972, 1981; Hall 1991), post-80–75 Ma (Mattinson and James 1985), or latest Cretaceous (Ducea *et al.* 2009).

- (2) The Nacimiento fault (*sensu stricto*) is a thrust fault (Page 1967, 1969, 1970a, 1970b, 1972, 1982; Silver 1983; Hall 1991; Page and Brocher 1993; Hall *et al.* 1995; Barth and Schneiderman 1996; Saleeby 1997, 2003; Barth *et al.* 2003; Kidder and Ducea 2006; Ducea *et al.* 2009; and the alternative thrust-model of Jacobson *et al.* 2011). Above a basal décollement, Salinia has internal low-angle

thrust and detachment faults that extend across the eastern boundary of Salinia and into the southern Sierra Nevada and the Mojave terrane.

- (3) The Pastoria fault is but one detachment fault in a system of faults. It is Late Cretaceous (ca. 85 Ma) in age (Chapman *et al.* 2012, figures 9 and 12).
- (4) The Pastoria fault is a low-angle normal fault. As a detachment fault, it everywhere places upper crustal rocks down onto lower crustal rocks. The Pastoria plate(s) is everywhere highly shattered and retrograded down to clay grade, typical of large crystalline detachment sheets. There is no root zone for a Pastoria thrust in the resolved native area of its upper plate, just a mid-crustal hole that was exhumed rapidly at ca. 85 Ma (Chapman *et al.* 2012, figure 9) with structural overprints that are typical of exhumed lower plate source areas for large detachment sheets (Wood and Saleeby 1997).

The fault has been considered a thrust fault (May 1989; Pitchett and Saleeby 1993; Kellogg *et al.* 2008) and/or a regional latest Cretaceous, extensional detachment fault (Wood and Saleeby 1997; Chapman *et al.* 2012, figures 1 and 12).

- (5) The White Wolf fault was a Late Cretaceous oblique dextral fault. This fault formed a continuous ductile damaged zone with the Late Cretaceous dextral Kern Canyon fault (Saleeby and Nadin 2008; Saleeby *et al.* 2009b; Chapman *et al.* 2010, 2012). Dextral separation of steep markers along this regional structure is zero near Mt Whitney, jumping to ~4 km (~3 mi) across the terminal Sierra Nevada Batholith (e.g. 84 Ma Paradise pluton), ~7 km (~4 mi) at Durrwood Creek, ~13 km (~8 mi) near Lake Isabella, and ~25 km (16 mi), as it curves westwards beneath the California Highway 58 near Bakersfield. Relative depth of Late Cretaceous exhumation across the structure (E–SE side-up) likewise increases from zero near Mt Whitney to ~10 km (6 mi) near California Highway 58. The Kern Canyon-Breckenridge segment of this huge basement structure was remobilized as a W-up normal fault in late Cenozoic time, while the White Wolf segment was remobilized as a S-up normal sinistral fault in the late Cenozoic, and far to the west a N-directed Quaternary blind thrust. Basement dextral offset appears to greatly exceed late Cenozoic sinistral offset – critical for palinspastic restoration of the basement.

The White Wolf fault has also been considered to be a sinistral fault [Stein and Thatcher (1981), late Miocene to Quaternary movement; Ross (1986, 1989) with a SE dip; Bartow (1991); Bawden (2001) with a 75° SW dip; Saleeby *et al.* 2007, figure 1, and E side-up (Nadin and Saleeby 2010)].

The associated Kern Canyon fault, northeast of the White Wolf fault (WWF), is an 88–84 Ma dextral fault along which slip had waned by 80 Ma time (Busby-Spera and Saleeby 1990; Nadin and Saleeby 2008; Saleeby *et al.* 2008).

- (6) The Garlock fault zone (GF, Figure 1) is a ~260 km (162 mi) long fault with 48–64 km (~30–40 mi) of sinistral slip (Davis and Burchfield 1973; Montasero *et al.* 1997; Smith *et al.* 2002; Chinn *et al.* 2012).
- (7) Correlations:
 - (a) Granitic rocks of the northern 150–200 km (93–124 mi) of Salinia were removed from the Sierra Nevada batholith (Silver 1982; Ross 1984; James 1992; Wood and Saleeby 1997, figure 2; Chapman *et al.* 2012, figures 1 and 12).
 - (b) Sur Series metasedimentary rocks in northern Salinia are correlated with Tehachapi pendants (TM, Figure 1) near Cummings Valley, southern Sierra Nevada batholith (Chapman *et al.* 2012). Cummings Valley is located west of Mojave (Mj, Figure 1) and Tehachapi, east of Highway 99, and south of Bakersfield (Bak, Figure 1).
 - (c) The Coast Ridge terrane (including orthogneiss, marble, and quartzite) in Monterey County and east of the Nacimiento fault (Figures 4 and 6) is correlated with a metamorphic core complex in the central Mojave terrane (Chapman *et al.* 2012) (Figure 2).
 - (d) Rocks in Salinia, south of PS in coastal Monterey County (Figure 1), with Permian isotopic signatures, are correlated with rocks dated as Permian in age present in the El Paso Mountains, northern Mojave terrane (Figure 2B) (Alvarado *et al.* 2003).

Conclusions

The offset of Mesozoic granitic rocks associated with the NSD (Mendocino County, Figure 1), west of the NSAF, and similar granitic rocks in the SEM–TMs (Kern and Los Angeles counties), east of the SAF system, is between 610 and 675 km (379 and 420 mi) (Figure 1). However, the cumulative dextral slip: (i) on the main trace of the SAF north of the Transverse Ranges is 315–322 km (196–200 mi); (ii) on the Hosgri–San Simeon–West Huasna–Oceanic–Reliz fault zone, a part of the SAF system, is 128 ± 2 km (80 ± 1.2 mi), and (iii) along the PiF, also a part of the SAF system, is 43 km (27 mi), for a total of from 171 km (106 mi) to 199 or 200 km (~124 mi) of cumulative dextral slip along faults within the

SAF system north of the TMs (Table 5; TM, Figures 1 and 2). Thus, there is a deficit of between 88 and 99 or ~ 100 km (~ 62 mi) to ~ 189 km (~ 118 mi) needed to palinsparactically restore crystalline rocks associated with the NSD or northern structural discontinuity (Figure 1) near PAR (Figure 1), west of the SAF system, with the crystalline rocks within the SEM and TMs (Figure 1), east of the fault system, as originally proposed by Reed and Hollister (1936).

Some of the key piercing points along the main trace of the SAF system are: (i) Jurassic (ca. 150 Ma) gabbroic rocks at Logan (L, Figure 1), on the SAF, offset ~ 322 km (~ 200 mi) from rocks of the same age and lithology at ERP or, preferably, the western San Emigdio mafic complex (Chapman *et al.* 2012; Chapman and Saleeby 2012) (ERP, Figure 1); (ii) uppermost Oligocene–lowermost Miocene (23.5 Ma) volcanic rocks in the PNM (Figure 1), on the west side of the SAF, offset ~ 315 km (196 mi) from rocks of the same age and lithology near Neenach, Los Angeles County (Ne, Figure 1).

Some of the key piercing points along the SAF system west of the main trace of the SAF, between Santa Barbara and Mendocino counties, are (Figure 1): (i) the Jurassic (ca. 150 Ma) ophiolite and nonconformably overlying Relizian or lower Miocene (17.79–17.39 Ma) Lospe Formation on the west side of the H–SS fault near SS (Figure 1), offset 100 km (62 mi) from the same stratigraphy at PSa (Figure 1); (ii) the stratigraphic sequence of Luisian or middle Miocene (16.9–15.7 or 15.5–15.3 Ma) Obispo Formation (tuff) and Mohnian or upper Miocene (ca. 8.6 Ma) sandstone offset 15 km (9 mi) along the OWHF (Figure 1), or alternatively an offset, based on gravity and magnetic anomalies, of 23 km (14 mi) between Point Buchon (near SLO Figure 1) and Cape San Martin (Figures 5 and 7); (iii) the structural discontinuity, largely offshore, west of the H–SS–SG fault zone (Figure 1), near ANP, south of PiP and Pescadero point (ANP, PiP, Figure 1), offset northward ~ 128 km (~ 80 mi) from the trace of the Nacimiento fault near Grimes Point (Figure 3), and east of the H–SS–SG fault zone (SGrF, SSF, HF, Figure 1); (iv) Late Cretaceous (ca. 80 Ma) granodiorite and the nonconformably overlying Penutian or lower Eocene (ca. 56 Ma) PR conglomerate west (PRe, Figure 1) of the H–SS–SG–ReF–PiF zone (Figure 1), offset northward 171 km (106 mi) from Late Cretaceous (82 Ma) granodiorite and nonconformably overlying Penutian or lower Eocene (53–51 Ma) Carmelo Formation (conglomerate) at PL (Figure 1), east of the fault zone; and (v) Saucian or upper Oligocene to lower Miocene (23.8 Ma) Iverson Basalt, near the NSD (Figures 1 and 2), east of the H–SS–SG–ReF–PiF–NSAF zone, offset ~ 200 km (~ 124 mi) northward from the Saucian or upper Oligocene to lower Miocene (20.2 ± 1.2 Ma) Mindego Basalt near Montara Mountain, east of the fault zone.

The terranes, thrust sheets, or nappes riding on the Nacimiento megathrust and its extension into the southern San Joaquin Valley include pre-Cretaceous igneous and metamorphic rocks representing former and now rootless magmatic or crystalline terranes. Nonconformably overlying these terranes, tectonostratigraphic units of Salinia, is a virtually uninterrupted and unmetamorphosed sequence of Upper Cretaceous (Campanian–Maastrichtian ages, 83.5–65.5 Ma) and Palaeogene conglomerate, sandstone, and siltstone. The Cretaceous strata rest nonconformably on the Sur Series of granitic and metamorphic rocks (Precambrian, 1.75 Ga, and Palaeozoic and Mesozoic protoliths, the latter with metamorphic ages of 130–108 Ma and 108–76 Ma). We infer that, during latest Late Cretaceous to earliest Palaeocene time (ca. 66 to ca. 61 Ma), a composite of three nappes (i.e. thrust sheets above thrust faults), forming the allochthon of Salinia, was carried northwestward from what is now the southern Sierra Nevada and western Mojave Desert region owing to large-magnitude extension above the retreating Farallon plate, as documented by Wood and Saleeby (1997), Saleeby (2003), Saleeby *et al.* (2007), and Chapman *et al.* (2010, 2012). Chapman *et al.* (2010, figure 2) and Chapman and Saleeby (2012) proposed that detachment faults displaced crystalline basement sheets to an ‘orphaned’ Salinia. In their models, the southern Sierra Nevada–northwestern Mojave region, which includes the Santa Lucia region (i.e. Monterey County, Figure 1) and SdS (i.e. Figures 1 and 2B), rapidly lost ~ 25 – 35 km (16–22 mi) of upper to middle crust as the Rand and SdS schists were underthrust and then rapidly extruded and cooled while the $\sim 10,000$ km² (~ 3900 mi²) extensional province subsided to marine conditions. This mega-extensional province likely continued southward to the upper plates of the Pelona–Orocopia schists. These schists moved out of their respective metamorphic cores to middle-to-upper crustal levels within their extrusion channels, and they were further exhumed by Neogene predominantly high-angle normal faults, and locally (e.g. SEM–TMs) by Quaternary thrust faults.

The Rand–SdS schist (Figures 2A and 9) are at the top of the subduction channel as shown by the convergence of a Barrovian zone-type metamorphism across their upper crystalline boundaries (i.e. Rand–Salinas megathrust faults, as well as hydrothermal fluxing and incipient melting across this boundary (Kidder and Ducea 2006; Saleeby *et al.* 2007; Chapman *et al.* 2011).

We note that as much as 50 km (30 mi) of horizontal extension in the Mojave structural terrane did not take place until Miocene time (Fletcher *et al.* 2002). This upper crustal extension was superimposed over basement that had been rapidly and deeply exhumed during Late Cretaceous time by much higher magnitude extension above the Rand schist extrusion channel (Chapman *et al.* 2010, 2011, 2012).

Evidence supporting the conclusion that the Nacimiento fault is a thrust fault include: (i) shear planes of the Nacimiento fault zone locally dip NE at low angles where the trace of the fault is sinuous (Figures 5A and 6A) to high angles where the trace is straight (e.g. Page 1970a, e.g. figure 5; Gilbert 1971; Greene 1990, figure 12; Hall 1991; Dibblee 1976, figure 21, 2007a–d; Jacobson *et al.* 2011, figure 2). Dips of the Nacimiento fault plane are locally at a high angle where they have been affected by Cenozoic (e.g. Pliocene–Pleistocene) folding. (ii) Klippen are present along the Nacimiento fault zone in the Big Creek–Vicente Creek region south of PS, Monterey County (Figures 3 and 6) and in the Lime Mountain–Rocky Butte area of SLO County (Figures 7 and 8). Gilbert (1971) considered the northeastern boundaries of these klippen to be high-angle normal faults. (iii) Ducea *et al.* (2009, p. 10) noted that the ‘original position of the Nacimiento (i.e. the Franciscan Complex) and the Salinian terrane during the latest Cretaceous are some 150–180 km (93–112 mi) apart, based on the well-established structural anatomy of California’s Cretaceous continental margin’. The allochthonous Salinian terrane was brought ~100 km (~60 mi) over the accretionary edge of the Franciscan Complex, analogous to the Vincent thrust in the San Gabriel Mountains (Ducea *et al.* 2009, p. 11). The shear sense signatures on the Vincent thrust show that the Pelona schist moved westward with respect to the crystalline complex of the San Gabriel upper plate, i.e. subduction return flow channel transport was similar to other lower-plate schist relationships of southern California and Salinia (Ehlig 1981). This is the key to the westward breaching of Salinia and the San Gabriel basement across the former forearc region, subsequently making these basement sheets liable for entrapment and dispersal along the Neogene–Quaternary SAF system.

Transport of a composite Salinia allochthon ~100 km (~62 mi) westward and northwestward from the Mojave terrane (Figures 1 and 2B), along the Nacimiento fault system, took place during latest Cretaceous–latest Maastrichtian to earliest Palaeogene or Danian (ca. 66–61 Ma) time. Thrusting and regional detachment occurred prior to the interaction of the Pacific plate with the North American plate and before the initiation of transform and dextral slip within the SAF system. The eastward extension of the Nacimiento megathrust, beneath Salinia, projects beneath the Sierra Nevada–Mojave region with structures such as the Rand fault, Salinas shear zone, Pastoria fault, and Edison–Maricopa detachment that all lie in the crust above the megathrust.

The palinspastic restoration of ~100 km (~62 mi) of westward and northwestward reverse slip of Salinia, followed by a phase of westward extrusion of the underplated Sur–Obispo Franciscan along the Nacimiento fault system contributes to the restoration of Salinia with equivalent terranes in the SEM–TMs that is not achieved alone by

palinspastic restorations along faults in the SAF system, thus resolving the enigma of Salinia.

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