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Forearc strike-slip displacement as an alternative to subduction erosion, with examples from Mexico and California (sinistral Nacimiento fault)¹

Raymond V. Ingersoll

Abstract: Slip on the Nacimiento fault of the central Coast Ranges of California has been variably interpreted as dextral, sinistral, or reverse. The currently prevailing interpretation is that the Nacimiento fault represents subduction erosion, by which the central to eastern part of the Cretaceous California batholith was thrust over the western part of the batholith and forearc basin, resulting in juxtaposition of the Salinian batholithic block against the Franciscan Complex, concurrently with Laramide flat-slab subduction (75–55 Ma) and underplating of the Pelona-Orocopia-Rand schist. No modern convergent plate margin includes such overthrusting. The closest modern analog to the likely configuration of the Salinian continental margin near the end of the Laramide deformation is southern Mexico, where arc plutons are exposed near the trench. Although commonly considered an example of subduction erosion, this margin is “missing” parts of the plutonic arc and forearc because they have been displaced to the southeast by sinistral slip. By analogy, the Nacimiento forearc was modified as a trench-trench-transform triple junction migrated southeastward along the continental margin during flat-slab subduction. This model makes testable predictions involving northwest-to-southeast younging of deep-marine deposits on batholithic crust underlain by contemporaneous schist. Correct restoration of later Cenozoic primarily dextral slip and Maastrichtian – Early Eocene primarily sinistral slip must result in realignment of north–south-trending belts of the Sierra Nevada – Salinia – Peninsular Ranges batholith, Great Valley forearc, and Franciscan Complex. These modern and ancient examples suggest that several “erosional” subduction zones are more plausibly explained by strike-slip truncation of forearcs.

Key words: tectonics, sedimentary basins, California paleotectonics, southern Mexico margin, sinistral transforms.

Résumé : Le rejet le long de la faille de Nacimiento, dans les chaînes côtières de la Californie, a été interprété, tour à tour, comme étant dextre, senestre ou inverse. L'interprétation dominante à l'heure actuelle veut que la faille de Nacimiento représente une érosion par subduction, un processus dans lequel la partie centrale à orientale du batholite de Californie d'âge crétacé a été charriée sur la partie occidentale du batholite et le bassin d'avant-arc, causant la juxtaposition du bloc batholitique salinien sur le complexe franciscain en même temps que la subduction de la plaque subhorizontale laramienne (75–55 Ma) et le sous-placage du schiste de Pelona-Orocopia-Rand (POR). Aucune marge convergente de plaque moderne ne montre un tel charriage. L'exemple moderne le plus semblable à la configuration probable de la marge continentale salinienne vers la fin de la déformation laramienne est le sud du Mexique, où des plutons d'arc sont exposés près de la fosse. Si cette marge est souvent considérée comme un exemple d'érosion par subduction, il lui « manque » des parties de l'arc plutonique et de l'avant-arc parce qu'elles ont été déplacées vers le sud-est par déplacement senestre. Par analogie, l'avant-arc de Nacimiento a été modifié durant la migration vers le sud-est d'une jonction triple fosse-fosse-faille transformante le long de la marge continentale durant la subduction de la plaque subhorizontale. De ce modèle découlent des prédictions vérifiables quant à la présence de dépôts marins profonds de plus en plus récents vers le sud-est sur une croûte batholitique sous-tendue par des schistes contemporains. Une bonne restauration du glissement principalement dextre plus tard au Cénozoïque et du glissement principalement senestre au Maastrichtien-Éocène précoce doit produire le réalignement de ceintures d'orientation nord-sud du batholite des Sierra Nevada – Salinia – chaînes péennulaires, de l'avant-arc de la grande vallée et du complexe franciscain. Ces exemples modernes et anciens donnent à penser que plusieurs zones « d'érosion » par subduction s'expliquent plus plausiblement par la troncation par décrochement d'avant-arcs.

Mots-clés : tectonique, bassins sédimentaires, paléotectonique de la Californie, marge du sud du Mexique, failles transformantes senestres.

Introduction

Dedication

This speculative contribution honors the decades of insightful paleotectonic analyses by my long-time friend A.M. Celâl Şengör.

Celâl and I came of age professionally during the exciting 1970s, following the wide acceptance of plate tectonics, just as the geological implications and usefulness of this new paradigm were being understood. We shared in the tutelage of some of the great masters of this effort, especially Kevin Burke, John Dewey, and Bill

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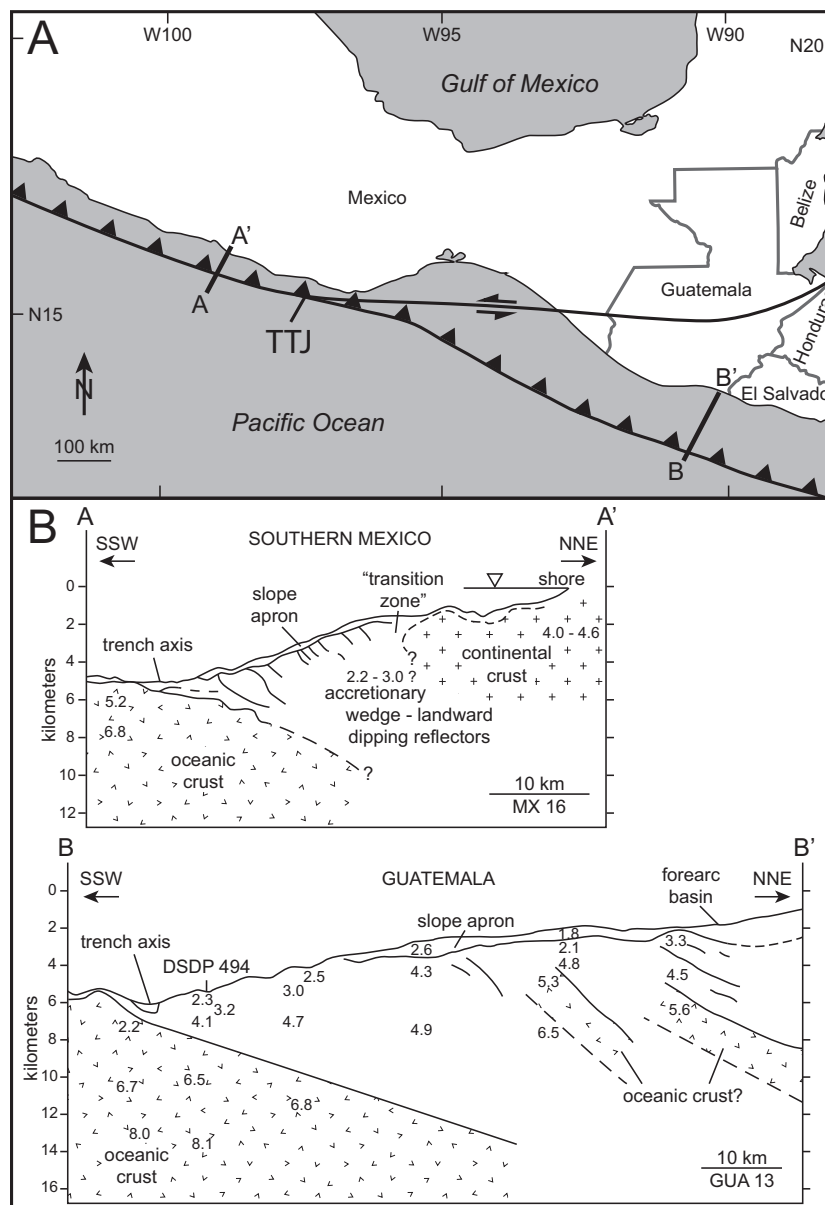
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Fig. 1. (A) Map of southern Mexico showing intersection of sinistral Cayman transform fault (arrows) (Pindell and Dewey 1982; Dickinson and Lawton 2001; Pindell et al. 1988, 2005) with part of Middle America Trench (barbed symbols) to form Tehuantepec triple junction (TTJ). Cayman transform is shown schematically as one through-going structure, whereas its modern expression consists of several subparallel faults (e.g., Authemayou et al. 2011). Locations of cross-sections A–A' and B–B' are also indicated. (B) Interpretive geologic cross-sections of southern Mexico and Guatemala forearcs showing reflectors, refraction, and interval velocities, and underlying basement (after McMillen et al. 1982). B–B' displays a wide accretionary prism, which underthrusts oceanic crust, on which a wide forearc basin has formed (analogous to Franciscan Complex, Great Valley ophiolite, and Great Valley forearc of northern California, respectively). A–A' displays a narrow accretionary prism against batholithic (continental) crust, with thin nonconformable forearc deposits (analogous to Nacimientito block juxtaposed against Salinian block along the Nacimientito fault, respectively). "Transition zone" represents "missing forearc basin and outboard magmatic arc" of the reverse-fault model for Nacimientito fault or the "transition zone" represents former location of Cayman transform fault of the sinistral model for Nacimientito fault. See text for discussion. Location of the Deep Sea Drilling Project (DSDP) hole 494 indicated in B–B'.



Dickinson. Even though our geographic areas of study have differed (Celâl's primarily in Eurasia and mine primarily in North America), we have always been united in our philosophical dedication to the actualistic (uniformitarian) approach to reconstructing orogenic belts (e.g., Lom et al. 2018). I cannot pretend to match Celâl's encyclopedic knowledge of the history of geologic and tectonic thought, as expressed in publications in many languages, but I can pretend to match his dedication to using actualistic plate-tectonic models to explain ancient orogenic belts (e.g., Ingersoll 2008, 2012). Our common foes include ad hoc hypotheses, terranol-

ogy, and geochemical and geophysical studies presented in the absence of geologic context. My hope is that this contribution provides Celâl and other readers new insights regarding the specific topics covered and illustrates the power of the application of actualistic approaches to the solving of paleotectonic problems.

Subduction erosion

"Convergent margins dominated by subduction erosion are the most prevalent type (von Huene and Scholl 1991; Cliff and Vannucchi 2004)" (von Huene et al. 2004, p. 913). This opinion is

based on worldwide compilations of the characteristics of convergent margins that separate them into accretionary and erosive plate margins (e.g., [Clift and Vannucchi 2004](#); [Scholl and von Huene 2007](#); [Clift et al. 2009](#)), an admirable actualistic approach. Careful examination of these compilations, however, reveals that many of the “erosive” plate margins can be explained using alternative interpretations of paleotectonic evolution of the margins. Four actualistic aspects of continental-margin arc-trench systems have been ignored during categorization of convergent plate margins as “erosive”: (i) arc-trench gaps widen through time following the initiation of subduction zones because of the refrigeration of forearcs (e.g., [Dumitru 1988](#)), which induces greater depth to melting on subducting slabs through time ([Dickinson 1973](#)) and results in migration of arcs away from trenches, independent of changes in slab dip; (ii) once thermal equilibrium is reached (as convection (sinking of oceanic slab) equals conduction (warming of slabs with depth)), magmatic arcs may migrate either away from or toward trenches during constant-depth, variable-dip subduction ([Keith 1978, 1982](#)); (iii) strike-slip motion in forearcs and within arcs can result in convergent margins with batholithic rocks at coasts, as illustrated in southern Mexico (see later in the text); and (iv) where subduction zones have initiated by polarity reversal following arc-arc collisions (a common mode of subduction initiation), batholithic rocks from older arcs may exist adjacent to these new trenches ([Dickinson 2008](#)). This last phenomenon has been especially significant in the development of the North and South American Pacific margins.

Southern Mexico

The Cocos plate currently subducts northeastward beneath southern Mexico along a coast containing Cretaceous and Paleogene batholithic and metamorphic rocks ([Schaaf et al. 1995](#)) ([Fig. 1](#)). The presence of batholithic rocks along the coast (e.g., near Acapulco) led to the hypothesis that the related forearc basin and subduction complex might have been “eroded” and subducted beneath the margin ([Karig 1974](#)). Subsequent investigations indicated, however, that accretion was occurring along this margin, so the presence of batholithic rocks close to the trench needed to be explained using a different hypothesis ([Karig et al. 1978](#); [Moore et al. 1979](#); [Shipley et al. 1982](#); [Moore and Shipley 1988](#)). The single argument by [Clift and Vannucchi \(2004\)](#) in favor of this being an “erosional” margin is based on controversial interpretations of benthic-foraminiferal paleobathymetry (see [McMillen and Bachman \(1982\)](#) for the counterargument). A more likely mechanism to expose batholithic rocks along the southern Mexican continental margin is through southeastward displacement of the Chortis block by sinistral slip along the Polochic-Motagua fault system (the northern boundary of the Caribbean plate) ([Aubouin et al. 1981](#); [Pindell and Dewey 1982](#); [Anderson and Schmidt 1983](#); [Burke 1988](#); [Pindell et al. 1988, 2005](#); [Authemayou et al. 2011](#)). This interpretation is consistent with regional relations as well as details along the coast, such as significant uplift, erosion, and subsidence and the development of unconformities concurrent with transpressional sinistral slip prior to southeastward initiation of the new convergent margin as the Tehuantepec trench-trench-transform triple junction migrated with the Caribbean plate (e.g., [Burke 1988](#); [Schaaf et al. 1995](#); [Silva-Romo 2008](#)). The result is a steep continental margin characterized by a narrow shelf, a steep inner slope, and no forearc basin, and a trench deeper than 5 km within ~60–70 km of the shoreline, ([Karig et al. 1978](#); [Moore et al. 1979](#)). Major submarine canyons (e.g., Ometepe Canyon) transport coarse sediment directly into the trench ([Aubouin et al. 1981](#); [Moore et al. 1982](#); [Moore and Shipley 1988](#)). Primary sources for sediment in the Mexican trench are local plutonic and metamorphic terranes along the rugged coast, producing primarily arkosic sand ([McMillen et al. 1982](#)). In contrast, volcanoclastic detritus derived from the Central American arc south of the Tehuantepec triple junction is trapped primarily in the broad forearc basin,

Fig. 2. Current tectonic setting of Salinia, Nacimient block, Nacimient fault, and related features. Faults (heavy lines): BPF, Big Pine; Cf, Calaveras; Hf, Hayward; Nf, Nacimient; nSAf, northern San Andreas; Pf, Pilarcitos; Rf, Rinconada; SGf, San Gabriel; SJf, San Jacinto. Sedimentary basins (inside hachured lines): LA, Los Angeles; SM, Santa Maria. Other features: ETR, eastern Transverse Ranges; LT, Lake Tahoe; MB, Monterey Bay; NSD, Navarro structural discontinuity; SB, Sutter Buttes; SF, San Francisco Bay; SGM, San Gabriel Mountains; SS, Salton Sea. Modified from [Dickinson et al. \(2005\)](#), which should be consulted for additional discussion.

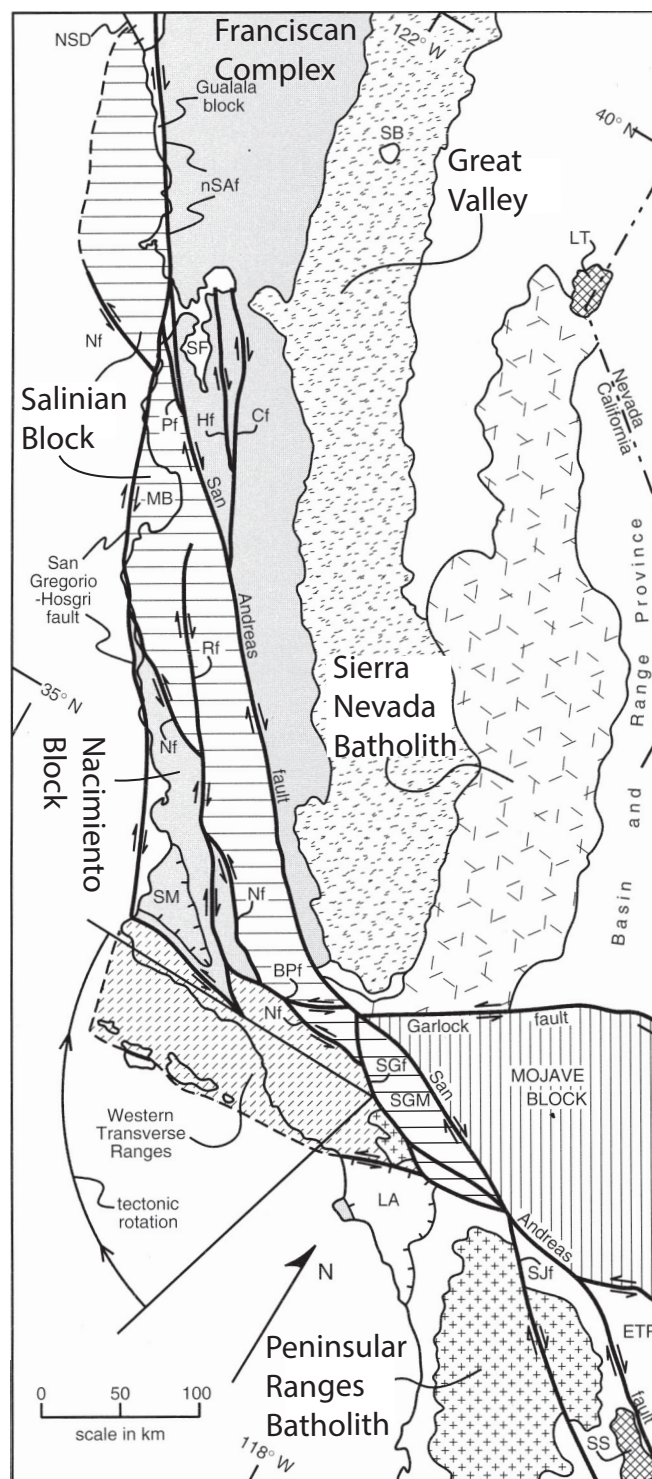


Fig. 3. True-scale actualistic analog sequential cross-sections for northern Coast Ranges, Great Valley, and Sierra Nevada. Mantle lithosphere (black) is defined geophysically rather than geochemically. Asthenosphere is orange; rising arc magma is red. Timing relations shown in cross-sections are consistent with relations along a line of latitude near San Francisco. Similar cross-sections, but with different ages, could be drawn along the southward propagating suture zone along the California and Mexican Pacific margins (e.g., Dickinson and Lawton 2001; Ingersoll 2008). CHGR, Copper Hill, Gopher Ridge arc complex; GVO, Great Valley ophiolite; LRPB, Logtown Ridge arc complex and 200 million year old Peñon Blanco arc complex; M, Mariposa Formation; SO, Smartville ophiolite. Modified after Ingersoll (2000, 2008), based partially on Schweickert (2015). [Colour online.]

without abundant detritus reaching the trench, except near a few major canyons (Seely 1979; Aubouin et al. 1981; McMillen et al. 1982; Shipley et al. 1982).

Nacimiento fault

The Sur-Nacimiento fault zone of coastal central California (Fig. 2) was defined by Page (1970) as extending from Point Sur through the Santa Lucia Range and into the Transverse Ranges. "In part, or possibly in entirety, the fault zone is the approximate boundary between an elongate, sialic tract called the Salinian block and a terrain underlain by the eugeosynclinal (trench?) deposits of the Franciscan assemblage" (Page 1970, p. 667). As Page (1970, 1981, 1982), Dickinson (1983), Hall (1991), Dickinson et al. (2005), and Hall and Saleeby (2013) document and discuss, the structural relations of the Sur-Nacimiento fault zone are complex because the fault zone locally cuts the Coast Range thrust (that places primarily Cretaceous forearc ophiolite and strata over the Franciscan subduction complex) and because the Nacimiento fault is locally offset by late Cenozoic dextral faults. The resulting structural complexity, when combined with generally poor exposure, has resulted in highly divergent interpretations and models, as discussed in the references mentioned earlier in the text. Orientations of the Nacimiento fault are highly variable, with a general tendency toward steep northeast dips, consistent with reverse-fault interpretations (Page 1970, 1981; Hall 1991; Hall and Saleeby 2013). On the other hand, there are excellent exposures where the fault is nearly vertical, with a straight trace unaffected by topography, consistent with strike-slip interpretations (Page 1970, 1981; Dickinson 1983; Dickinson et al. 2005). My conclusion is that the current orientations of segments of the Nacimiento fault are poor representations of its orientation during the latest Cretaceous–Paleogene slip (75–60 Ma; Dickinson et al. 2005). The interested reader should consult these references for additional details; for the purpose of the current contribution, I define the Nacimiento fault as the southwestern edge of the Salinian basement and overlying sedimentary strata, as used by Dickinson et al. (2005).

The reader is referred to Keppie et al. (2012) and Ducea and Chapman (2018) for alternative interpretations of most of the information presented earlier and discussed later in the text.

Paleotectonics of California

Nevadan orogeny

It is important to understand the paleotectonic settings of terranes traversed by the Nacimiento fault, because this knowledge constrains fault reconstructions. Prior to the initiation of subduction of the Farallon plate (and possible related oceanic plates), two Jurassic magmatic arcs faced each other, an intraoceanic east-facing arc and a continental-margin west-facing arc, as expressed by coeval magmatic rocks now located in the Foothills belt of the Sierra Nevada and eastern California, respectively (Schweickert and Cowan 1975; Ingersoll and Schweickert 1986; Ingersoll 2000, 2008; Schweickert 2015, and references therein) (Fig. 3). The Late Jurassic Nevadan orogeny involved north-to-south closure of a remnant ocean basin between these two arcs and initiation of subduction of the Farallon plate at the Franciscan trench (Fig. 3). In the process, the Great Valley ophiolite was trapped within the new arc–trench gap, and forearc sedimentation began (Ingersoll 1982, 2000, 2008; Dickinson 1995). Confidence in this model for

the Nevadan orogeny has been strengthened by documentation of oceanic slabs in the mantle, consistent with subduction of the Mezcalera plate between the colliding arcs (Sigloch and Mihalynuk 2017), as proposed by Moores (1998) and Dickinson and Lawton (2001) for all of southwestern North America. Claims that Franciscan subduction initiated as early as 180–165 Ma (e.g., Wakabayashi 2015; Mulcahy et al. 2018; and references therein) are based on the ages of high-grade metamorphic rocks within the Franciscan Complex. Figure 3 illustrates that these high-grade rocks could have been incorporated into the Franciscan Complex as the Farallon plate began its descent beneath the accreted arc terranes around 155 Ma, following the Nevadan orogeny. Complex pressure–temperature paths (as discussed by Mulcahy et al. 2018) would certainly occur during this process. The significant aspect of this model for the current contribution is that the suture zone between the colliding arcs is now found in the western foothills of the Sierra Nevada (Schweickert 2015) and the Peninsular Ranges (Dickinson and Lawton 2001), where it is overlapped by the youngest part of the post-Nevadan forearc basin, as discussed later.

Northern California convergent margin

As the post-Nevadan forearc evolved, three coeval processes resulted in distinctive north–south-trending belts: (i) the new magmatic arc that formed in the western foothills (including 150 Ma plutons) gradually migrated eastward during the Cretaceous as the depth of melt generation increased; (ii) the Franciscan subduction complex built upward and westward as additional trench sediment was accreted; and (iii) the Great Valley forearc basin subsided and widened by westward and eastward onlap, with eventual filling to sea level by the Paleogene (Dickinson and Seely 1979; Ingersoll 1979, 1982, 2008; Dickinson 1995). As a result, the northern Coast Ranges, Sacramento Valley, and northern Sierra Nevada preserve the following nine belts, from west to east: Franciscan coastal, central, and eastern; Great Valley western, central, and eastern; and Sierra Nevada Foothills, Early Cretaceous plutons, and Late Cretaceous plutons (Fig. 4). This northern California transect is the only locality along the western North American coast that exposes all nine belts, which serve as guides to reconstructing comparable belts along the California continental margin.

Laramide orogeny

The Laramide orogeny (~75–35 Ma; Bird 1998) occurred during flat-slab subduction of the Farallon (and possibly Kula) plate (Dickinson and Snyder 1978; Bird 1988, 1998; Dickinson et al. 1988). Flattening of the slab may have been induced by a combination of rapid convergence and subduction of a buoyant oceanic plateau or aseismic ridge (Livaccari et al. 1981; Henderson et al. 1984; Barth and Schneiderman 1996; Gutscher et al. 2000; Liu et al. 2010; Jacobson et al. 2011). Details of relative plate motions and the four-dimensional architecture of interactions between North America and buoyant ocean crust are difficult to constrain (e.g., Henderson et al. 1984; Engebretson et al. 1985; Liu et al. 2010).

Nonetheless, if a northeast–southwest-trending oceanic aseismic ridge or the leading edge of a plateau on the Farallon plate intersected the California convergent margin, then the intersection point would have migrated southeastward along the margin,

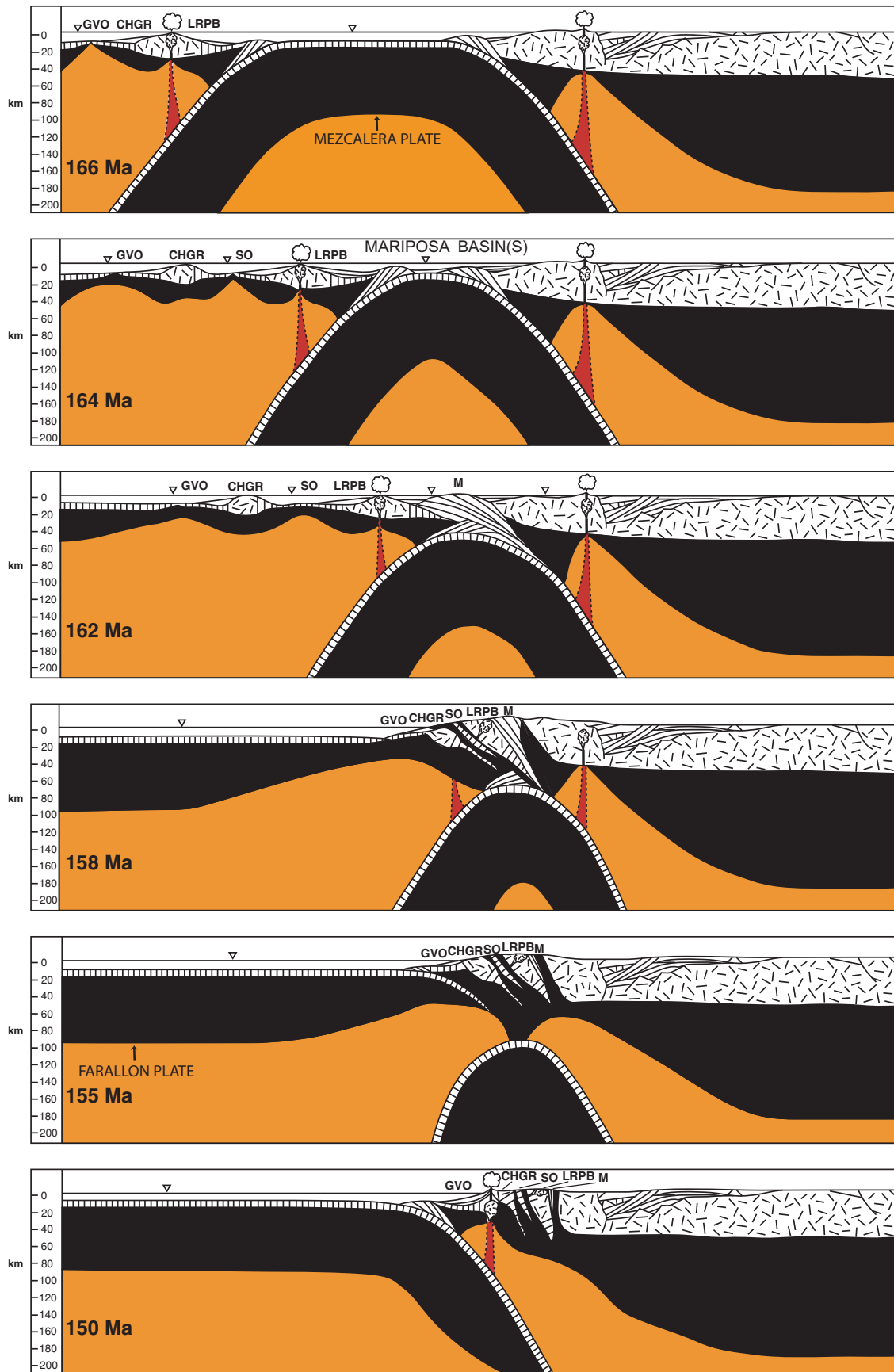
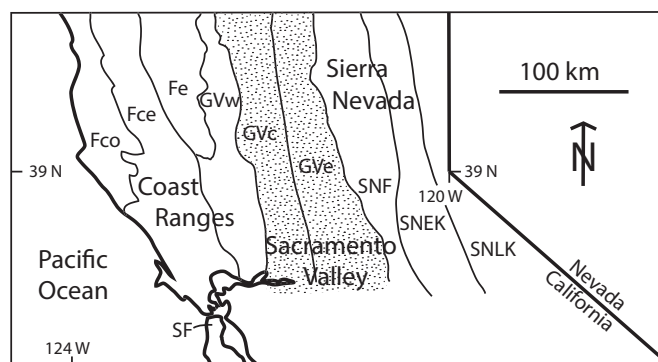


Fig. 4. Generalized map of nine tectonolithologic belts of northern California. Fco, Franciscan coastal belt; Fce, Franciscan central belt; Fe, Franciscan eastern belt; GVw, Great Valley western belt; GVC, Great Valley central belt; Gve, Great Valley eastern belt; SNF, Sierra Nevada Foothills belt; SNEK, Sierra Nevada Early Cretaceous plutonic belt; SNLK, Sierra Nevada Late Cretaceous plutonic belt; SF, San Francisco. See Fig. 8 for subsurface characteristics of Great Valley forearc belts. Belts broadly follow those of Williams and Graham (2013), Ernst (2018), and Dumitru et al. (2018) and references therein.



possibly as a trench-trench-transform triple junction (Fig. 5), similar to the Tehuantepec triple junction along the southern Mexico convergent margin (Fig. 1).

Nacimiento fault

Models

Three models have been proposed to explain the juxtaposition of the Franciscan Complex and Salinia along the Nacimiento fault: (i) dextral slip, (ii) reverse slip, and (iii) sinistral slip (Page 1970). Dextral slip is ruled out because “no viable candidates for an offset segment of the Salinian block are known anywhere to the north along the Cordilleran margin (Dickinson 2004)” (Dickinson et al. 2005, p. 14).

Reverse-slip model

Reverse slip on the Nacimiento fault has been favored by many workers and has been especially championed by Hall (1991), Saleeby (2003), and Hall and Saleeby (2013). Without delving into all of the detailed criticisms of Dickinson et al. (2005) by Hall and Saleeby (2013), many of which involve nomenclatural disagreements about which is the true Nacimiento fault, I suggest the following major difficulties with a model that includes purely reverse slip along the Nacimiento fault:

1. The entire forearc basin, with its ophiolitic basement, the foothill metamorphic belt, and the western batholithic belt are “missing” along the Nacimiento fault (Page 1981, 1982; Dickinson 1983). All of these components would have underthrust the eastern batholith by ~150 km. The reverse fault would have nucleated in the center of the batholith. Alternatively, the entire batholith was uplifted and gravitationally spread, so that the Nacimiento fault is the surface expression of gravity slides (Saleeby 2003). Ignoring the mechanical difficulties of either of these scenarios, they both fail the actualistic test. In spite of several modern examples of low-angle subduction (e.g., parts of the Andean system), there is no example of any process approaching these scenarios in either scale or type.
2. “Subduction erosion”, which has been documented in some modern trenches, does not approach the scale needed to “erode” ~150 km of a forearc basin, metamorphic belt, and half of a batholith, especially in close proximity to adjoining accretionary continental margins (e.g., concurrent Franciscan

accretion to the north and south of Salinia). Rather, where subduction erosion does occur, it is associated with minimal sedimentary cover in the trench (von Huene and Scholl 1991; Cliff and Vannucchi 2004). Subduction erosion does not exist in trenches with abundant sediment, as in the Laramide Franciscan trench.

3. Abundant arkosic sediment that was supplied to the Laramide trench along the entire California convergent margin was derived from the dissecting batholithic roots of the arc, whose activity had migrated eastward during low-angle subduction. The latest Cretaceous–Paleogene trench was likely full of sediment and strongly accretionary, as documented in the northern Coast Ranges Franciscan Complex (e.g., Dumitru et al. 2015, 2018).
4. This arkosic sediment was both accreted into the frontal prism and underplated beneath the continental margin during low-angle subduction. The San Emigdio – Rand – Sierra de Salinas – Pelona – Orcopia (or POR) schist is found in thrust contact beneath the continental margin wherever uplift and erosion have exposed it (e.g., Barth et al. 2003; Grove et al. 2003; Jacobson et al. 2011). It would be impossible to expose the underplated schist over such a wide area without seeing any hint of the “missing forearc and western batholith” that was supposedly underthrust at the same time (Dickinson et al. 2005; Jacobson et al. 2011). In addition, having typical Franciscan Complex juxtaposed against Salinia directly west of a fenster exposing the meta-arkosic schist of Sierra de Salinas (e.g., Kidder et al. 2003; Kidder and Ducea 2006; Ducea et al. 2009) presents insurmountable geometric obstacles for the reverse-fault model. The only architecture consistent with these observations involves thrusting the schist over the “missing” western arc and forearc (e.g., Johnston et al. 2018), in which case the protolith for the POR schist would consist of forearc sand, rather than trench sand. In this scenario, there would be no mechanism to incorporate oceanic components such as metabasite, metachert, marble, serpentinite, and talc-actinolite rock into the POR schist, together with the dominant arkosic sand that was eroded, transported, deposited, and rapidly accreted and metamorphosed during subduction (Jacobson et al. 2011).

Sinistral-slip model

Sinistral slip of hundreds of kilometres along the Nacimiento fault system, as proposed by Dickinson (1983) and modified by Dickinson et al. (2005), explains all observations without the difficulties of the reverse-fault model. Oblique subduction of an aseismic ridge provides a mechanism to induce sinistral slip along the California convergent margin, as illustrated by Jacobson et al. (2011) and Fig. 5. On the other hand, Singleton and Cloos (2012) noted that uncertainties concerning Farallon – North American convergence vectors are sufficient to allow sinistral oblique convergence during Laramide time without an aseismic ridge. Regardless of the mechanism to induce sinistral slip, migration of a stable trench-trench-transform triple junction southeastward along the California margin would successively expose inboard parts of the margin, so that successively southeastward and inboard components would be exposed at the new trench. The triple junction would result in a stable configuration if the northern subduction zone paralleled the sinistral fault (Fig. 6).

Current constraints are insufficient to determine precise locations for the triple junction through time, orientations of the three plate boundaries, or plate velocities. The original model of Dickinson (1983) showing a westward protruding margin prior to sinistral slip (reproduced by Jacobson et al. (2011; their fig. 10)) likely should be replaced by a straight margin, in which case the Nacimiento fault could cut inboard at a higher angle to the trench, as shown in Fig. 5 and in fig. 10 in Johnston et al. (2018). Increasing the angle between the continental margin and the Nacimiento fault

Fig. 5. Schematic illustration of possible configuration of triple junction where Farallon, North American, and Peninsular Ranges plates interacted during subduction of an aseismic ridge, as discussed in text. Oblique interaction of seismic ridge with subduction zone would have induced southeastward displacement of the Peninsular Ranges plate, thus exposing increasingly inboard parts of North American margin at lengthening subduction zone northwest of triple junction. Sinistral slip along Nacimiento fault would have accommodated this motion. Geometric and kinematic details are poorly constrained, but fundamental relations are robust and are based on analog of current southern Mexican margin (Fig. 1). Inspired by Dickinson (1983) and Jacobson et al. (2011).

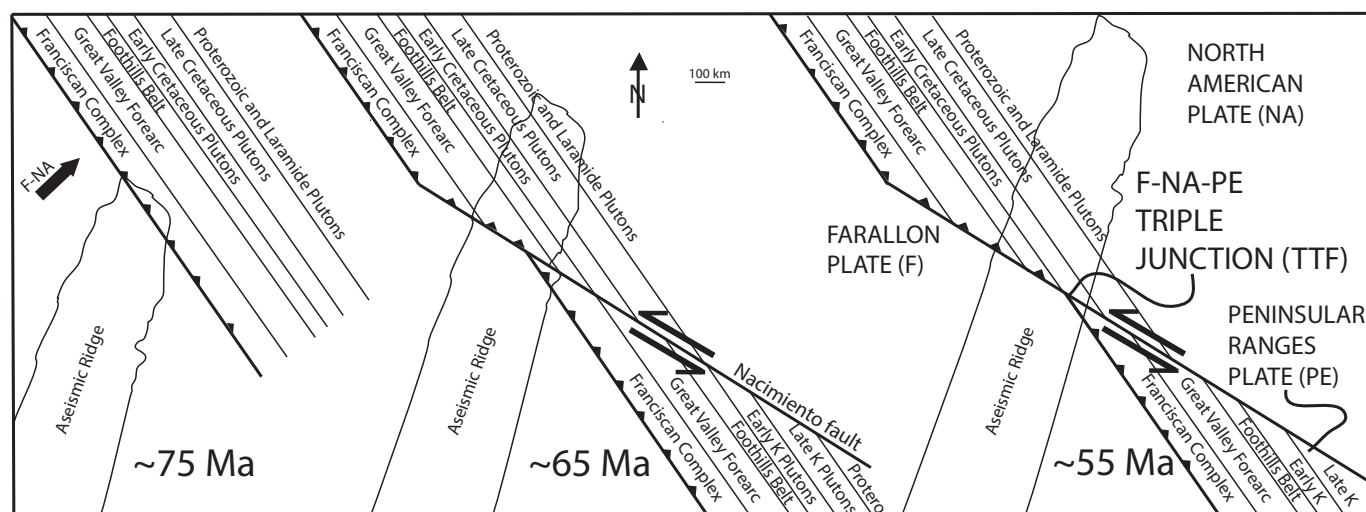
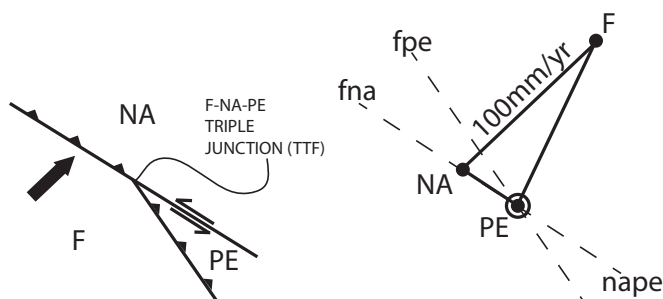


Fig. 6. Triple-junction vector triangle and stability test (after McKenzie and Morgan 1969; Dickinson and Lawton 2001). With Farallon (F) – North American (NA) convergence rate set at 100 mm/year, Nacimiento fault slip rate of 35 mm/year is reasonable, and Farallon – Peninsular Ranges (PE) convergence continues, as shown. Triple junction is stable as long as Farallon – North American trench is parallel to Nacimiento fault, as illustrated by intersection of dashed lines (fna, fpe, and nape) at velocity PE. Thus, triple junction has velocity of PE (i.e., both migrate southeastward along coast). Refinement of geometry and kinematics awaits further investigation.



decreases the slip needed to superpose the Nacimiento Franciscan block with Salinia, thus allowing the Nacimiento Franciscan block to be restored farther south prior to Nacimiento fault slip (more consistent with detrital zircon provenance signatures) (e.g., Chapman et al. 2016; Johnston et al. 2018). In any case, the fundamental relations illustrated in Figs. 5 and 6 are robust and are based on the actualistic example of the Tehuantepec triple junction.

Sinistral slip along the Nacimiento fault during Laramide flat-slab subduction would have obliquely truncated the forearc margin of California and thus created a very dynamic setting that would include local rapid uplift and subsidence along the fault trend, as is typical of strike-slip systems (e.g., Crowell 1974a, 1974b; Reading 1980; Christie-Blick and Biddle 1985; Nilsen and Sylvester 1995). The evolving continental margin along the southwestern coast of Salinia likely experienced rapid subsidence of local fault-controlled basins resting directly on recently exhumed batholithic crust, as has been described throughout Salinia (e.g., Nilsen

and Clarke 1975; Graham 1978; Howell and Vedder 1978; Nilsen 1987; Grove 1993). A striking characteristic of these Maastrichtian – Early Eocene (71–49 Ma) basins is rapid cutting of submarine canyons into batholithic basement, with subsequent filling with conglomerate. Cross-section A–A' of Fig. 1 illustrates a possible modern analog.

Singleton and Cloos (2012) documented mélangé fabrics in the Franciscan Complex near San Simeon in the Nacimiento block that are consistent with sinistral slip during late stages of accretion. These observations are consistent with relations illustrated in Fig. 5, whereby subduction of the Nacimiento Franciscan Complex along the southwest side of the Peninsular Ranges plate would occur concurrently with sinistral slip along the Nacimiento fault located to the northeast.

An additional speculative aspect of this model is that lateral removal of the outer part of the Franciscan Complex at the original location of the triple junction in central California (75–65 Ma of Fig. 5) could induce rapid cutting of submarine canyons in the adjoining forearc basin as gradients from the forearc basin to the new trench northwest of the triple junction steepened. The Martinez, Meganos, and Princeton submarine canyons were cut into the Sacramento Valley during the Early Paleocene (66–62 Ma) (Almgren 1978; Dickinson et al. 1979; Redwine 1984). The preserved lower reaches of these now-filled canyons converge near the San Francisco Bay area, suggesting that this may have been close to the location of the triple junction at this time.

Model tests

The model of a triple junction with sinistral Nacimiento fault makes testable predictions:

1. POR schist should young from northwest to southeast during Laramide flat-slab subduction.
2. Initiation of forearc deep-marine sedimentation directly on Mesozoic magmatic arc basement of Salinia should young from northwest to southeast.
3. Detrital zircon age spectra and other provenance indicators should correlate with potential source areas following palinspastic reconstruction.
4. Metamorphic and plutonic belts of the batholithic belt should realign following palinspastic reconstruction.

5. Great Valley forearc belts should realign following palinspastic reconstruction.
6. Franciscan belts should realign following palinspastic reconstruction.

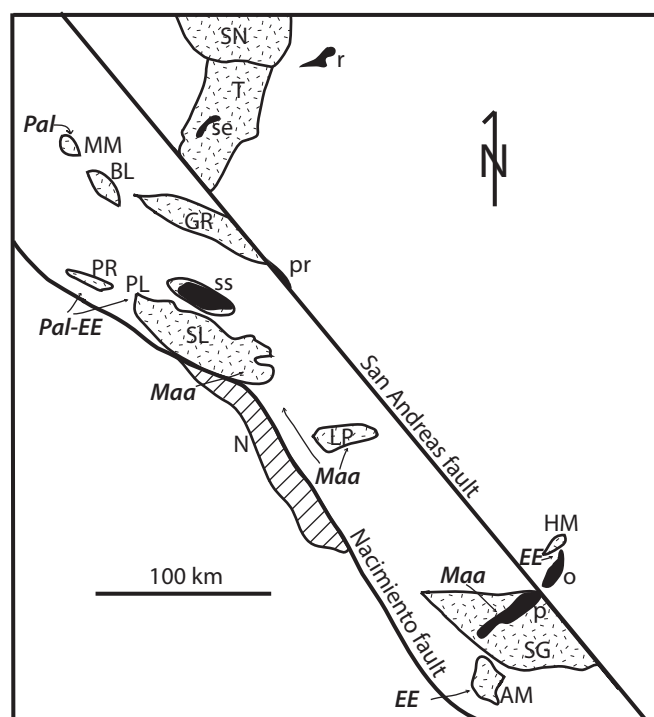
Discussion

These six tests of the sinistral-slip model for the Nacimiento fault have been applied to varying degrees. Details of the geometry, velocities, and locations of the triple junction through time are poorly constrained but should be refined by the results of these tests. In addition, all tests must rely on accurate Cenozoic palinspastic reconstruction of the entire California margin, a formidable task in itself (e.g., [Nicholson et al. 1994](#); [Dickinson et al. 2005](#); [Jacobson et al. 2011](#); [Sharman et al. 2013, 2015](#); [Ingersoll et al. 2014](#); [Ingersoll and Coffey 2017](#); and references therein). A key question is how does the Nacimiento fault continue southeastward between the San Gabriel block and the northern Peninsular Ranges, where it is intersected by the San Andreas fault (Figs. 2, 5). Restoration of San Andreas slip may indicate that sinistral slip along the Nacimiento fault contributed to sinistral slip along the trend of the older Coahuila-Tamaulipas transform (e.g., [Dickinson and Lawton 2001](#)) or Mojave-Sonora megashear (e.g., [Anderson et al. 2005](#)).

Herein is a summary of the current state of these tests.

1. [Jacobson et al. \(2011, fig. 3\)](#) documented general northwest-to-southeast younging of the schist bodies, based on detrital zircon to constrain maximum depositional age and metamorphic ages to constrain minimum depositional age. On the other hand, schist ages based on this same data set can also be interpreted as representing southwest-to-northeast younging. Conversely, new dates from schist exposures farther from the coast in Arizona complicate the southwest-northeast younging interpretation (e.g., [Jacobson et al. 2017](#); [Seymour et al. 2018](#)). A combination of northwest-southeast younging and southwest-northeast younging would result in general eastward younging, not inconsistent with the model. Additional detrital zircon and metamorphic data may clarify these relations, but Cenozoic palinspastic reconstructions of the schist bodies are the biggest unknown.
2. [Figure 7](#) presents a preliminary palinspastic map, with age ranges based on published data. There are no forearc marine strata older than Maastrichtian (71–66 Ma) nonconformably on the Salinian crystalline basement ([Dickinson et al. 2005](#)). The ages of basal deep-marine (dominantly submarine canyon) deposits, as shown on the palinspastic map of [Fig. 7](#), neither support nor negate the sinistral-slip model. The presence of Maastrichtian basal ages in the northwestern Salinian terrane and Early Eocene basal ages only in the southeast support northwest-to-southeast younging. In addition, strata young southeastward from nonconformable Maastrichtian strata in the La Panza Range to nonconformable Eocene strata in the Alamo Mountain area ([Fig. 7](#)). On the other hand, Paleocene (and possibly Early Eocene) basal ages within the northwestern exposures do not support northwest-to-southeast younging. The available data from poorly preserved scattered remnants of once more-extensive deposits may represent northeastward transgressing shorelines and deep-marine equivalents more than southeastward younging. In the San Gabriel Mountains area, a small remnant of Maastrichtian strata is overlain by coarse-grained deep-marine Paleocene strata ([Kooser 1982](#)). To the northeast, these deep-marine deposits are interpreted as having connected with Early Eocene submarine canyon deposits in the Orocopia Mountains area, thus representing backfilling during northeastward transgression ([Advocate et al. 1988](#); [Ingersoll et al. 2014](#)). Northeast onlap of Maastrichtian–Eocene strata is also documented in the central Santa Lucia Range, where Paleocene–Eocene strata are

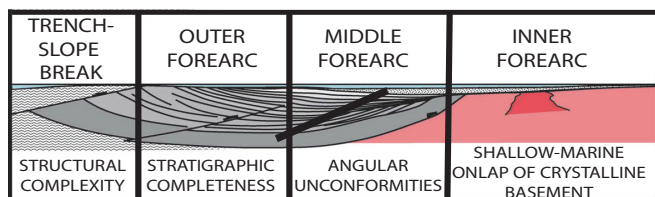
Fig. 7. Pre-Oligocene schematic palinspastic map for Salinia and adjoining areas. Dextral slip along San Andreas fault and related faults has been removed, as well as documented vertical-axis rotations and shortening across Salinia and southern California. San Andreas fault is shown as a straight line roughly parallel to North American – Pacific plate motion (i.e., parallel to modern San Andreas fault in central California), based on assumption that originally straight transform has been severely deformed during last 5–6 million years (e.g., [Ingersoll and Coffey 2017](#)). Reconstruction draws freely from [Dickinson et al. \(2005\)](#), [Burnham \(2009\)](#), [Jacobson et al. \(2011\)](#), and [Sharman et al. \(2013, 2015\)](#). Restored locations of modern exposures of batholithic rocks are indicated by granite symbol: AM, Alamo Mountain; BL, Ben Lomond Mountain; GR, Gabilan Range; HM, Hayfield Mountains; LP, La Panza Range; MM, Montara Mountain; PL, Point Lobos; PR, Point Reyes area; SG, San Gabriel Mountains; SL, Santa Lucia Range; SN, Sierra Nevada; T, Tehachapi Mountains. Restored locations of modern exposures of San Emigdio – Rand – Sierra de Salinas – Pelona – Orocopia schist are indicated by solid black: o, Orocopia Mountains; p, Sierra Pelona and Mount Pinos; pr, Portal Ridge; Rand Mountains; se, San Emigdio Mountains; ss, Sierra de Salinas. Nacimiento block (primarily Franciscan Complex) is indicated by diagonal lines (N). Ages of basal submarine canyon deposits nonconformable on Salinian basement are indicated by bold italic font: ***Maa***, Maastrichtian (71–66 Ma); ***Pal***, Paleocene (66–56 Ma); ***EE***, Early Eocene (56–49 Ma) (radiometric ages based on [Gradstein et al. 2004](#)). Sources for stratigraphic ages: AM ([Squires 1987](#)); HM (Maniobra Formation; [Crowell and Susuki 1959](#); [Advocate et al. 1988](#)); LP ([Chipping 1972](#); [Saul 1986](#); [Sliter 1986](#); [Grove 1993](#)); MM (strata of Point San Pedro; [Nilsen and Yount 1981](#)); PL (Carmelo Formation; [Bowen 1965](#); [Clifton 1981](#)); PR (Point Reyes Conglomerate; [Galloway 1977](#); [Clark et al. 1984](#)); SG (San Francisquito Formation; [Kooser 1982](#)); SL ([Ruetz 1979](#)).



also interpreted as submarine canyon deposits ([Graham 1978, 1979](#); [Ruetz 1979](#); [Anderson et al. 2006](#)). Thus, southeastward younging of basal strata along the southwestern edge of Salinia may have overlapped in age with northeastward onlap as the seaward side of Salinia subsided.

3. Are detrital zircon age spectra and other provenance indicators (e.g., [Seiders and Cox 1992](#)) consistent with proposed fault offsets? This question is debated as data are being rap-

Fig. 8. Tectonostratigraphic cross-section showing a hypothetical reconstruction of the Sacramento basin at the end of Santonian time. Heavy black line indicates approximate position of outcrop section along west side of Sacramento Valley (see Fig. 4). Relations west of heavy black line are highly inferential. Subsurface relations are partially based on Constenius et al. (2000). Modified from Williams and Graham (2013). [Colour online.]



idly generated and synthesized throughout California (e.g., DeGraaff-Surpless et al. 2002; Barbeau et al. 2005; Jacobson et al. 2011; Dumitru et al. 2015, 2018; Sharman et al. 2015; Chapman et al. 2016; Hartford and Chapman 2018; Johnston et al. 2018). Any answer to this question is critically dependent on details of Neogene palinspastic reconstruction of coastal California (as schematically depicted in Fig. 7), as well as on Laramide-age reconstruction during movement along the Nacimiento fault (as schematically depicted in Fig. 5). Small changes in slip rate, fault orientation, fault location, and pre-existing terrane configurations, as shown in Fig. 5, could cause significant changes in Laramide palinspastic reconstruction. Matching of detrital zircon age spectra with source areas northeast of the San Andreas transform system is also dependent on Cenozoic palinspastic reconstruction of extended terrane of the Basin and Range Province (e.g., Wernicke 1992; Dickinson and Wernicke 1997; Dickinson 2002, 2006, 2013), especially in the Mojave Block (Fig. 2). A major concern in matching age spectra of subduction complexes with possible onshore sources is the likelihood of extensive coast-parallel transport of turbidite detritus within trenches. My conclusion is that the jury is still out on how to best match detrital zircon age spectra and other provenance indicators with source areas during and before Laramide deformation.

4. Does this reconstruction realign metamorphic and plutonic belts in the batholithic belt, including compositional, isotopic, and age boundaries? As demonstrated by Dickinson (1983), Dickinson et al. (2005), and Jacobson et al. (2011), the answer is "Yes". Jacobson et al. (2011, fig. 10; after Dickinson 1983) illustrated how the Foothills belt and plutonic age belts of the Sierra Nevada, Salinia, and Peninsular Ranges align using the Nacimiento sinistral-slip model. Dickinson et al. (2005, figs. 10, 14) demonstrated how the $^{87}\text{Sr}/^{86}\text{Sr} = 0.7065$ isopleth and age trends in the southern Sierra Nevada and Salinia match following the palinspastic reconstruction, as illustrated in modified form in Fig. 7. Matching these trends with comparable trends in the Peninsular Ranges batholith will provide an important additional test.
5. Are pre-Laramide Great Valley forearc belts realigned following palinspastic reconstruction? Of the six tests, this one likely requires the most subtle evaluation. Williams and Graham (2013) provided a synthesis of forearc architecture for the Sacramento Valley, as represented in Fig. 8. The predictive value of this architecture is that it identifies four forearc zones: (i) trench slope break, involving structural complexity and interaction with the inner part of the Franciscan belts; (ii) outer forearc, characterized by stratigraphic completeness, with the potential for strata approaching 18 km in thickness, deposited on ophiolitic crust; (iii) middle forearc, characterized by angular unconformities at the transition between oceanic and magmatic arc crust; and (iv) inner forearc,

characterized by shallow-marine onlap of crystalline basement.

Most exposures of forearc strata in southern California and Baja California (e.g., Nilsen and Abbott 1981; Abbott 1984) represent the inner forearc, where Upper Cretaceous strata are nonconformable on the western edge of the Peninsular Range batholith. Forearc strata exposed in the western San Joaquin Valley (e.g., Mansfield 1979; Ingersoll 1988) and in parts of the Nacimiento terrane (e.g., Page 1981; Johnston et al. 2018) have significant unconformities (primarily middle Cretaceous is absent), which are typical of the middle forearc. Additional analyses and palinspastic reconstructions are needed to test these relations.

6. Are Franciscan belts realigned following palinspastic reconstruction? The answer to this question is similar to the answer for 5; more analyses are needed to more clearly define Franciscan belts within the Nacimiento block, as well as along the western side of the San Joaquin Valley.

Conclusions

These speculations indicate that sinistral slip of hundreds of kilometres likely occurred along the Nacimiento fault during Laramide flat-slab subduction (~75–55 Ma). Although many details of geometry and kinematics remain to be determined, all tests of this hypothesis have failed to nullify it. In addition, the Nacimiento sinistral-slip hypothesis is plausible, based on comparison with actualistic examples, especially the Tehuantepec trench-trench-sinistral transform triple junction of southern Mexico. Not only does this modern example provide an actualistic example, it also suggests that several "erosional" subduction zones are more plausibly explained by strike-slip truncation of forearcs, as discussed herein.

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