**Geoscience Canada**
Journal of the Geological Association of Canada
Journal de l’Association Géologique du Canada

# Arc and Slab-Failure Magmatism in Cordilleran Batholiths II – The Cretaceous Peninsular Ranges Batholith of Southern and Baja California

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Volume 41, numéro 4, 2014

URI : https://id.erudit.org/iderudit/1062260ar
DOI : https://doi.org/10.12789/geocanj.2014.41.059

Éditeur(s)

The Geological Association of Canada

ISSN

0315-0941 (imprimé)
1911-4850 (numérique)

Citer cet article

Hildebrand, R. & Whalen, J. (2014). Arc and Slab-Failure Magmatism in Cordilleran Batholiths II – The Cretaceous Peninsular Ranges Batholith of Southern and Baja California. *Geoscience Canada*, *41*(4), 399–458. https://doi.org/10.12789/geocanj.2014.41.059

Résumé de l'article

Depuis la fin des années 1960, Warren Hamilton a proposé que les grands batholites de la Cordillère de l'ouest des Amériques sont les racines d’arcs volcaniques andéens issus de la subduction vers l'est de longue durée, et depuis la plupart des géologues ont emboîté le pas, bien qu’un nombre croissant d’indications montrent que de nombreux batholites de la Cordillère sont des entités composites complexes qui se sont développés lors d’intervalles intenses de contraction et d’exhumation, durant et entre les périodes de magmatisme. Le batholite Peninsular Ranges du Sud de la Californie et de Baja California est un excellent endroit permettant de démêler les choses parce qu'il y a beaucoup de données et parce qu'il est composé longitudinalement de deux parties: une partie occidentale plus ancienne, faiblement à modérément déformée, de roches volcaniques de faible métamorphisme et de roches plutoniques épizonales âgées d’environ 128 Ma à 100 Ma; et, d’un segment plus à l'est de roches amphiboliques déformées recoupées par des roches de composition zonée des complexes mésozonaux plutoniques de la suite de la Posta, mises en place entre 99 Ma et 86 Ma. Bien que les plutons de la suite La Posta sont généralement considérés comme le produit d’une subduction soutenue vers l’est, ils posent problème, parce qu'avec leurs roches encaissantes, ils ont été rapidement exhumés de profondeurs aussi grandes que 23 km, et érodées durant et juste après leur mise en place, contrairement aux plutons des arcs magmatiques, qui sont généralement mis en place dans les zones de subsidence. Dans le présent article, nous proposons une solution à ce problème, avec un modèle de subduction vers l'ouest qui conduit à un magmatisme d'arc du secteur ouest, l'arc composite de Santiago Peak-Alisitos, durant la période d’environ 128 Ma à 100 Ma. Le magmatisme d’arc s’est arrêté lorsque l'arc est entré en collision avec une marge passive à pendage ouest du début du Crétacé, il y a environ 100 Ma. Lors de la collision, le contraste de flottabilité entre la croûte continentale du bloc de est et la lithosphère océanique qui y est rattachée a conduit à l'avortement de la plaque plongeante. La cassure a entrainé la remontée de l’asthénosphère sous-jacente, sa fusion adiabatique, et sa remontée dans la plaque supérieure pour former les grands complexes zonés de tonalite-granodiorite-granite de La Posta. Bien que de composition similaire aux plutons d'arc à bien des égards, les exemples des segments de batholites de Californie du Sud et de Baja ont une géochimie qui indique qu'ils proviennent de la fusion partielle de l’asthénosphère à des niveaux plus profonds dans le manteau que les magmas d'arc typiques, à l’intérieur du domaine de stabilité du grenat. Ce qui correspond à une remontée d’asthénosphère à travers une dalle de plaque inférieure cassée. Nous connaissons des roches semblables avec les relations géologiques similaires dans d'autres batholites de la Cordillère des Amériques, tel celles de la Sierra Nevada, ce qui nous amène à penser que le magmatisme de cassure de plaque est commun, tant spatialement et temporellement.

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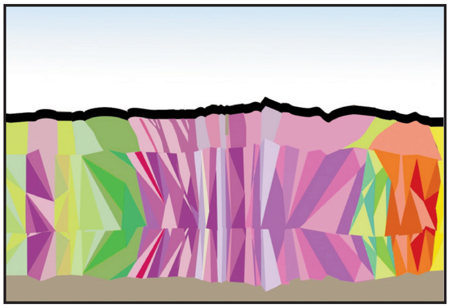

## Arc and Slab-Failure Magmatism in Cordilleran Batholiths II – The Cretaceous Peninsular Ranges Batholith of Southern and Baja California

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### SUMMARY

Ever since the late 1960s when Warren Hamilton proposed that the great Cordilleran batholiths of the western Americas are the roots of volcanic arcs like the Andes and were generated by longstanding eastward subduction, most geologists have followed suit, despite the evergrowing recognition that many Cordilleran batholiths are complex, composite bodies that developed with intervals of intense shortening and exhumation between and during periods of magmatism.

The Peninsular Ranges batholith of Southern and Baja California provides a superb place to unravel the complexities because there is a lot of data and because it is longitudinally composed of two parts: an older western portion of weakly to moderately deformed, low-grade volcanic and epizonal plutonic rocks ranging in age from ~128–100 Ma; and a more easterly sector of deformed amphibolite grade rocks cut by compositionally zoned, mesozonal plutonic complexes of the La Posta suite, emplaced from 99–86 Ma. While plutons of the La Posta suite are generally considered to be the product of continued eastward subduction, they are enigmatic, because they and their wall rocks were rapidly exhumed from as deep as 23 km and eroded during, and just after, their emplacement, unlike plutons in magmatic arcs, which are generally emplaced in zones of subsidence.

Here we resolve the enigma with a model where westward-dipping subduction led to arc magmatism of the western sector, the Santiago Peak–Alisitos composite arc, during the period ~128–100 Ma. Arc magmatism shut down when the arc collided with a west-facing Early Cretaceous passive margin at about 100 Ma. During the collision the buoyancy contrast between the continental crust of the eastern block and its attached oceanic lithosphere led to failure of the subducting slab. The break-off allowed subjacent asthenosphere to upwell, adiabatically melt, and rise into the upper plate to create the large zoned tonalite–granodiorite–granite complexes of the La Posta suite. While compositionally similar to arc plutons in many respects, the examples from the Southern California and Baja segments of the batholith have geochemistry that indicates they were derived from partial melting of asthenosphere at deeper levels in the mantle than typical arc magmas, and within the garnet stability field. This is consistent with asthenosphere upwelling through the torn lower-plate slab. We identify kindred rocks with similar geological relations in other Cordilleran batholiths of the Americas, such as the Sierra Nevada, which lead us to suggest that slab failure magmatism is common, both spatially and temporally.

### SOMMAIRE

Depuis la fin des années 1960, Warren Hamilton a proposé que les grands batholites de la Cordillère de l'ouest des Amériques sont les racines d'arcs volcaniques andéens issus de la subduction vers l'est de longue durée, et depuis la plupart des géologues ont emboîté le pas, bien qu'un nombre croissant d'indications montrent que de nombreux batholites de la Cordillère sont des entités composites complexes qui se sont développés lors d'intervalles intenses de contraction et d'exhumation, durant et entre les périodes de magmatisme.

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## INTRODUCTION

Cordilleran batholiths are elongate masses – many over 1000 km long – of gregarious plutons emplaced within the American Cordillera during the Cretaceous (Larsen et al. 1958). They comprise hundreds, if not thousands, of individual plutons, dykes and plugs ranging in composition from gabbro to granite and are related to many important mineral deposits of the region.

In his now classic report on the geology of the US–Canada boundary region, Reginald Daly recognized that the batholiths were emplaced in mountain belts (Daly 1912), but ultimately it was Hamilton (1969a, b) who associated the batholiths with subduction: specifically, long-lived eastward subduction of Pacific lithosphere beneath the Americas. He argued, based on previous work elsewhere (Hamilton and Myers 1967), that the batholiths were the roots of volcanoes built along the western margins of the Americas and were analogous to the modern Andean volcanic arc. These concepts provided a basis for the more recent interpretation of Cordilleran batholiths as magmatic arc rocks emplaced during compressional deformation and great crustal thickening, which is considered to be related to (1) voluminous influx of magmas from the mantle; (2) underthrusting of the crust in either a fore-arc or retro-arc setting, commonly with shallow subduction; or (3) a combination of the two (Isacks 1988; Allmendinger et al. 1997; Ducea 2001; Kay et al. 2005; Grove et al. 2008; DeCelles et al. 2009; Paterson et al. 2012; Chin et al. 2012). There are, however, complications.

Based on his work in California's Sierra Nevada, the tireless Swedish-American economic geologist, Waldemar Lindgren, knew in a general way that irrespective of age, plutonic compositions there graded from more mafic in the west to more siliceous in the east (Lindgren 1915), but it was up to the great American petrologist, Arthur Buddington, to clearly articulate that the titanic Cordilleran-type batholiths of western North America could be divided longitudinally into parts: (1) a western zone of plutons with dominantly dioritic and more mafic compositions; and (2) a more easterly tract of more siliceous and potassic-rich plutons, such as granodiorite and quartz monzonite (Buddington 1927). By 1948 Larsen had also realized that the more mafic bodies in the Peninsular Ranges batholith of Southern and Baja California were confined to the western parts; but despite these early forays into batholithic division, it took until 1959 for J.G. Moore to carry the observations over the length of North America, and name the boundary between the zones the quartz diorite line (Moore 1959; Moore et al. 1961).

The idea took root and isotopic investigations by Kistler (Kistler and Peterman 1973, 1978; Kistler 1990) led to recognition that the eastern and western sectors of the Sierra Nevada batholith have different basements. Similarly, detailed field studies and geochronology within the Coast batholith of Canada and southeastern Alaska led to the realization that it too could be readily divided into two parts, there separated by the collapsed Nutzotin-Dezadeash-Gravina basin and related fold–thrust belt (Rubin et al. 1990; Journeay and Friedman 1993; Gehrels et al. 2009). And farther south, additional studies within the Peninsular Ranges batholith demonstrated that it could be readily divided into an older, more westerly, magnetite-bearing suite and a younger, ilmenite bearing, high Sr/Y suite to the east (Gastil et al. 1975, 1990; Silver et al. 1979; Silver and Chappell 1988; Kimbrough et al. 2001; Tulloch and Kimbrough 2003).

So despite widespread recognition among Cordilleran geologists that the major Cretaceous batholiths appeared to be constructed of two halves (Fig. 1), our understanding of Cordilleran batholiths has barely progressed since the late 1960s, largely because most workers still follow Hamilton's original concept that the Sierran and Peninsular Ranges batholiths were built entirely by eastward subduction of oceanic lithosphere beneath the western margin of the Americas (Todd et al. 1988, 2003;

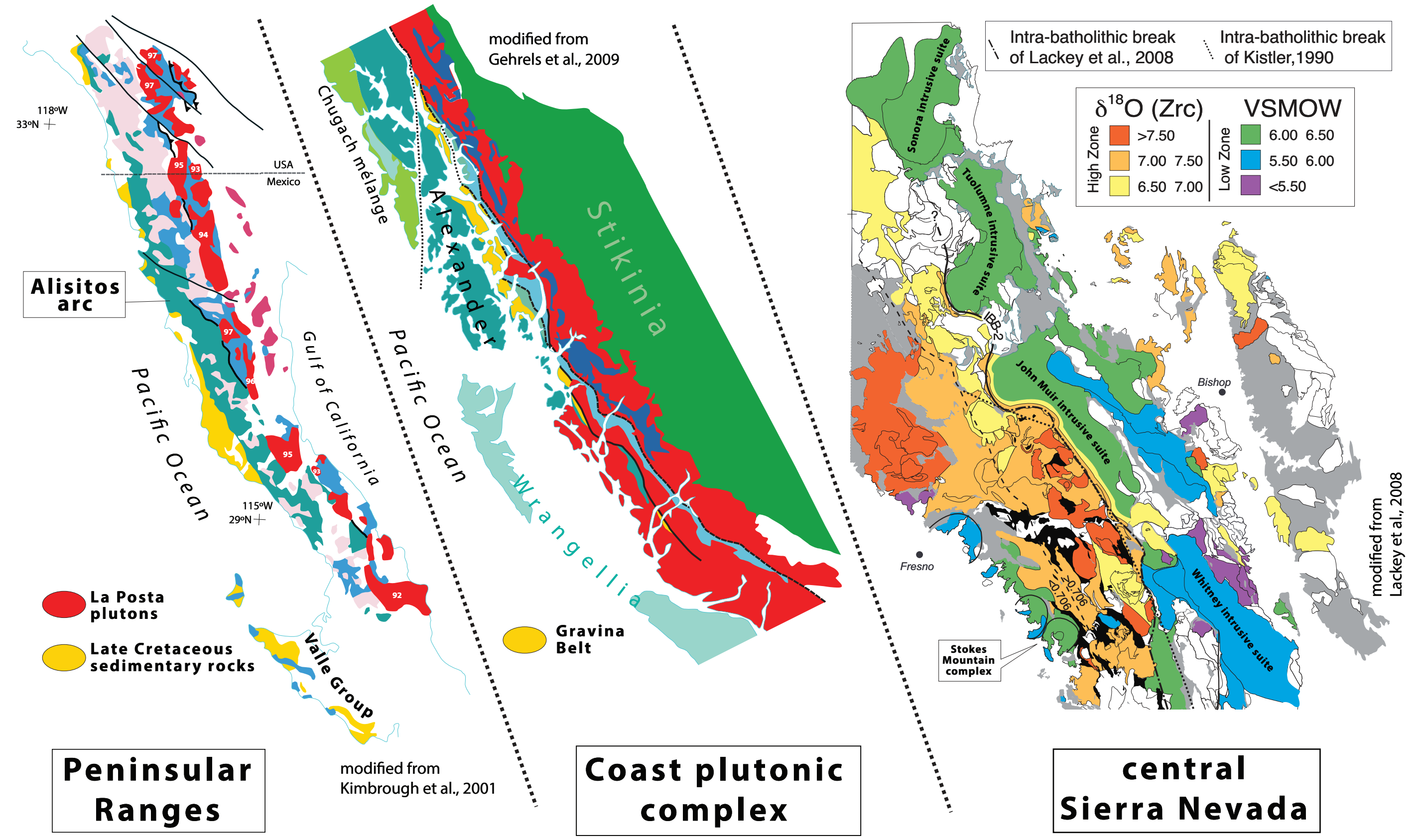

**Figure 1.** Sketch maps illustrating the composite nature of three Cordilleran batholiths of North America as recognized by others. Peninsular Ranges modified from Kimbrough et al. (2001); Coast plutonic complex of British Columbia modified from Gehrels et al. (2009); central Sierra Nevada batholith adapted from Lackey et al. (2008).

Walawender et al. 1990; Kimbrough et al. 2001, 2014a; Ducea 2001; Schmidt et al. 2002, 2009; Grove et al. 2003; Tulloch and Kimbrough 2003; Wetmore et al. 2003; Busby 2004; Lee et al. 2007; Gehrels et al. 2009; DeCelles et al. 2009; Paterson et al. 2012; Kimbrough et al. 2014a; Shaw et al. 2014). In this paradigm, two subvariant models, both with eastward-directed subduction, dominate the discussion: (1) the younger, more siliceous and potassic easterly plutons are related to, and thus document, progressive shallowing of eastward subducting oceanic lithosphere with or without subduction of the older arc and forearc sediments; or (2) the western sector was separated from the eastern sector by a narrow back-arc basin, and following closure, subduction-related magmatism simply continued to produce the eastern sector of the batholiths.

In his regional synthesis of the North American Cordillera, Hildebrand (2013) noted that within the Sierran and Peninsular Ranges batholiths there was a period of intense deformation at ~100 Ma, which occurred between the magmatism of the older western and the younger eastern sectors. He outlined a model in which the deformation was caused by a collision between the two sectors, and that plutons emplaced during and after collision likely originated by break-off and failure of the descending oceanic lithosphere due to the buoyancy contrast between continental and oceanic lithosphere. As the detached slab sank into the mantle, the widening gap allowed the subjacent asthenosphere to upwell and melt adiabatically to create magmas that rose into, and interacted with, the overlying mantle lithosphere and lower crust. It was those magmas that led to the younger, post-collisional halves of Cordilleran batholiths.

For this contribution then, we examine the geology and geochemistry of the Peninsular Ranges batholith of Southern and Baja California in the context of arc, collision and slab failure to elucidate the geological development of the batholith, test the viability of the model, identify possible geochemical characteristics of slab failure magmas, and end by integrating our results with other similar magmatic suites. This is the second in a planned series on Cretaceous batholiths of the American Cordillera (Hildebrand and Whalen 2014) and is an outgrowth of both authors' long-standing interest in plutons and batholithic terranes (Hildebrand 1981, 1984; Whalen 1985; Whalen and Chappell 1988).

## GEOLOGICAL SETTING

The Peninsular Ranges batholith, which comprises hundreds of distinct plutons, extends over 1000 km from just south of Los Angeles, California, at 34ºN to at least 28ºN near Guerrero Negro (Fig. 2), located just south of the frontier of Baja Norte de California (Gastil et al. 1975). As the western half forms a continuous linear belt of magnetic anomalies visible beneath the extensive Cenozoic volcano-sedimenta-

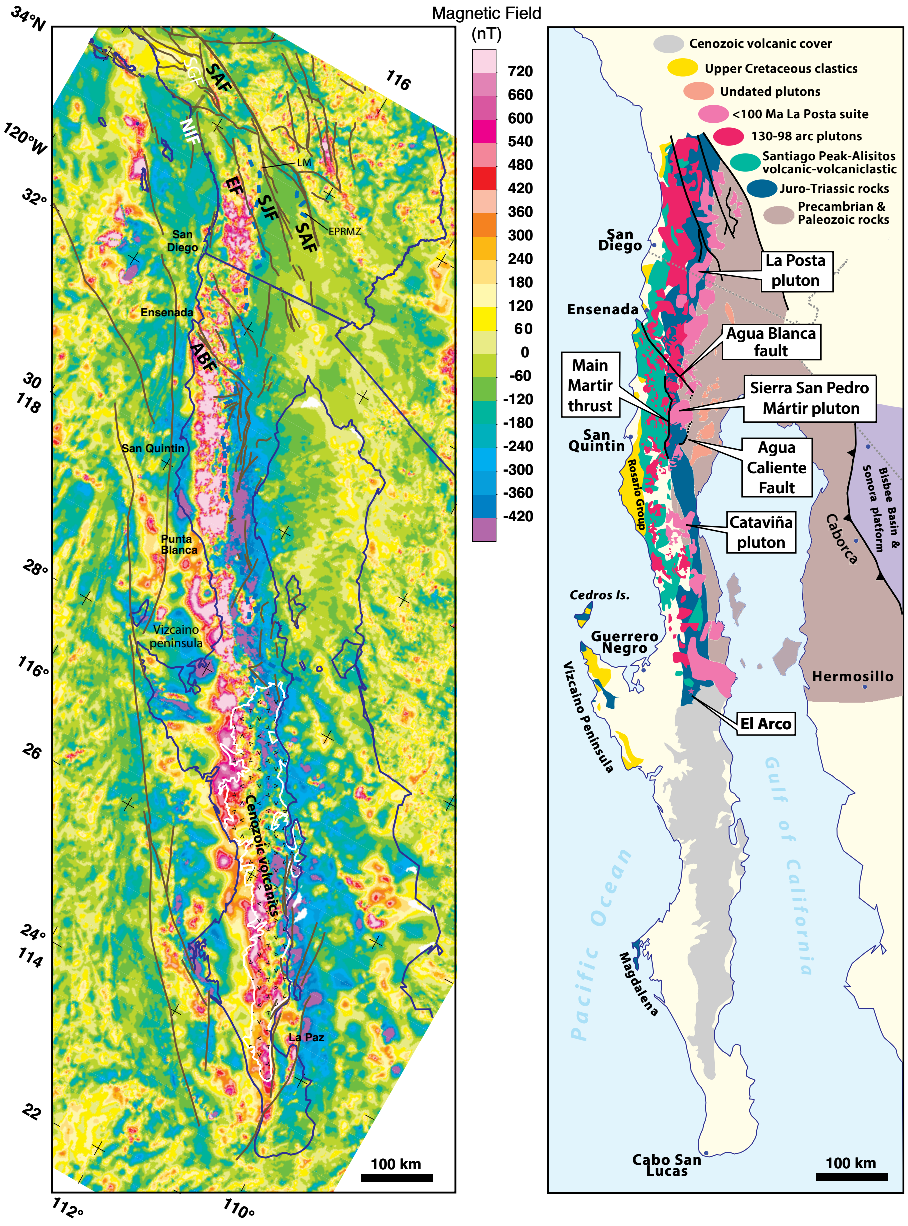

**Figure 2.** Aeromagnetic anomaly map of Southern and Baja California showing the presumed continuation of the western part of the batholith southward beneath Cenozoic volcanic cover (modified from Langenheim et al. 2014) and a geological sketch and location map based largely on Kimbrough et al. (2001) but updated from various sources cited in the text. SAF–San Andreas fault, SJF–San Jacinto fault, EF–Elsinore fault, ABF–Agua Blanca fault.

ry cover (Langenheim et al. 2014), it probably extends another 400 km to near Cabo San Lucas at the tip of the peninsula. As mentioned briefly in the introduction, the batholith and its wall rocks are traditionally divided into two distinct zones based on different temporal, lithological, geochemical, geophysical, and isotopic characteristics that parallel the axis of the batholith (Gastil 1975; Silver et al. 1979; DePaulo 1981; Baird and Miesch 1984; Todd et al. 1988; Silver and Chappell 1988). Wall rocks in the west consist of Lower Cretaceous volcanic and related volcaniclastic rocks, typically little metamorphosed, but generally deformed. The volcanic and sedimentary rocks are collectively known as the Santiago Peak volcanics in the United States and the Alisitos Group on most of the Baja Peninsula, Mexico. They presumably sit upon deformed and metamorphosed Triassic–Jurassic rocks whereas to the east Upper Cretaceous plutons intrude mainly Jurassic and Paleozoic upper amphibolite grade metasedimentary rocks that sit on unexposed crystalline basement.

Within the batholith itself, gabbroic plutons are mostly confined to the western half (Larsen 1948; Kimbrough et al. 2014b) and so, according to some workers, their eastern boundary defines a gabbro line (Walawender 1979; Smith et al. 1983). The gabbro line coincides closely with the western extent of gneissic Jurassic plutons (Shaw et al. 2003). An I–S line, which largely reflects Jurassic plutonism, and an oxygen isotope gap, also closely approximate the other lines (Taylor and Silver 1978; Todd and Shaw 1985). In the west, Cretaceous plutons range in age from 128–100 Ma and have no systematic age distribution; whereas to the east large nested tonalite–granodiorite–granite complexes, called the La Posta suite, range in age from 99–92 Ma and young progressively eastward (Silver and Chappell 1988; Walawender et al. 1990; Johnson et al. 1999b; Kimbrough et al. 2001; Schmidt et al. 2014). This distribution of ages led Silver (Silver et al. 1979; Silver and Chappell 1988) to suggest that a magmatic arc remained fixed in the west until ~105 Ma and then migrated eastward. Geophysical data also support the two sector division in that the western more mafic part is dense, magnetic, has low heat flow, sparse seismicity, and seismic velocities > 6.25 km/s, whereas the more siliceous eastern sector is less dense, weakly and magnetically quiet, has higher heat flow, abundant microseismicity, and seismic velocities < 6.25 km/sec (Langenheim et al. 2014).

Due to the abundance of both pre- and post-deformational plutons, and cover related to the opening of the Gulf of California, the inferred boundary between the two zones is difficult to locate, varies from worker to worker, and is possibly different at depth than at the surface. In the Sierra de San Pedro Mártir of Baja (Fig. 2) there are two recognized boundaries, both marked by significant faults: (1) a western fault known as the Main Mártir fault, which dips steeply eastward and places Jurassic and Lower Cretaceous amphibolite grade gneiss, metavolcanic rocks of the Santiago Peak volcanics, and plutons on the east over much lower grade rocks of the Alisitos Group and plutons to the west (Johnson et al. 1999b; Schmidt et al. 2009, 2014); and (2) a more easterly fault, known as the Agua Caliente, that dips moderately westward, and places high-grade migmatitic and ultramylonitic gneiss on the west over an amphibolite grade carbonate–quartzite succession intruded by Jurassic gneissic plutons (Measures 1996; Schmidt et al. 2009, 2014). Farther south, in the Sierra Calumague, the eastern boundary is thought to be represented by ductile faults, which commonly, but not everywhere, dip steeply eastward, and are probably normal faults as they place lower grade rocks atop higher grade rocks (Griffith and Hobbs 1993).

Within the US segment of the batholith, the contact is generally inferred to coincide with the geophysical, isotopic, and geochemical breaks, yet similar plutonic rocks appear on both sides of it, leading some workers, such as Todd et al. (2003) to argue that Cretaceous arc magmatism simply migrated eastward over a pre-existing Late Jurassic–Early Cretaceous crustal boundary. They did not explain why plutons and wall rocks older than about 100 Ma are deformed and metamorphosed, whereas younger plutons are not. Unfortunately, post-deformational plutons paid little heed to the inferred crustal boundary and were also emplaced on both sides of the boundary.

Whatever form it takes, and whether observed or not, the contact is considered by most workers to represent a suture zone related to either a closed marginal basin or a collision in a doubly eastward-dipping subduction model (Todd et al. 1988; Johnson et al. 1999b; Schmidt and Paterson 2002; Busby 2004; Lee et al. 2007; Schmidt et al. 2014; Wetmore et al. 2014; Shaw et al. 2014). Only Dickinson and Lawton (2001a) and a French group (Tardy et al. 1992, 1994) proposed westward-dipping subduction models. Here we will argue that the contact, inferred to be an important crustal boundary is an unconformity between Jurasso–Triassic rocks and overlying Lower Cretaceous volcanic and sedimentary rocks and that the critical suture lies well to the east on the Mexican mainland.

## PRE-BATHOLITHIC ROCKS

The rocks on each side of the traditionally inferred crustal boundary (Fig. 3) are quite different, both in terms of lithology and metamorphic grade. At the surface in the west, a Jurassic clastic succession (Silberling et al. 1961), the Bedford Canyon Formation, is unconformably overlain by the Cretaceous volcanic and volcaniclastic rocks of the Santiago Peak volcanics and Alisitos Group, which are themselves unconformably overlain by upper Cretaceous sandstone and conglomeratic units. Basement to the volcanic and volcaniclastic rocks appears to be dominantly Jurassic and to comprise a group of deformed and metamorphosed Jurassic plutons, known as the Harper Creek and Cuyamaca Reservoir suites, that intruded Jurasso–Triassic high-grade migmatitic schist and gneiss, known as either the Julian or Stephenson Peak schist (Shaw et al. 2003; Todd 2004).

Supracrustal rocks in the east are scarce, not only due to the emplacement of post-deformational plutons, but also because they are buried by extensive volcanic and sedimentary cover related to the Tertiary opening of the Gulf of California. Additionally, the structure is overprinted by structures formed both during the Laramide event (Hildebrand 2013) and extensional denudation during opening of the Gulf. Where they do outcrop, such as in the San Jacinto Mountains (Fig. 3), they are found to be a sequence of interbedded quartzite and carbonate rocks of Paleozoic age and finer grained siltstone, chert and argillite, commonly assumed to represent deeper water equivalents of the quartzite–carbonate sequences (Gastil and Miller 1981; Gastil et al. 1991; Gastil 1993).

### Western Sector

The Bedford Canyon Formation (Fig. 3) comprises thousands of metres of slightly metamorphosed argillite and slate, with lesser amounts of feldspathic sandstone, lenses of limestone, and pebbly conglomerate (Larsen 1948). The base of the formation is unexposed and the rocks are probably isoclinally folded making thickness estimates unreliable (Schoellhamer et al. 1981). Fossiliferous limestone units contain Callovian fossils, although some geologists are concerned that the fossils are allochthonous and were resedimented, but nevertheless the rocks predate the Santiago Peak volcanics (Silberling et al. 1961; Imlay 1963; Moran 1976).

Just north of San Diego, a latest Jurassic group of marine volcaniclastic rocks, collectively named the Peñasquitos Formation, was folded, in places even overturned, prior to deposition of the Santiago Peak volcanics (Kimbrough et al. 2014a). Their detrital zircon data, plus similar fossils, suggest that these rocks correlate with other volcaniclastic rocks on the Vizcaino Peninsula of Baja, as originally suggested by Kimbrough and Moore (2003), and possibly with the lowermost strata of the Great Valley Group to the north. They are probably correlative with rocks of similar age and deformation in Sonora, where they are known as the Cucurpe Formation (Mauel et al. 2011).

Preserved volcanic rocks, collectively known as the Santiago Peak–Estelle Mountain volcanics, are 128–110 Ma in age and consist of thousands of metres of basaltic to rhyolitic lava and breccia, tuff, and volcaniclastic rocks that sit unconformably upon rocks of the Bedford Canyon Formation and are overlain unconformably by Turonian fanglomerates of the Trabuco Formation (Larsen 1948; Fife et al. 1967; Schoellhamer et al. 1981; Tanaka et al. 1984; Buesch 1984; Gorzolla 1988; Anderson 1991; Wetmore et al. 2003; Herzig and Kimbrough 2014). Although there is a variety of more siliceous rocks, including hypabyssal intrusions, porphyritic basaltic andesite, andesitic lava and related breccia are the most common and widespread volcanic rocks in the formation (Schoellhamer et al. 1981; Herzig and Kimbrough 2014). Rocks in the west are less deformed and only weakly metamorphosed whereas to the east amphibolite grade and isoclinally folded tuff, breccia, and basaltic, andesitic, and dacitic lava flows occur as concordant screens between and within Cretaceous plutonic sheets of the western section and are the same age as the Santiago Peak volcanics

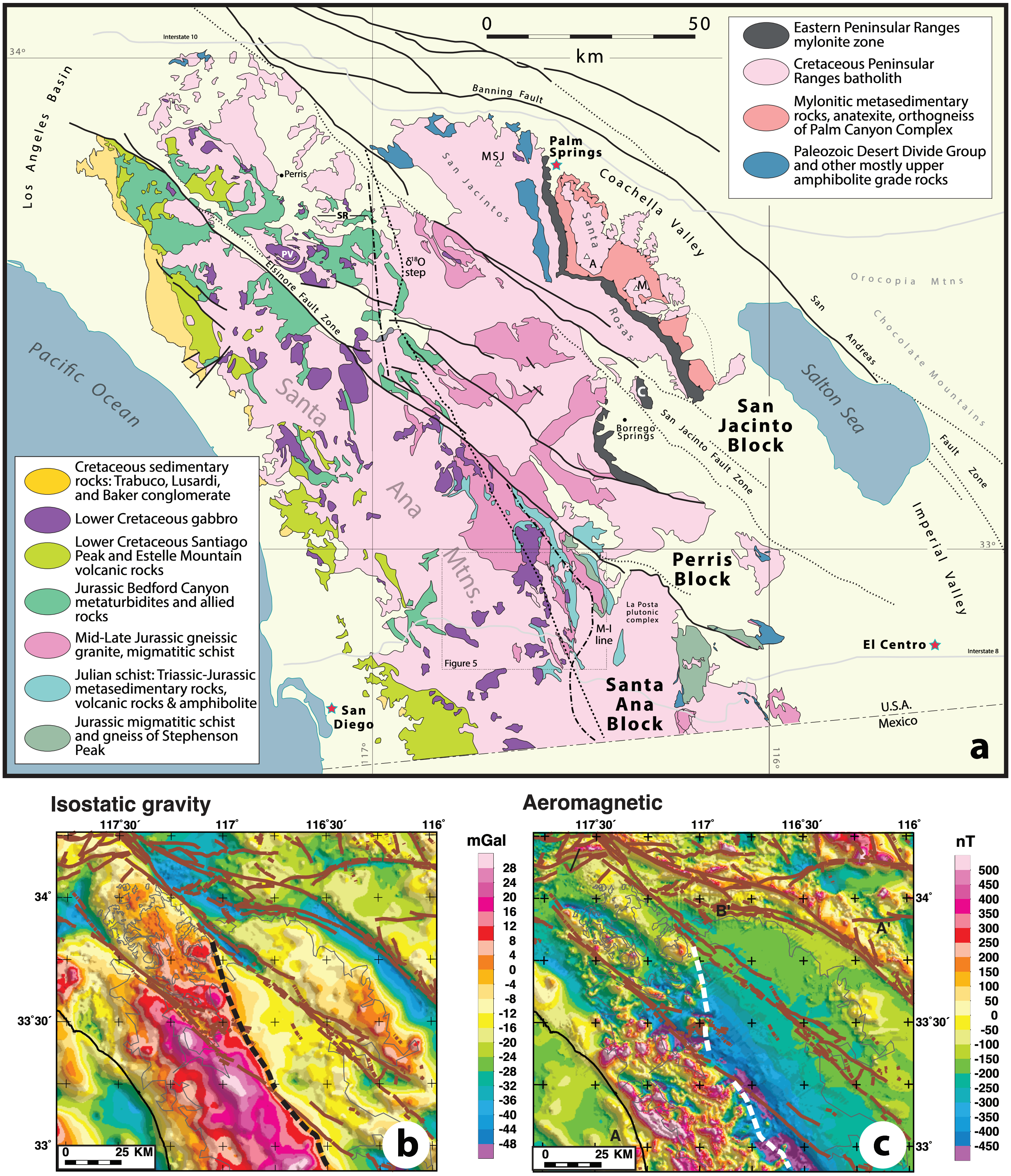

**Figure 3.** (a) Geological sketch map modified from Jennings (1977), Morton and Miller (2006), Todd (2004), and Todd et al. (1988) illustrating the general geology of the Peninsular Ranges of Southern California, the location of Figure 5, as well as the M–I (magnetite–ilmenite) line, the $\delta^{18}O$ step, and the eastern limit of gabbroic rocks (Todd et al. 1988). PV–Paloma Valley ring complex; SR–Searl Ridge, MSJ–Mount San Jacinto, A–Asbestos Mountain, M–Martinez Mountain, C–Coyote Mountain. (b) Isostatic gravity anomaly map and (c) aeromagnetic anomaly map, both modified from Langenheim et al. (2004). Note the change in gravity and aeromagnetic anomalies coincident with other signatures between western Santiago Peak volcano-sedimentary rocks and more easterly units.

(Todd 2004; Shaw et al. 2014).

Based on the geochemistry of the volcanic rocks, which are altered and dominantly metamorphosed to greenschist grade, they represent both tholeiitic and subalkaline series, with overall compositions similar to the contemporaneous plutonic rocks (Tanaka et al. 1984; Herzig and Kimbrough 2014). Wetmore et al. (2003) used the Tanaka et al. (1984) data as well as those of Gorzolla (1988) and Herzig (1991) and, based on the large number of rhyolitic analyses compared to basalt analyses – but without any volume estimates – as well as the presence of xenocrystic zircon grains, concluded that the arc was built on continental crust, although the variety and size of granitoid plutons demonstrate that as well. Premo and Morton (2014) dated a number of detrital zircon grains within metasedimentary rocks and found abundant Triassic and 1740–1650 Ma grains, whereas high-grade gneiss units contained concordant Proterozoic zircon and where discordant, Proterozoic upper intercept ages, similar to those reported from volcanic rocks by Herzig and Kimbrough (2014).

Nd and Sr isotopic values for the volcanic rocks are mostly similar to plutons of the western sector of the batholith (Herzig and Kimbrough 2014), and when coupled with the overall intermediate to siliceous compositions and xenocrystic zircon, clearly indicate that the arc was built on continental, not oceanic, crust.

Rocks included in the Santiago Peak volcanics continue for at least 300 km southward to just south of the Agua Blanca fault in Mexico (Fig. 2). There a NW-striking, steeply NE-dipping mylonitic shear zone, 50–100 m thick, separates the Santiago Peak volcanics from rocks of the Alisitos Group, which were deformed into southwest-vergent overturned folds and thrusts prior to intrusion of 108 Ma plutons (Wetmore et al. 2005; Alsleben et al. 2008). The zone is also the locus of a modern strike-slip fault with ~22 km of dextral separation (Allen et al. 1960). South of the fault, in the type area, at least 7 km of Late Aptian–Early Albian volcanic, volcaniclastic rocks, and shallow marine sedimentary rocks with abundant Tethyan bivalves define most of the Alisitos Group (Allison 1974). There, 2 km-thick piles of andesitic lava, breccia, volcaniclastic rocks, and intrusive porphyry, likely representing ancient stratocones, are capped by reefal limestone bioherms.

Farther south on the Baja Peninsula, rocks of the formation are mostly greenschist grade, but generally lower grade in the west away from the plutons, compositionally diverse, deposited in both marine and subaerial settings, and comprise andesitic stratocones, silicic ignimbrite and associated calderas, a variety of volcanclastic rocks, hypabyssal porphyritic rocks and granitoid plutons of dominantly Cretaceous age (White and Busby-Spera 1987; Schmidt et al. 2002; Busby et al. 2006). Volcanic rocks and associated plutons range from 116 to 100 Ma and are not known to contain inherited zircon (Wetmore et al. 2003; Schmidt et al. 2014).

A 330º-trending swarm of ~126 Ma basaltic to rhyolitic dykes, known as the San Marcos dyke swarm occurs north of the Agua Blanca fault where it appears to be related to the Santiago Peak volcanics (Farquharson 2004). A similar swarm south of the fault, with the same major and trace element contents as those to the north, but at higher metamorphic grade, was correlated with the northern swarm by Schmidt et al. (2014), who used it to suggest continuity between the Santiago Peak and Alisitos segments, although only one dyke there is dated, at 120 Ma. If Schmidt et al. (2014) were correct then the Agua Blanca fault is not a fault of great significance, at least after about 126–120 Ma.

Basement outcrops other than the deformed Bedford siliciclastic rocks were previously considered to be scarce, but we believe them to be more common. Near the state line at El Arco (Fig. 2) is a 6 km-thick section of andesitic lava and breccia, and associated pyroclastic and epiclastic rocks, all cut by a monzodioritic body dated at ~165 Ma (Barthelmy 1975; Weber and Lopéz Martínez 2006). These rocks are probably basement to the Alisitos Group, although the contact itself is not exposed. Jurassic orthogneiss (Fig. 4) occurs throughout the central portions of the Baja peninsula south of the Agua Blanca fault, ranges in age from 170–149 Ma and is cut by gabbroic and tonalitic plutons ranging in age from 132–100 Ma, typical of the western sector (Schmidt et al. 2014). The gneiss is most likely rock exhumed from deep beneath the Alisitos arc and if so, would provide a reasonably clear picture of the basement, which is continental, but young, consistent with primitive isotopic ratios obtained by Weber and Lopéz Martinez (2006) at El Arco.

A steeply dipping panel of amphibolite-grade, highly strained metavolcanic rocks of the Santiago Peak volcanics lies along the western flank of the gneiss, but east of the Main Mártir fault (Schmidt et al. 2014). We speculate that the contact between the gneiss and volcanic rocks is most likely a highly tectonized unconformity and that the gneiss lies beneath the volcano-sedimentary package. A careful search along this contact might yield some evidence for this in the form of stretched pebbly conglomerate and/or arkosic sand lenses.

Within the US sector of the batholith (Fig. 3) is another likely basement assemblage, comprising the Julian Schist and associated Jurassic ortho- and paragneiss. Rocks included in the Late Triassic–Mid Jurassic Julian Schist are diverse and include predominantly schist and quartzite with subordinate quantities of amphibolite, mafic schist, gneiss, metaconglomerate, calc-silicate rock, quartzite, marble and talc schist (Todd et al. 1988; Germinario 1993; Shaw et al. 2003). Although the rocks are typically isoclinally folded, foliated and metamorphosed, holding porphyroblasts of sillimanite and/or andalusite, relict bedding is commonly observed (Germinario 1982). Todd et al. (2003) considered that the Julian Schist was restricted to the western sector, but suggested that just to the east were similar rocks containing greater amounts of marble and quartz-rich metasandstone. The Jurassic metasedimentary rocks contain abundant Paleozoic and Proterozoic detrital zircon (Gastil and Girty 1993; Grove et al. 2008).

A band of deformed Jurassic granitoid rocks intruded the Julian Schist and extends through the western part of the eastern zone from southern

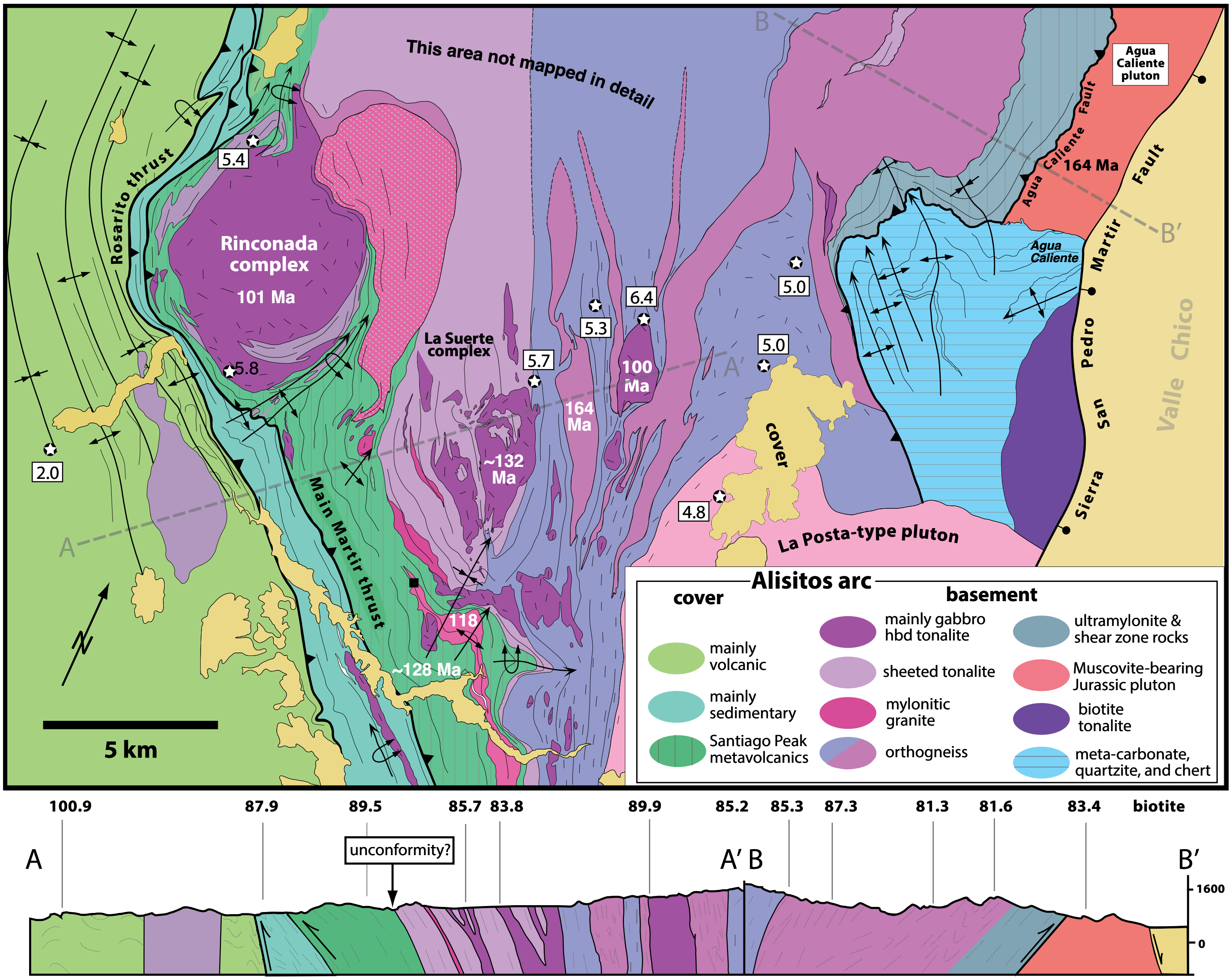

**Figure 4.** Geological sketch map and section from Schmidt and Paterson (2002); Schmidt et al. (2014) showing the location and local geology in and around the Main Mártir thrust, the Agua Caliente fault, and the doubly vergent fan structure. Note that plutons older than 100 Ma occur east of the Main Mártir thrust, indicating that it cannot be the main suture. Similarly, 164 Ma Jurassic plutons occur on either side of the Agua Caliente thrust suggesting that it also is not the bounding suture. We infer, based on relations elsewhere as discussed in the text, that the contact between the metavolcanic rocks and Jurassic rocks east of the Main Mártir thrust is a tectonized unconformity.

California well into Baja California. The plutons, dated to be 234–149 Ma, were subdivided into two suites, both of which are dominantly ilmenite-bearing and strongly deformed: (1) the peraluminous Harper Creek suite and (2) the Cuyamaca suite, which is transitional in bulk composition between metaluminous and peraluminous (Todd and Shaw 1985; Shaw et al. 2003). They have $\delta^{18}O$ ranging from 12 to 20 per mil, initial $^{87}Sr/^{86}Sr$ ratios from ~0.706 to ~0.713, zircon Hf data representing model ages between 1200 and 800 Ma, and Proterozoic xenocrystic zircon (Shaw et al. 2003, 2014). Large numbers of enclaves, as well as exterior mantling by intensely migmatitic and gneissic sheaths of Stephenson Peak schist, are typical of the Harper Creek suite (Todd and Shaw 1985). The plutons are elongate in the north-northwesterly direction and are strongly foliated, gneissic, or mylonitic (Todd 2004). They are generally considered to be within the Cuyamaca–Laguna Mountain shear zone, which is a 5–20 km wide polygenetic feature that extends for about 50 km, and dips steeply eastward (Thomson and Girty 1994). The nature and origin of the sheared rocks, which are cut by a 104 Ma pluton, are obscure, as deformed, but coherent and mappable, Jurassic and Cretaceous plutons occur within the zone (Todd 2004). If the mylonitic fabrics in the wall rocks represent a shear zone of sizable displacement it must have been active prior to emplacement of the Jurassic plutons.

West of the San Jacinto fault zone (Fig. 3), the regional plunge appears to be gently to the northwest, as evidenced by the abundance of strongly deformed and amphibolitegradeJurassic plutons and gneiss and absence of volcanic rocks in the southeast, and the abundance of greenschist-grade volcanic rocks and absence of Jurassic plutons to the northwest. This fits with observations in the western part of the block, where Shaw et al. (2003) found that plutonic contacts of the Jurassic plutons are sharper, marginal facies more leucocratic, coarser grained, and with amphibole more common than biotite, whereas to the east, the plutons are much richer in metasedimentary enclaves, clots of mica, their outer contacts tend to be more gradational, up to a km across, and are strongly oriented parallel to gneissic foliation.

All of the data presented above indicate that the Santiago Peak volcanics, or as they are sometimes called the Western metavolcanic rocks, sit unconformably upon the Julian Schist and the associated plutons and migmatite. The contact is readily visible on Figure 5, where 128–100 Ma plutons intrude both sides of the contact. It is implausible that it is a fault as the volcano-sedimentary package is the same age as, or only very slightly older than, the plutons that intruded the contact: it must be an unconformity. This implies that the Jurassic rocks were exposed at the surface during the early Cretaceous, and that there was a significant basement complex beneath the Santiago Peak rocks. In fact, the presence of Proterozoic xenocrystic zircon within the Harper Creek rocks indicates that the basement contained Proterozoic rocks or sedimentary rocks containing Proterozoic detrital zircon. As all the Jurassic basement rocks were strongly deformed and metamorphosed prior to the deposition of the Santiago Peak rocks, it is reasonable to infer that they were involved in a latest Jurassic–earliest Cretaceous collision, likely the event responsible for the deformation of the Peñasquitos and Cucurpe formations, which is bracketed to be between about 145 and 136 Ma (Peryam et al. 2012; Kimbrough et al. 2014a) more or less contemporaneous with the widespread Nevadan event (Schweickert et al. 1984). An older event, at ~160 Ma, postdated the emplacement of the Harper Creek and Cuyamaca Reservoir suites and affected Jurassic arc rocks from the Klamath Mountains and western Nevada southward to the Sonoran Desert region (figure 42 in Hildebrand 2013).

A folded and now steeply eastward-dipping unconformity between basement and cover can satisfy the various elements, such as oxygen isotopic step, aeromagnetic anomaly, gravity, and I–M line that generally have been interpreted to represent a suture zone. Cretaceous plutons intruded the basement, their own cover, and the unconformity between them (Fig. 5).

On the Vizcaino Peninsula of Baja (Fig. 2), over 10 km of turbidites of the Valles Group, interpreted to represent a deep-sea fan complex deposited on the edge of an ocean basin (Minch et al. 1976), have a diverse fauna indicating an Albian to Santonian age (Berry and Miller 1984). They sit on older Jurasso–Triassic ophiolitic, sedimentary, and volcanic rocks (Smith and Busby 1993). According to Kimbrough et al. (2001), the Valle Group is divided into three subbasins containing sections of early Cenomanian to middle Turonian coarse clastic rocks enveloped in much finer grained shaly strata. The clastic sections contain coarse conglomerate beds and abundant sand-rich turbidites, some of which are tightly dated by fossils as 92–91 Ma and contain abundant 100–90 Ma detrital zircon grains, which are interpreted to have been derived from the La Posta plutons (Kimbrough et al. 2001).

Another package of Upper Cretaceous sedimentary rocks extends for over 500 km along the western side of the Peninsular Ranges (Fig. 2), where they unconformably sit on rocks of the Santiago Peak volcanics, Alisitos Group and the western batholith (Bottjer and Link 1984). Outcropping to the north above the unconformity, are weakly consolidated sedimentary strata of Turonian age comprising coarse conglomerate with clasts up to 2 m, sandstone, and clayey siltsone (Popenoe 1941; Schoellhamer et al. 1981). According to Popenoe (1941), who counted clasts in several of the Late Cretaceous conglomeratic units, the clasts are dominantly porphyritic andesite with lesser quantities of granitoid, metamorphic and sedimentary rocks. U–Pb dating of zircon from four dacitic clasts within one of the conglomerate units yielded ages of 108–106 Ma (Herzig and Kimbrough 2014).

In the San Diego and northernmost Baja areas Turonian–Campanian non-marine bouldery fanglomerate and sandstone of the Trabuco, Baker, Lusardi, and Redonda formations (Fig. 3) sit unconformably above plutonic and volcanic bedrock on a surface of high relief and contain mostly clasts of plutonic and pre-batholithic rocks to 10 m (Flynn 1970; Nordstrom 1970). The conglomerate is unconformably overlain by Campanian–Maastrichtian marine sandstone and shale (Kennedy 1975). Farther south in Mexico, the Turonian–Campanian section is unconformably overlain by Campanian to Maastrichtian sedimentary rocks of non-marine to shallow marine clastic formations overlain by deep marine fan deposits of the Rosario Formation (Morris and Busby-Spera 1990).

### Eastern Sector

Pre-batholithic rocks in the eastern half of the batholith are highly varied, typically strongly deformed, metamorphosed to amphibolite grade, and without exposed crystalline basement in the Peninsular Ranges. Paleozoic clastic and carbonate rocks dominate and, based on age and lithology, most workers interpreted them as part of North America. In the US sector Paleozoic metasedimentary rocks of the Desert Divide Group (Fig. 3) are well exposed along the spine of the San Jacinto Mountains, where it comprises over 4 km of quartzose schist, paragneiss, metacarbonate rock and quartzite, all at amphibolite grade (Brown 1980, 1981). Gastil et al. (1991) described the rocks as compositionally similar to Neoproterozoic and Lower Paleozoic sedimentary rocks of central Nevada.

Just to the east, sitting structurally above the Cretaceous plutons in the Santa Rosa Mountains and rocks of the Desert Divide Group (Fig. 3), is the Eastern Peninsular Ranges mylonite zone and its hanging wall of intensely deformed metasedimentary rocks of the Palm Canyon complex, which itself sits structurally beneath Cretaceous plutons (Todd et al. 1988). Within the mylonite zone itself, which has Late Cretaceous deformation and

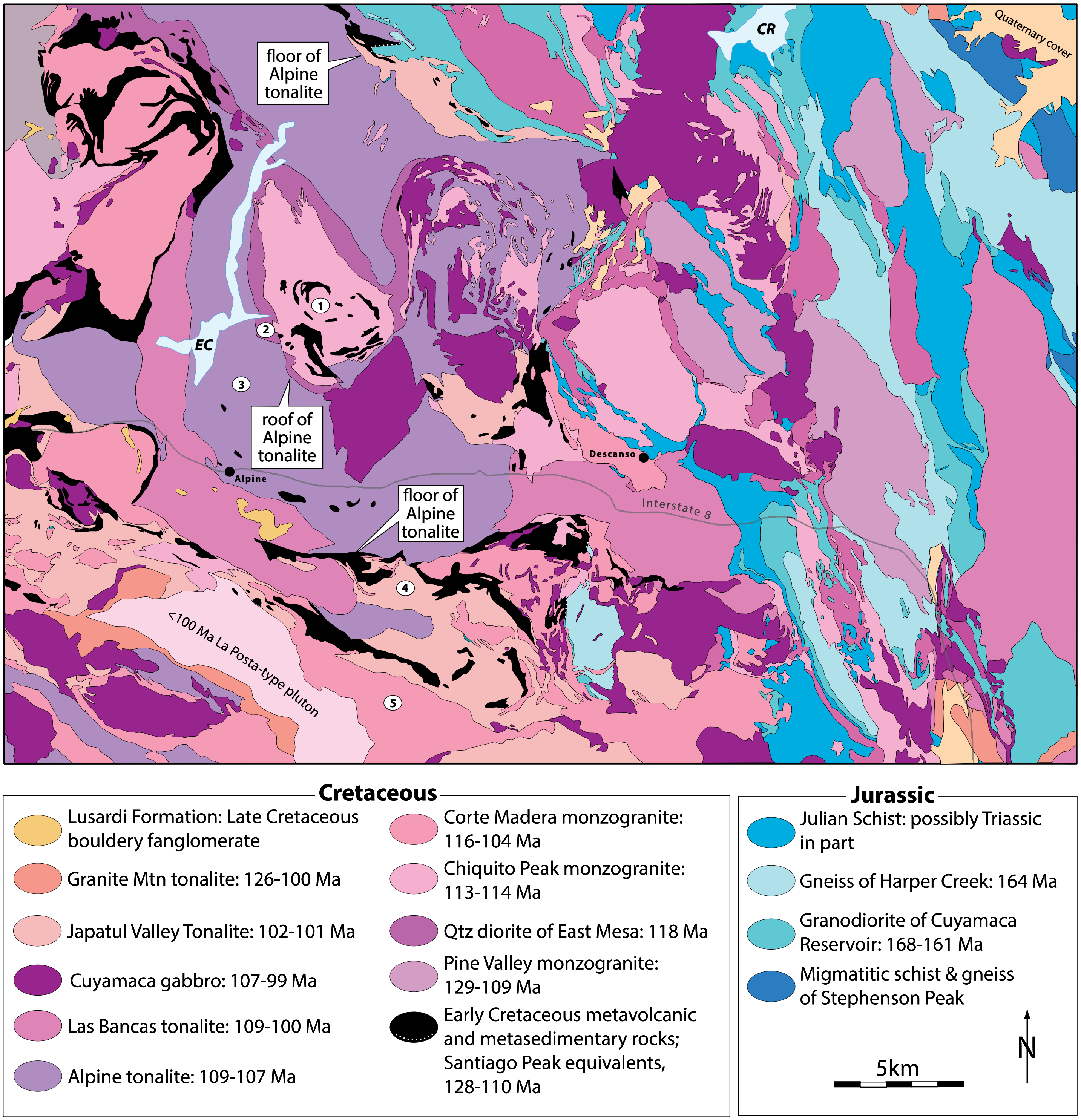

**Figure 5.** Simplified geological map of part of the El Cajon map area (Todd 2004) showing the relationship of Early Cretaceous metavolcanic and allied rocks (black) to the Jurassic rocks (blues). We interpret the relationship between the two as an unconformity because the contact is cut by plutons only slightly younger than the volcanic rocks. Note that metavolcanic rocks don't occur east of, nor Jurassic rocks west of, the interpreted unconformity. This figure also shows that the Early Cretaceous plutons, which are characterized by wall-rock contacts that are generally concordant with bedding, were sill-like in their original form and are now complexly folded into a typical dome and basin interference pattern (see also Hildebrand 2013). The unconformity is overturned, dipping east (Langenheim et al. 2014), provides pre-deformational way-up to the west, and the map view is an oblique crustal section. One can readily see how the sheets (numbered 1–5 to denote their relative structural position), although irregular in detail, are concordant on a large scale and form concentric layers around cores of folds. Note that the floor of the Alpine tonalite is exposed again in the core of the WNW-trending synform between 4 and 5. Age data from Todd et al. (2003) and Shaw et al. (2014). CR –Cuyamaca, Reservoir, EC –El Capitan Reservoir.

exhumation, recognizable sedimentary units are as thin as a 1 m thick bed of marble to huge westerly vergent imbricate stacks and recumbent nappes of amphibolite grade marble, feldspathized quartzite, gneiss and metapelite more than 15 km thick – all overprinted by Miocene detachment faulting and younger strike-slip deformation (Engel and Schultejann 1984). The westward thrusting was likely related to the Laramide event at 80–75 Ma, as suggested by cooling ages of Grove et al. (2003) and Dokka (1984). Fossils are scarce, but conodonts from the carbonate units in the thrust stack at Coyote Mountain (Fig. 3) are Early Ordovician in age (Miller and Dockum 1983). Similar rocks are recognized southward through the eastern Baja Peninsula to the Sierra de San Pedro Mártir (Gastil et al. 1991).

Still farther south at 29°N, several km of Devonian–Mississippian black chert, argillite, pillowed and massive alkali basalt were recumbently and isoclinally folded and are correlated with the Golconda–Roberts Mountain allochthons of Nevada (Gastil et al. 1991; Campbell and Crocker 1993; Leier-Engelhardt 1993).

Rocks of the eastern block, which extend onto mainland Mexico, were correlated on the basis of lithology and detrital zircon profiles with rocks of the North American passive margin (Gastil et al. 1991; Gastil 1993; Alsleben et al. 2012). However, as they occur west of known exotic terranes such as Caborca and Guerrero (Sedlock 1993; Tardy et al. 1994; Centeno-García et al. 2008;), locally contain sequences and rocks similar to those of the Roberts Mountain and Golconda allochthons, during the Lower Cretaceous they were more likely to have been part of Rubia, the Cordilleran Ribbon Continent of Hildebrand (2009, 2013), although their ultimate origin was Laurentia. The presence of abundant Baltic and North Atlantic fauna in Ordovician carbonate rocks just south of the international border (Gastil and Miller 1981; Gastil et al. 1991; Lothringer 1993) support this conclusion.

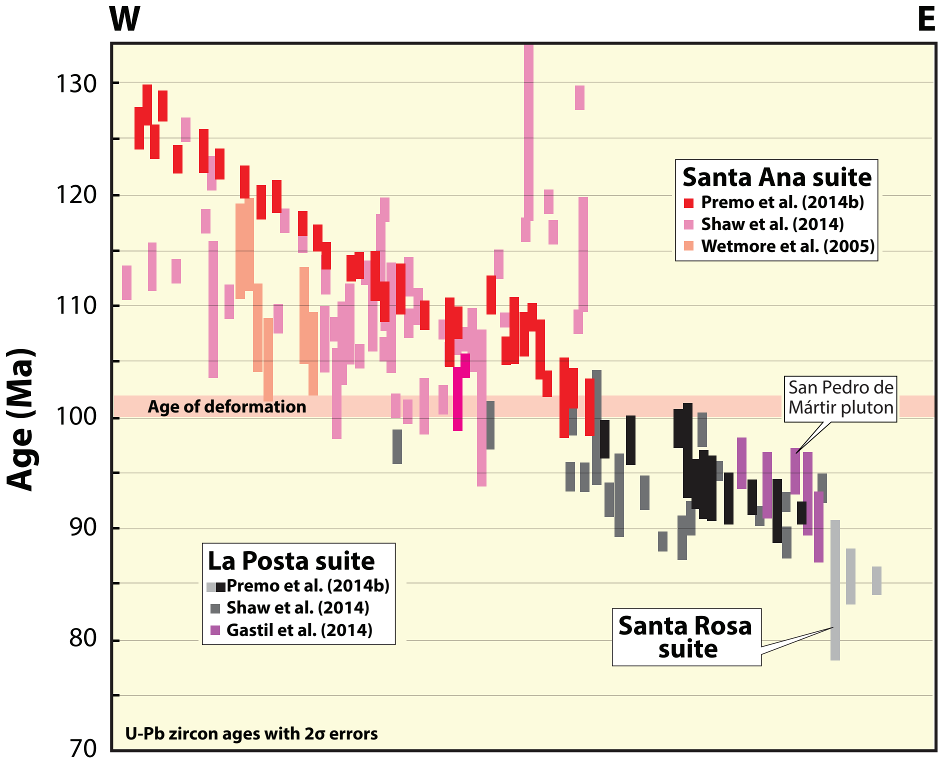

**Figure 6.** U–Pb zircon ages with 2σ errors for the Peninsular Ranges batholith plotted versus general longitude. Modified from Premo et al. (2014b) with additional ages from Shaw et al. (2014), Gastil et al. (2014), and Wetmore et al. (2005). The pluton ages prior to 100 Ma are not aligned by geography, but by age. Most workers have recognized that the western Santa Ana suite didn't migrate with time (Silver and Chappell 1988; Shaw et al. 2014).

## THE CRETACEOUS BATHOLITH

Cretaceous plutonic rocks in the western sector of the batholith are 128–100 Ma (Fig. 6), variably deformed, but much more so to the east, range in composition from gabbro to leucogranite, and show no directional variation in composition with time (Silver and Chappell 1988; Clausen et al. 2014; Premo et al. 2014b; Morton et al. 2014). We use the informal name Santa Ana suite for these rocks after extensive outcrops within the Santa Ana Mountains (Fig. 3). This suite includes the more localized Escondido plutons recently studied by Clausen et al. (2014).

Overall, the Santa Ana suite is a calcic I-type suite with abundant prismatic hornblende and lesser interstitial and anhedral biotite. In Mexico, a number of small (< 10 km), dominantly epizonal gabbro–tonalite–trondhjemite complexes are interpreted to represent subvolcanic centres, ranging in age from 117–100 Ma (Johnson et al. 1999a, 2002; Tate and Johnson 2000; Schmidt and Paterson 2002; Schmidt et al. 2009). Many plutons of the Santa Ana suite were originally a series of sheets or sills (Fig. 5) as they have contacts that are concordant with bedding in their wall rocks and with foliation adjacent to both shallow and steep contacts (Todd 2004). They appear to be more prevalent above (west of) the contact of the Jurassic basement, where they intruded what is assumed to be their own volcanic cover (Fig. 5). Recently acquired Hf in zircon data from the western plutons, including gabbro, indicate model ages of 900–250 Ma, which implies that the original primitive mantle-derived melts likely mixed or assimilated more than 50% crustal material (Shaw et al. 2014).

Gabbroic plutons are scarce in the east and common in the west (Figs. 3, 4, 5), where they tend to be large, foliated and cumulate-layered plutons of hornblende-bearing troctolite; anorthositic gabbro; and amphibole–olivine gabbronorite, surrounded by much smaller bodies of finer-grained hornblende gabbro, all of which have ambiguous temporal and mingled relations with granitic plutons

(Walawender 1979; Todd 2004). Field relations indicating consanguinous emplacement were confirmed by Kimbrough et al. (2014b), who showed that dated gabbroic plutons were emplaced over the same time interval as other plutons of the Santa Ana suite in that they range between, or are within analytic error of, 128–100 Ma.

Plutons of the Santa Ana suite within the southern California sector are both normally and reversely zoned, isotropic to foliated or protomylonitic, sheeted plutonic complexes, highly variable in composition ranging from tonalite through quartz diorite and granodiorite to leucomonzogranite, locally with abundant wall rock screens and mafic inclusions and containing varying proportions of clinopyroxene ± orthopyroxene ± biotite ± hornblende and mafic inclusions (Todd et al. 2003; Todd 2004). Morton et al. (2014) noted that the westernmost plutons are isotropic whereas those farther east are foliated so that there is a megascopically visible deformation gradient from west to east. This gradient might reflect the deeper levels of plutonic emplacement to the east with the more westerly isotropic plutons emplaced into their own cover at no more than 2–3 kbar, whereas the foliated rocks were emplaced at pressures twice as large or greater (Morton et al. 2014). Alternatively, the foliated plutons might be closer to the deformational front.

Cumulate layering in gabbroic plutons is now mostly steeply dipping; contacts of plutons are folded, in many places isoclinally, along with their wall rocks; mineral foliation is steep and commonly transects plutonic contacts; and dykes of one pluton within another are isoclinally folded (Todd and Shaw 1979). Todd and Shaw (1979) also pointed out that in thin section, Santa Ana plutons typically have broken phenocrysts, a lack of oscillatory zoning in plagioclase, and both quartzo-feldspathic and mafic minerals recrystallized under strain. These features, plus the map patterns (Fig. 5), clearly indicate that, prior to deformation at 100 Ma, many plutons of the Santa Ana suite were flat sheets, sills, or laccoliths with dominantly concordant contacts and were subsequently recumbently folded. Even seemingly isotropic plutonic complexes of the western zone such as the Paloma ring complex (Fig. 3) appear to us to be folded sheets (Morton and Baird 1976) especially considering that the geological map (Morton and Miller 2006) shows the Santiago Peak wallrocks to be folded.

In Baja California, large pre-100 Ma plutons are also strongly deformed with concordant contacts, transecting cleavage, and obvious folds (Murray 1979; Johnson et al. 1999b, 2003). Some plutons there, such as the Rinconada pluton (Johnson et al. 2002), were recumbently folded (Fig. 4; see also figure 5 in Johnson et al. 2002). Overall, the data are compelling that pre-100 Ma plutons of the Peninsular Ranges batholith are complexly folded sills or sheets. This should be evident, for if the wall rocks were recumbently folded at 100 Ma then the pre-100 Ma plutons must have been as well.

Plutonic rocks of the eastern suite, named the La Posta plutons (Figs. 2 and 6), after a compositionally zoned plutonic complex that spans the international border (Walawender et al. 1990), range in age from 99–86 Ma (Premo et al. 2014b), possibly young slightly eastward (Ortega-Rivera 2003), and are dominated by large, concentrically zoned, mostly weakly foliated complexes comprising biotite and hornblende-bearing tonalitic marginal phases grading inward over several tens of metres to granodiorite and cored by granite, in places containing both biotite and muscovite (Hill 1984; Silver and Chappell 1988; Walawender et al. 1990). While xenocrystic zircon is scarce in both suites, local garnet-bearing monzogranite in the eastern suite does contain it. Euhedral titanite is characteristic of the La Posta plutons (Silver and Chappell 1988). Plutons of this suite were emplaced both above and below the basal unconformity (Johnson et al. 1999b; Schmidt and Paterson 2002; Shaw et al. 2014), although most were emplaced farther east at greater depth within the basement complex.

The ilmenite-bearing 94 Ma La Posta intrusive complex comprises: (1) an outer titanite–hornblende–biotite tonalite, that is locally banded near the outer contact, but characterized internally by inclusion-free hornblende prisms up to 1 cm long, 0.5 cm titanite crystals, and books of biotite; (2) a titanite–biotite granodiorite characterized by poikilitic potassium feldspar and hexagons of biotite up to 1 cm across; and (3) an inner zone with small euhedral biotite, potassium feldspar oikocrysts up to 5 cm across, and typically less than a couple percent muscovite (Walawender et al. 1990).

Plutons of similar composition, but slightly younger age (Fig. 6), sit structurally above the Eastern Peninsular Ranges mylonite zone and are informally grouped as the Santa Rosa suite, after their location within the Santa Rosa Mountains (Fig. 3). All three suites of plutons, Santa Ana, La Posta, and Santa Rosa, were recognized and dated from core recovered from drill holes in the Los Angeles basin area farther north, demonstrating that the batholith presently extends to the Transverse Ranges (Premo et al. 2014a), where similar rocks outcrop in the Santa Monica Mountains just north of Los Angeles (R. Powell, D. Morton, personal communication 2014). Limited Hf isotopic data from the La Posta plutons have model ages of about 2300 Ma (Shaw et al. 2014).

Plutons of the La Posta–Santa Rosa suites probably extend eastward across the Gulf of California into Sonora and Sinaloa, where a compositionally similar suite of 101 ± 2 to ~90 Ma foliated to non-foliated tonalite plutons occurs within 50 km of the coast (Henry et al. 2003). They were intruded into Jurassic and older greenschist-grade rocks common to the eastern side of the Gulf (Gastil and Krummenacher 1977; Gastil 1979; Ramos-Velázquez et al. 2008). K–Ar biotite and hornblende ages are also in the range 100–90 Ma (Henry et al. 2003).

In the Sierra de San Pedro Mártir of Baja California (Figs. 2 and 4), which might provide the best exposed section across the boundary between eastern and western sectors, the Main Mártir thrust, commonly considered by previous workers as the suture between the two sectors, dips eastward as the westerly part of a doubly vergent fan structure (Goetz 1989; Johnson et al. 1999b; Schmidt and Paterson 2002; Schmidt et al. 2009, 2014); however, there are many Lower Cretaceous gabbro bodies, characteristic of the western sector located east of the fault. This suggests that any suture may lie farther east.

Jurassic orthogneiss and paragneiss, located within the more central parts of the fan structure (Fig. 4), appear to be part of the same package as Jurassic rocks that we reason to lie unconformably beneath the Santiago Peak rocks in the Santa Ana mountains of southern California (Fig. 5). Plutons in both places are dated at 164 Ma (Schmidt and Paterson 2002; Shaw et al. 2003). Thus, it is plausible, but perhaps difficult to document due to high strain, that the contact between higher grade and very strongly deformed rocks of Santiago Peak on the west (Schmidt et al. 2014), and the Jurassic gneissic rocks and pre-134 Ma rocks might be an unconformity (Fig. 4). If correct, then the fan structure contains a tectonically compressed section of crust within the Alisitos–Santiago Peak arc, much as the northwest plunge appears to do to the north in the Southern California region.

One possible candidate for a suture appears to be the Agua Caliente thrust (Fig. 4), which is a major fault that dips moderately westward and along which migmatitic flysch, deformed Cretaceous plutons, and sheeted gabbro plutons as young as 100.1 ± 0.5 Ma, were transported eastward over carbonate–quartzite metasedimentary rocks, prior to emplacement of the La Posta plutons (Schmidt and Paterson 2002; Schmidt et al. 2009). The fault zone was recognized by Measures (1996) who mapped a section across it and described it as a 200–500 m thick migmatitic zone containing imbricated slivers of amphibolite, Cretaceous orthogneiss, prebatholithic schist, ultramylonite, and S–C mylonitic gneiss with northwest over southeast shear at amphibolite-facies conditions. The main problem with selecting the Agua Caliente fault as the suture is that the footwall contains a muscovite-bearing pluton dated at 164 Ma that intruded the carbonate–quartzite succession. As this is the same age and similar composition to dated plutons beneath the arc complex, this fault is unlikely to be the suture. If the Agua Caliente fault is not the suture then it must be located farther east, which barring structural complications, implies that the arc basement contained Paleozoic metasedimentary rocks and very likely their basement, which we presume to be Precambrian. It also implies that the Baja Peninsula contains the arc and significant quantities of basement. We will return to this topic and its implications later in the paper.

## AGE OF DEFORMATION

The best constraints on the age of deformation within the Cretaceous Peninsular Ranges batholith (Fig. 6) come from the detailed work of Premo and Morton (2014) who dated a wide variety of rocks on Searl Ridge (Fig. 3) in the Perris block where they found and dated zircon in a pre- to syn-metamorphic diorite dyke to be 103.3 ± 0.7 Ma and in a post metamorphic pegmatite dyke to be 97.53 ± 0.18 Ma, which they interpreted to have been emplaced just after metamorphism. Additionally, they dated more than 30 hornblende separates and determined that metamorphism took place at or before 100.1 ± 0.6 Ma. This is consistent with older data collected farther south in the Sierra de San Pedro Mártir, where the age of the deformation is tightly constrained by plutons. There, 100 Ma gabbro and the 101 Ma gabbro–tonalite–trondhjemite Rinconada complex, are compositionally linked to the western zone, strongly deformed, and folded (Johnson et al. 2002; Alsleben et al. 2008; Schmidt et al. 2009), yet the 97–90 Ma La Posta-type Sierra de San Pedro Mártir plutonic complex, which cuts the contact between the eastern and western sectors does not contain the same level of deformation (Ortega-Rivera et al. 1997; Gastil et al. 2014). Similarly, the El Potrero pluton, located just 1–2 km west of the San Pedro Mártir body, is a strongly deformed tonalite with U–Pb zircon age of 102.5 ± 1.6 Ma and $^{40}$Ar/$^{39}$Ar ages of 101 ± 5 Ma for hornblende and 94 ± 1.4 Ma for biotite (Johnson et al. 1999b; Chávez Cabello et al. 2006).

We will use 100 Ma as the best estimate for the age of deformation, but realize that some plutons of the Santa Ana suite may still have been crystallizing as late as 98 Ma or that early La Posta bodies might have characteristics of the Santa Ana suite. It is also important to note that we are referring here to deformation of the Alisitos–Santiago Peak arc, and not older deformations, such as the ~160 Ma Jurassic and 145–139 Ma post-Peñasquitos, both of which are confined to the basement, nor the younger ~75 Ma Laramide deformation, as it is the short-lived 100 Ma deformation that appears to coincide with a major change in Cretaceous magmatism.

## EXHUMATION

The La Posta plutons (Fig. 6) represent an intense magmatic pulse ranging in age from 99–85 Ma (Silver and Chappell 1988; Walawender et al. 1990; Kimbrough et al. 2001; Premo et al. 2014b). The plutons were emplaced at depths of 5–23 km into upper greenschist, but mainly amphibolite, grade wall rocks that are in many places migmatitic (Gastil et al. 1975; Ague and Brimhall 1988; Todd et al. 1988, 2003; Grove 1993; Rothstein 1997; Rothstein and Manning 2003; Gastil et al. 2014). The plutons were intruded during a period of exhumation when rocks at depths of 15–23 km were brought rapidly to the surface by detachment faulting and collapse (Krummenacher et al. 1975; George and Dokka 1994; Ortega-Rivera et al. 1997, Ortega-Rivera 2003; Grove et al. 2003; Miggins et al. 2014). Large volumes of sediment were eroded from the uplifted terrane, as documented by abundant 100–90 Ma detrital zircon and feldspar deposited as part of a voluminous pulse of early Cenomanian to Turonian coarse clastic sedimentation in basins located to the west (Lovera et al. 1999; Kimbrough et al. 2001).

In the Southern California segment of the batholith the depth of emplacement of all plutons, based on Al-in-hornblende barometry, increases from about 2 kbar or less in the west, to more than 5 kbar in the eastern zone (Ague and Brimhall 1988; Todd et al. 2003). In the Sierra de San Pedro Mártir, farther south (Fig. 4), emplacement depths are similar, except there is a marked jump on the west from 2 kbar to 5 kbar that coincides with a series of closely spaced, easterly dipping, reverse faults (Schmidt et al.

2009). On the eastern side of the Gulf of California rocks are dominantly greenschist and we are unaware of any geobarometric studies on the plutons there.

At a regional scale, K–Ar ages decrease eastward across the batholith (Silver et al. 1979), but there has been little agreement on the origin of the pattern, with some relating it to regional tilt, others to eastward-migrating magmatism, and still others to two discrete events. Those who favour the idea of a regional tilt, based on shallower emplacement depths of plutons in the east, generally relate the tilting to opening of the Gulf of California (Krummenacher et al. 1975), but based on modern seismic analyses the effects of the Neogene uplift extend only halfway across the Baja Peninsula (Lewis et al. 2001), so it is unlikely to be the cause. Models that relate the younging to migrating magmatism (Ortega-Rivera 2003) don't resolve the problem, for the K–Ar ages in the east are as much as 20 m.y. younger than La Posta magmatism. Using $^{40}$Ar/$^{39}$Ar in biotite and potassium feldspar collected in a more focused area across the central boundary, Grove et al. (2003) recognized two distinct periods of exhumation and cooling in rocks of the Peninsular Ranges batholith: an early ~95–86 Ma period, which they ascribed to emplacement of the La Posta suite; and a < 78 Ma period, located farther east, which they related to the Laramide event. They clearly recognized two events and so explained the regional timing, but their tectonic model failed to explain the origin of the La Posta plutons as well as the 19–23 km of uplift and exhumation during their emplacement.

## GEOCHEMISTRY

The geochemistry of the Peninsular Ranges batholith is historically important because it is close to the Southern California megalopolis and its geologically rich university community, so that over the years many geochemical and petrological studies were completed. The early field and petrological studies by Larsen (1948) were highly regarded and strongly influenced several generations of petrologists studying batholithic rocks. His geochemical data set was employed for the 'type' calcic suite used to define the boundary between alkali-calcic and calcic plutonic suites on the SiO$_2$–MALI diagram of Frost et al. (2001). His data set was also used to define the calcic trend on the normative Q'–ANOR diagram (Whalen and Frost 2013).

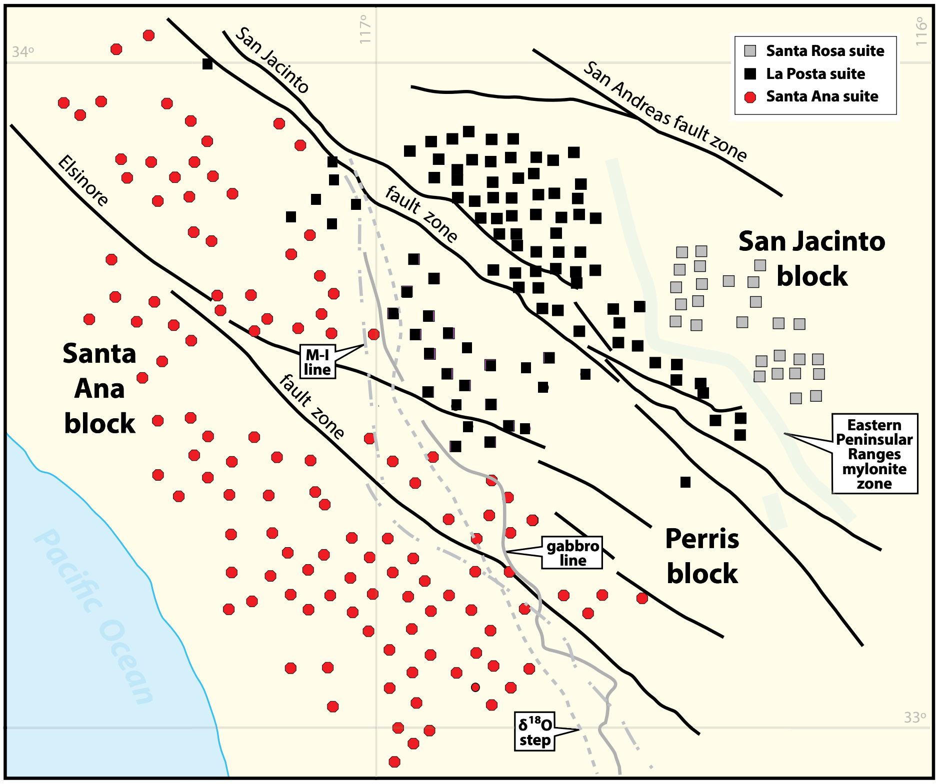

**Figure 7.** Map showing tectonic blocks (Santa Ana, Perris and San Jacinto), bounding faults, and locations of geochemical samples in the northern Peninsular Ranges batholith of southern California based on figures 1 and 2 of Kistler et al. (2003) and figure 68 from Morton et al. (2014).

During the late 1970s, A.K. Baird and coworkers collected 334 granitic rock samples on a uniform grid from the northern Peninsular Ranges batholith in Southern California (Baird et al. 1979). To obtain representative compositions, they collected 8 samples within a 400 x 400 foot (122 x 122 m) square from each site. The samples were then crushed and combined to yield one homogeneous powder from each sample site. To our knowledge, this represents the most systematic and representative geochemical sampling of a batholith carried out to date. Major element results from this collection were discussed by Baird et al. (1979) and published (without MnO and $P_2O_5$ determinations) by Baird and Miesch (1984). Subsequently, Kistler et al. (2003) published a compilation of isotopic data that contained results for whole rock Sr, 83 for bulk rock oxygen and 103 for whole rock Pb isotopes. This isotopic dataset, or portions thereof, was presented and interpreted in several papers (Kistler 1990, 1993). More recently, a subset of 287 rocks from the Baird collection was re-analyzed by ICP–MS for major and trace elements by Lee et al. (2007).

For this paper (Fig. 7), we utilized the Lee et al. (2007) data set, which included published sample location and initial Sr isotopic ratios (Kistler et al. 2003). To these data, we added O and Pb isotopic data from Kistler et al. (2003) and more recent Sr and Nd analyses from Premo et al. (2014b). We also added whole rock geochemical data from a recent study of the largest La Posta-type pluton in Baja California, the Sierra de San Pedro Mártir, by Gastil et al. (2014).

Instead of the purely geographic division of plutonic rocks into a western and eastern half favoured by most previous workers, we used a basic two-fold subdivision: pre- and post-100 Ma deformation, which does have some geographic connotations in that the pre-deformational plutons of the Santa Ana suite are concentrated, but not limited to, the west, and post-100 Ma plutons of the La Posta suite are concentrated in the east. We use this separation because we believe that the deformation represents a regional tectonic event and that magmatism before and after are compositionally quite different, which suggests to us that they have distinct origins. Based on a new generalized geological map of the northern Peninsular Ranges batholith showing Baird's sample locations (figure 68 in Morton et al. 2014), followed up by discussions with Doug Morton, who has detailed location maps, we filtered the Lee et al. (2007) data to exclude mylonitic, contact zone, sedimentary and Jurassic plutonic samples, so as to include only Santa Ana and La Posta suite samples in this study.

As discussed earlier, we believe that the major break defined by various attributes on the surface reflects the Cretaceous–Jurassic unconformity (Fig. 5) rather than a steeply dipping and fundamental crustal break or suture, and that the contact was more or less horizontal prior to deformation at 100 Ma. It now dips steeply eastward (Langenheim et al. 2014) and may represent the eroded remnant of an overturned limb of a large nappe formed during the deformation.

Within the post-deformational La Posta suite we recognize two subgroups: (1) the La Posta plutons proper; and (2) plutons, which we call the Santa Rosa suite, that are similar to rocks of the La Posta, but slightly younger, and which are exposed in the Santa Rosa Mountains (Figs. 3, 6). Santa Rosa plutons have a limited geographical distribution in that they occur above the East Peninsular Ranges mylonite zone (Fig. 3), which is a Laramide-age, westerly vergent, shear zone (Todd et al. 1988; Morton et al. 2014). We cannot rule out the unlikely possibility that the plutonic rocks of the Santa Rosa suite are not genetically related to the La Posta plutons, so we use different symbols to represent them on many of our geochemical plots.

### General Geochemical Features

As outlined above, samples from the Peninsular Ranges batholith were subdivided into two main groups based on age. Rocks of the calcic Santa Ana suite (Fig. 8a) span a broad silica range, from 48 to 77% $SiO_2$, whereas the range of the La Posta suite is much more limited, as all samples contain greater than 60% $SiO_2$ (Fig. 8b). In general, mainly metaluminous compositions (Fig. 8e) and amphibole-bearing mineralogy indicate that both suites are comprised of I-type granite (Silver and Chappell 1988; Chappell and Stephens 1988). Santa Ana granitoid rocks define the calcic trend in Figure 8a, and lie in the calcic field on Figure 8c, whereas La Posta samples exhibit a calcic to calc-alkalic affinity. Similarly, samples from Santa Ana plutons plot almost exclusively in the medium-K field (Fig. 8d), whereas members of the La Posta suite spread upward into the high-K field at higher silica contents. Samples from both suites with < 70 wt.% $SiO_2$ plot in the magnesian (oxidized) field in Figure 8b, but cross over into the ferroan (reduced) field at higher silica levels. On a $SiO_2$ vs. $Al_2O_3$ plot (Fig. 9a), the rocks of both suites exhibit a high-Al trend (Barker and Arth 1976), but with rocks of the La Posta suite defining a slightly higher Al trend than analyses from rocks of the Santa Ana suite. For any given silica content, rocks of the Santa Ana suite have higher concentrations of transition metals, such as V+Cr, (Fig. 9b) than samples from the La Posta suite. For samples with silica contents lying between 60 and 70 wt.% $SiO_2$, rocks of the La Posta suite tend to exhibit significantly higher Ba and Sr and lower Y contents than samples from the Santa Ana suite (Fig. 9c to 9e). While both suites have similar Rb contents, the suites are readily divisible on a Rb–Sr plot (Fig. 9f) due to contrasting Sr contents (Wallawender et al. 1990; Tulloch and Kimbrough 2003). Rocks of the Santa Ana and La Posta suites also display marked differences in La/Yb, Gd/Yb, Nb/Y, and Sr/Y values and these are readily apparent on histograms and Harker plots (Fig. 10).

Extended element-normalized plots of average compositions (Table 1 and Fig. 11) show that the La Posta average over the 60–70 wt.% silica range is more enriched in all trace elements to the left of Zr and more depleted in heavy rare earth elements (HREE) than the Santa Ana average over similar silica contents. Both the La Posta and Santa Ana suites have well developed negative K, Nb, Zr, P, and Ti anomalies. In rocks with > 70 wt.% silica, the Santa Ana average is more enriched in all elements, except for Ba, P, and Ti than the felsic La Posta average, but has a pronounced negative Sr anomaly. The felsic La Posta average is greatly depleted, and the Santa Ana is enriched, in HREE relative to their 60–70 wt.% silica range suite averages. Extended element-normalized compositional average patterns for the well studied Tuolumne intrusive suite of the Sierra Nevada (Fig. 11b) closely match the patterns and overall elemental abundances of the La Posta rocks. We also plotted averages for the La Posta suite, again over the 60–70% silica range, and compared them with compositional averages for other high-Al and La/Yb suites (Fig. 11c). Both adakite suites differ from the La Posta suite in that they are more depleted in large ion lithophile elements (LILE) and HREE, but have strong positive Sr anomalies. On Figure 11d we compare rocks of the Santa Ana suite with compositional averages for primitive to evolved arc-type suites. There, the pattern for the Santa Ana rocks more closely resembles the continental arc average, but is more depleted in the LIL elements to the left of Zr, where they define a trend about halfway between the continental and oceanic arc patterns.

## PREVIOUS MODELS

Silver et al. (1963; written in 1956) first suggested that the western part of the Peninsular Ranges batholith represents a primitive island arc constructed on oceanic lithosphere. In a subsequent contribution, Silver and Chappell (1988) recognized the dual nature of the batholith; that the western batholith formed between 140–105 Ma as a static arc above an eastward-dipping subduction zone; that magmatism migrated eastward between 105–80 Ma; and that it was derived from a deeper, subcrustal eclogitic source to yield La Posta plutons. They considered the batholith was a juvenile addition to the crust and formed where no continental lithosphere existed. On the other hand, based on Nd and Sr iso-

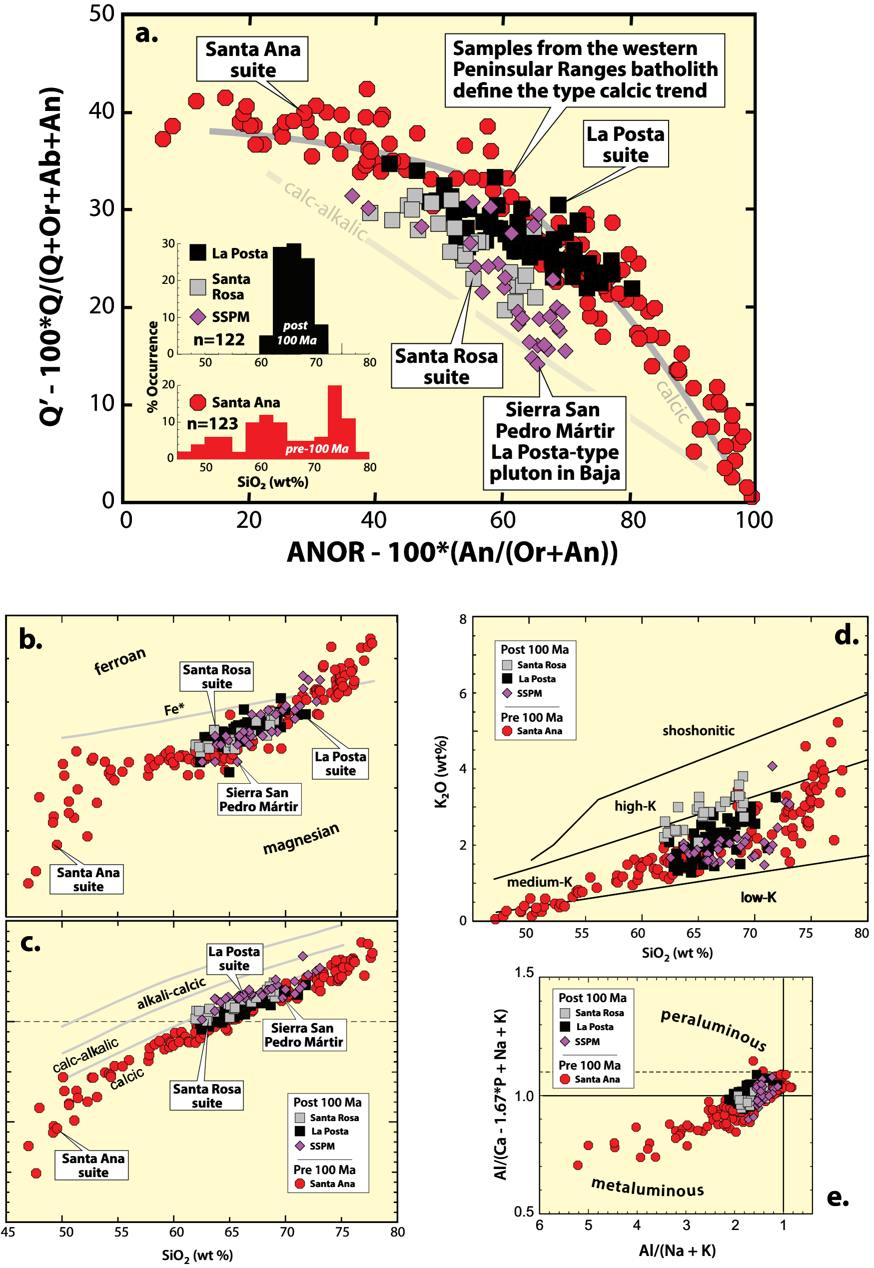

**Figure 8.** (a) Representative samples from the two main suites of the Peninsular Ranges batholith plotted on the normative Q' (100*(Q/ (Q+Or+Ab+An)) versus ANOR (100*(An/ (Or+An)) classification diagram (Streckeisen and LeMaitre 1979). We use the Whalen and Frost (2013) compositional trends. $SiO_2$ histograms are for the Santa Ana and La Posta suites. Sample subdivision is shown in the symbol legend and discussed in the text. (b) Peninsular Ranges batholith samples plotted on the: $FeO^{total}/(FeO^{total} + MgO)$ (or Fe*) vs. $SiO_2$; the boundary between ferroan and magnesian plutons has been modified as suggested by Frost and Frost (2008); (c) $Na_2O+K_2O-CaO$ (or MALI) vs. $SiO_2$ granitic rock classification diagrams of Frost et al. (2001). Ranges for alkali-calcic, calc-alkalic, and calcic rock series, based on the alkali–lime classification of Peacock (1931). Together with aluminum saturation index (ASI) (Shand 1943) (Fig. 8e), these plots comprise a three-tiered geochemical scheme for granitoid rock classification. The horizontal dashed line at ASI= 1.1 in the Shand plot, modified after Maniar and Piccoli (1989), is the dividing line between I- and S-type granites (Chappell and White 1992); and (d) a $SiO_2$ vs. $K_2O$ plot with suite subdivisions: low-, medium-, and high-K fields from LeMaitre (1989) and high-K, shoshonitic fields after Peccerillo and Taylor (1976). Analyses from Lee et al. (2007) and Gastil et al. (2014).

topes, Allègre and Othman (1980) recognized that plutons of the Peninsular Ranges and Sierra Nevada batholiths were formed from mantle melts plus significant quantities of continental crust.

In their landmark book on the reconnaissance geology of Baja, Gastil et al. (1975, submitted in 1971) were understandably coy in their tectonic interpretation, as plate tectonics had only recently "come on land" (Hoffman 2013); yet in the time it took to publish the book, Gastil created and published a short paper waxing poetically on a simple eastward-dipping subduction model in which "*great welts of tonalitic magma accumulated near the base of the pre-existing crust . . . spawned plutons that rose as diapirs . . . then bled upward into shallow plutons and extrusive masses*" (Gastil 1975). By 1981, he had developed a more complex model involving two eastward-dipping subduction zones, one beneath a more westerly fringing arc and the other to the east beneath the continental margin (Gastil et al. 1981). Following closure of the eastern basin, which led to crustal thickening and uplift, eastward subduction continued and a shallowing slab led to arc magmatism farther east.

Based largely on differences in degree of deformation between the Bedford Canyon and Santiago Peak rocks, Todd et al. (1988) also utilized a two-arc model but argued that "*Collision of the Santiago Peak–Alisitos arc with western North America in the Early Cretaceous resulted in folding of the continental-margin deposits and eventual underthrusting of the arc beneath the continental margin.*"

Contemporaneously with subduction of the western island arc, magmatism migrated slightly eastward where it produced melts from the subducted arc crust. Fifteen years later, Todd et al. (2003) concluded that "*a single Cretaceous arc migrated from west to east across a preexisting Late Jurassic–earliest Cretaceous lithospheric boundary.*"

Meanwhile Busby et al. (1998) also developed a fringing arc model based on their extensive work in Baja. They posited that a Jurassic arc, which developed offshore, grew into a more mature fringing arc separated from North America by a back-arc basin, and that, "*an increase in plate convergence collapsed the fringing arc against the continent*

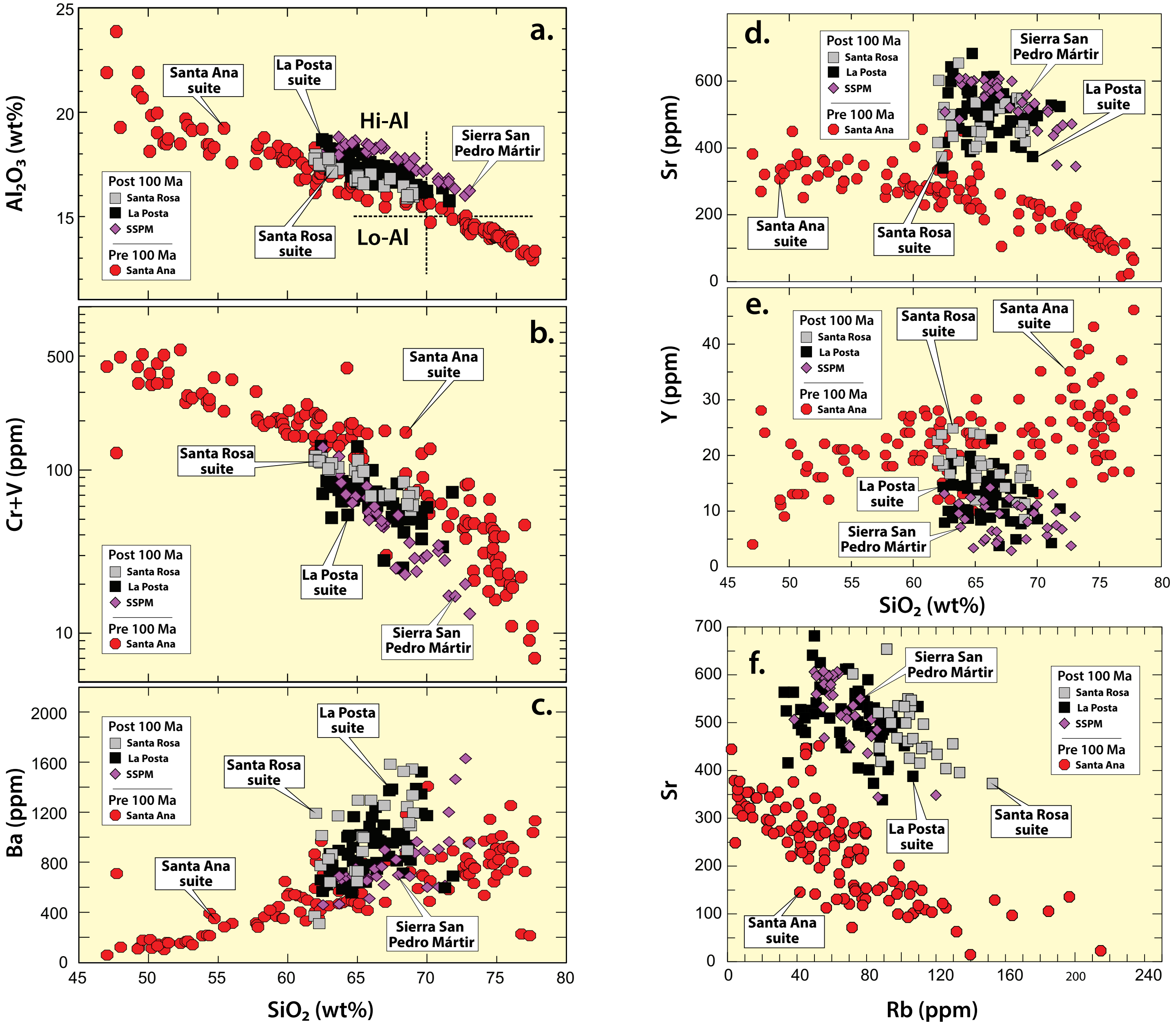

**Figure 9.** Harker variation diagrams for (a) $Al_2O_3$; (b) Cr + V; (c) Ba; (d) Sr; (e) Y; and (f) Sr–Rb for Peninsular Ranges batholith sample groups. In (a) the dividing line of Barker (1979) between high- (> 15 wt.%) and low-Al tonalite suites at $SiO_2$ = 70 wt.% is shown. Sample subdivision is shown in the symbol legend and discussed in the text. Note that on most of these plots pre- and post-deformational plutons are compositionally distinct.

*and caused the reverse faulting and uplift".*

Based on geological mapping and dating Johnson et al. (1999b) invoked a double eastward subduction model with two eastward-dipping subduction zones, largely because they believed that Nd and Sr isotopic values, coupled with the absence of inherited zircon in the Alisitos and related plutonic rocks, indicated an absence of continental input. Collision of the arc with a more easterly arc built on western North America led to crustal thickening whereas continued easterly subduction led to the younger magmatism.

Several researchers developed single eastward subduction models based largely on the composition and characteristics of the La Posta suite. Walawender et al. (1990) devised a simple model where increased convergence caused the eastward-dipping subducting slab to shallow, buckle and break, so that continued subduction was able to melt the overlying oceanic crust and mantle to produce the La Posta magmas.

In an important paper, Kimbrough et al. (2001) tied together many critical elements, such as the post-deformational nature of the La Posta suite, the rapid exhumation, and coeval sedimentation to the west, which they viewed as the fore-arc region, but in the end they attributed the La Posta suite to nothing more than a transient episode of high-flux magmatism. Tulloch and Kimbrough (2003) expanded

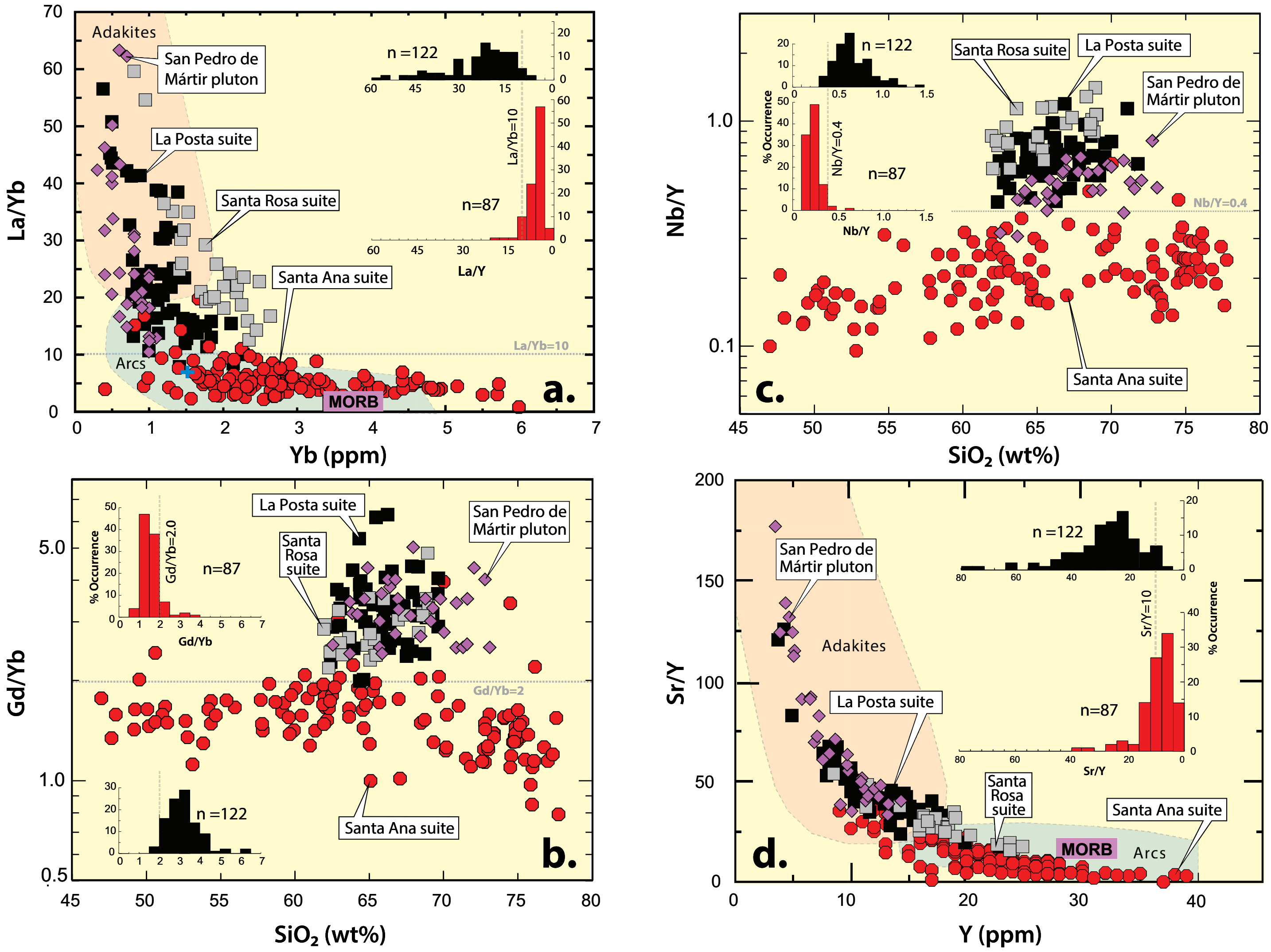

**Figure 10.** Some trace element ratio plots for Peninsular Ranges plutonic suites. (a) La/Yb versus Yb plot and La/Yb histograms; (b) Gd/Yb versus $SiO_2$ and Gd/Yb histograms; (c) $SiO_2$ versus Nb/Y plot and Nb/Y; (d) Sr/Y versus Y plot and Sr/Y histograms. In all insert histograms and 10a and 10d X-Y plots, only samples with > 60% silica are plotted, whereas in 10b and 10c X-Y plots all samples are plotted, as in Figures 8 and 9. Fields are shown for adakite, arc andesite–dacite–rhyolite and MORB from Richards and Kerrich (2007), as is the average medium-K arc andesite (blue cross in a). In the histograms, vertical lines approximately separate pre- and post-deformational granitoid rocks.

on the earlier model by recognizing that the La Posta suite was a high Na, Sr and low Y suite and so created a model in which the older, western and low Sr, Y Santiago Peak–Alisitos arc was underthrust beneath the arc during slab-flattening, which shut off normal arc magmatism and generated the burst of La Posta magmatism. Grove et al. (2003) related the pre-90 Ma exhumation to the emplacement of the La Posta suite. Subsequently, Grove et al. (2008) developed a complex model – based largely on detrital zircon, their Th/U ratios, and whole rock Pb isotopes of the plutonic rocks – of eastward-directed subduction, slab-flattening and subduction of forearc and accretionary prism rocks, such as the Catalina schist. In their model, a hypothetical deep lithospheric mantle root had formed beneath the La Posta belt but was removed by Laramide shallow subduction, so that it no longer exists beneath the region.

Ortega-Rivera (2003), noting the general eastward younging of plutonic ages, advanced a model of long-lived eastward subduction and variations in dip and velocity of the subducting plate to generate the magmatism. Miggins et al. (2014) developed a vague model, based on that of Grove et al. (2008), where eastward subduction built a near-margin or fringing extension arc built entirely on oceanic crust, and that as arc magmatism migrated eastward the tectonic regime went from extensional to compressional, which caused thrusting and exhumation of the western arc rocks between 105 and 98 Ma. They then stated that between 98 and 91 Ma large amounts of highly enriched magma were formed and that it was the emplacement of the magma that led to the exhumation of the eastern region. The reader was left to imagine what caused the events.

Schmidt et al. (2014) summarized over a decade of work by stu-

**Table 1. Average compositions of Peninsular Ranges Batholith plutonic suites.**

| Group | Santa Ana Suite | | | | La Posta Suite | | | |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ Range | 60-70% | 1σ | >70% | 1σ | 60-70% | 1σ | >70% | 1σ |
| No. Samples | 39 | | 41 | | 110 | | 12 | |
| Major Elements (wt.%) | | | | | | | | |
| $SiO_2$ | 66.48 | 8.46 | 76.47 | 0.77 | 65.93 | 2.14 | 71.54 | 0.84 |
| $TiO_2$ | 0.61 | 0.25 | 0.16 | 0.06 | 0.71 | 0.16 | 0.29 | 0.07 |
| $Al_2O_3$ | 16.08 | 2.27 | 12.64 | 0.33 | 16.77 | 0.78 | 15.86 | 0.44 |
| $Fe_2O_3^{Total}$ | 3.09 | 2.05 | 1.87 | 0.35 | 4.27 | 2.00 | 2.01 | 0.94 |
| MnO | 0.07 | 0.03 | 0.05 | 0.02 | 0.08 | 0.03 | 0.04 | 0.02 |
| MgO | 1.25 | 0.62 | 0.22 | 0.11 | 1.47 | 0.48 | 0.46 | 0.17 |
| CaO | 4.01 | 1.27 | 1.14 | 0.41 | 4.52 | 0.67 | 2.91 | 0.48 |
| $Na_2O$ | 3.89 | 0.73 | 3.59 | 0.28 | 3.93 | 0.61 | 4.49 | 0.44 |
| $K_2O$ | 2.36 | 0.77 | 3.79 | 0.77 | 2.21 | 0.55 | 2.45 | 0.78 |
| $P_2O_5$ | 0.18 | 0.06 | 0.07 | 0.02 | 0.20 | 0.04 | 0.09 | 0.03 |
| Trace Elements (ppm) | | | | | | | | |
| Cr | 17 | 32 | 12 | 9 | 16 | 9 | 6 | 4 |
| Co | 6 | 5 | 2 | 1 | 7 | 4 | 1 | 2 |
| Sc | 7 | 4 | 6 | 4 | 7 | 3 | 5 | 2 |
| V | 49 | 26 | 8 | 6 | 55 | 19 | 21 | 15 |
| Cu | 12 | 11 | 8 | 8 | 14 | 11 | 3 | 3 |
| Zn | 66 | 19 | 30 | 11 | 73 | 12 | 52 | 13 |
| W | 0.3 | 0.2 | 0.4 | 0.2 | 0.3 | 0.2 | 0.0 | 0.1 |
| Mo | 1.8 | 1.4 | 3.8 | 1.7 | 1.8 | 1.2 | 0.2 | 0.4 |
| Rb | 80 | 30 | 123 | 47 | 77 | 24 | 70 | 22 |
| Cs | 2.3 | 1.0 | 2.9 | 2.1 | 2.3 | 0.8 | 2.2 | 0.7 |
| Ba | 899 | 317 | 809 | 316 | 920 | 302 | 962 | 328 |
| Sr | 465 | 145 | 83 | 34 | 515 | 67 | 459 | 61 |
| Ta | 0.8 | 0.5 | 0.8 | 0.4 | 0.8 | 0.6 | 0.4 | 0.2 |
| Nb | 8.5 | 4.5 | 6.4 | 1.8 | 9.3 | 4.6 | 4.8 | 1.4 |
| Hf | 4.4 | 1.2 | 4.3 | 1.3 | 4.6 | 1.1 | 3.2 | 0.5 |
| Zr | 160 | 44 | 124 | 35 | 171 | 40 | 128 | 20 |
| Y | 14 | 7 | 27 | 9 | 13 | 5 | 8 | 3 |
| Th | 10.8 | 7.4 | 15.8 | 7.4 | 10.8 | 7.5 | 6.7 | 2.9 |
| U | 1.9 | 1.2 | 3.2 | 1.6 | 1.9 | 1.1 | 0.8 | 0.2 |
| La | 26.8 | 12.1 | 19.4 | 5.2 | 28.8 | 12.3 | 20.1 | 6.6 |
| Ce | 55.8 | 25.1 | 43.7 | 11.1 | 60.0 | 25.6 | 37.8 | 12.0 |
| Nd | 25.0 | 10.1 | 19.0 | 3.8 | 27.0 | 9.9 | 15.4 | 4.3 |
| Sm | 5.1 | 2.0 | 4.7 | 1.4 | 5.4 | 1.9 | 2.9 | 0.8 |
| Eu | 1.2 | 0.4 | 0.7 | 0.5 | 1.3 | 0.4 | 0.8 | 0.3 |
| Gd | 3.7 | 1.4 | 4.2 | 1.3 | 3.8 | 1.3 | 2.1 | 0.6 |
| Tb | 0.6 | 0.3 | 0.8 | 0.3 | 0.6 | 0.2 | 0.3 | 0.1 |
| Yb | 1.4 | 0.9 | 3.5 | 1.2 | 1.3 | 0.6 | 0.7 | 0.2 |
| Parameters | | | | | | | | |
| Q' | 26.6 | 6.5 | 39.8 | 1.4 | 25.1 | 4.3 | 29.9 | 2.6 |
| ANOR | 55.8 | 15.9 | 19.4 | 9.0 | 61.5 | 8.2 | 49.8 | 11.3 |
| MALI | 2.2 | 1.8 | 6.2 | 1.0 | 1.6 | 1.1 | 4.0 | 1.1 |
| Fe* | 0.74 | 0.10 | 0.89 | 0.04 | 0.73 | 0.03 | 0.80 | 0.03 |
| Zr Temp.(C) | 748 | 89 | 766 | 23 | 760 | 31 | 726 | 16 |
| ASI[1] | 0.99 | 0.12 | 1.05 | 0.02 | 1.00 | 0.03 | 1.04 | 0.02 |
| Alkali Index | 1.79 | 0.32 | 1.27 | 0.09 | 1.90 | 0.17 | 1.59 | 0.12 |
| Isotopes | | | | | | | | |
| $\delta^{18}O$‰ | 6.7 | 0.7 | 6.4 | 1.8 | 9.3 | 0.7 | 10.5 | 3.0 |
| i $^{87}Sr/^{86}Sr$ | 0.7050 | 0.0054 | 0.7040 | 0.0006 | 0.7070 | 0.0001 | 0.7055 | 0.2720 |
| i$^{206}Pb/^{204}Pb$ | 18.772 | 0.092 | 18.867 | 0.110 | 19.211 | 0.181 | 18.931 | |
| i$^{207}Pb/^{204}Pb$ | 15.603 | 0.020 | 15.612 | 0.017 | 15.682 | 0.024 | 15.626 | |
| i$^{208}Pb/^{204}Pb$ | 38.446 | 0.138 | 38.496 | 0.118 | 38.787 | 0.125 | 38.657 | |
| Ratios | | | | | | | | |
| La/Yb | 5.86 | 2.96 | 6.62 | 3.18 | 26.80 | 19.22 | 31.90 | 14.07 |
| Gd/Yb | 1.15 | 0.41 | 1.25 | 0.35 | 3.23 | 0.74 | 3.13 | 0.63 |
| Sr/Y | 4.45 | 4.33 | 3.43 | 1.77 | 49.26 | 30.88 | 67.22 | 32.07 |
| Ba/Y | 27.7 | 13.3 | 31.9 | 13.3 | 86.1 | 61.0 | 147.0 | 102.6 |
| Nb/Y | 0.22 | 0.07 | 0.25 | 0.05 | 0.71 | 0.21 | 0.64 | 0.19 |

[1.] ASI = Al saturation index.

dents at USC and concluded that the Santiago Peak rocks were deposited upon Jurassic basement whereas the Alisitos rocks were established upon oceanic crust. In their model, the Alisitos and Santiago Peak arcs collided along the ancestral Agua Blanca and Main Mártir thrusts prior to 108 Ma and the resulting contractional deformation and crustal thickening "*culminated in a major pulse of arc magmatism that formed the 99–92 Ma La Posta suite*." Numerous difficulties with this model, which was based largely on work by Wetmore et al. (2002), were summarized by Busby (2004), and include the similar basements and the presence of inherited zircon for both groups of rocks, as well the presence of abundant siliceous volcanic rocks within the Alisitos arc, including ignimbrite sheets (Busby et al. 2006), all cut by numerous intermediate–siliceous composition plutons, which are atypical of arcs built on oceanic crust.

Another group of researchers linked the Alisitos–Santiago Peak arc to the Guerrero composite terrane located on the Mexican mainland (Centeno-García et al. 2008). A French group (Tardy et al. 1992, 1994) also argued that the Alisitos arc was part of the Guerrero composite terrane but reasoned that it collided with the western margin of North America over a westward-dipping subduction zone. Dickinson and Lawton (2001a) presented a model in which the Santiago Peak volcanics represented an arc accreted to the western margin of the Caborca block, but that the contact was obscured by younger plutons.

In an important contribution, Centeno-García et al. (2011) noted the strong ties between the history of Baja California and the Guerrero composite terrane, as well as the strong detrital zircon ties of both to North America, and so speculated that the arc fringed the continent and was separated from it by a marginal basin. They argued that the closure of the basin started in the west during the Cenomanian, migrated eastward, and ended prior to deposition of Santonian sediments between about 93–84 Ma. They stated that "*Arc extension ended by the Albian–Cenomanian boundary in Baja California, when the Early Cretaceous Alisitos fringing arc underthrust the Mexican continental margin and the crust*

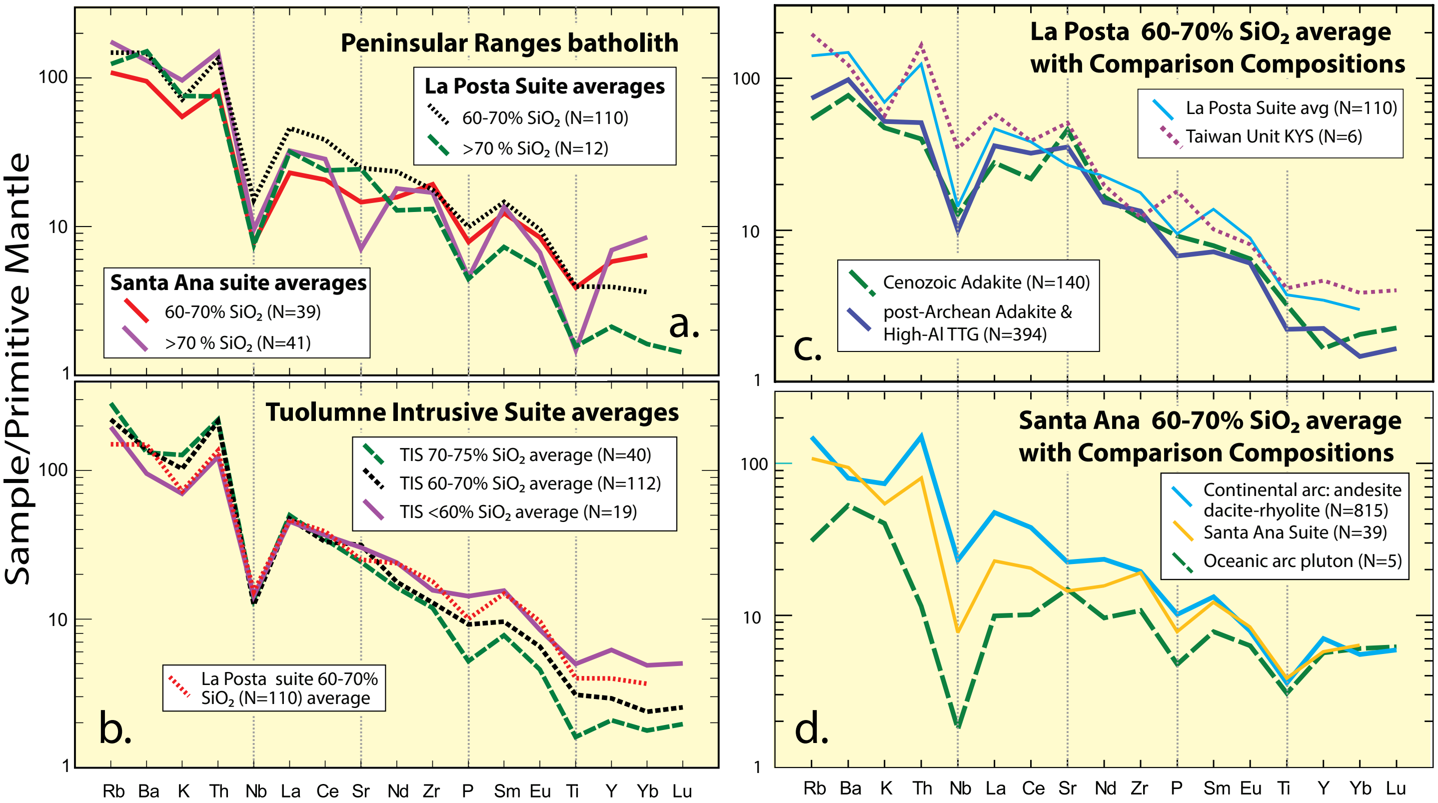

**Figure 11.** Primordial mantle-normalized extended element plots for: (a) Peninsular Ranges batholith plutonic suite compositional averages from Table 1 for 60–70 and > 70 wt.% silica ranges; (b) Tuolumne Intrusive Suite compositional range averages compared to La Posta 60–70% $SiO_2$; (c) La Posta 60–70% $SiO_2$ average compared to other similar units including KYS from Taiwan (Wang et al. 2004), Cenozoic adakite bodies, post-Archean adakite bodies, and high-Al TTG suites; and (d) Santa Ana suite 60–70% average, oceanic arc pluton, and continental arc. Comparison compositions in (c) and (d) from Drummond et al. (1996) and Whalen (1985); data in (b) are based on a compilation of data from various sources including Memeti (2009). Primordial mantle-normalizing values are from Sun and McDonough (1989).

*was greatly thickened"* without explaining how the arc ended up on the lower plate and the continental margin the upper.

## INTERPRETATION

In what follows we show how the various components of the Cretaceous Peninsular Ranges batholith can be combined into a new, dynamic, but entirely actualistic, model. We do this first by succinctly examining some critical attributes of modern arc terranes, then we move on to examine the subduction polarity for the Santiago Peak–Alisitos arc. This leads us directly into a discussion of lithospheric slab failure during collision and how it can parsimoniously explain major features in the development of the batholith. Next we look at the exhumation of the batholith and touch on the formation of the doubly vergent fan structure.

We then interpret the geochemistry of the pre-collisional and post-collisional plutonic rocks in order to better understand the sources of the magmatism. To end – but prior to presenting our final conclusions – we concisely compare the development of the Peninsular Ranges batholith with some other Cordilleran batholiths of the Americas.

### Arcs

Although Coats (1962) clearly argued that subduction of oceanic crust created the volcanoes of the Aleutian arc, it was Hamilton (1969a, b) who hypothesized that the only modern volcanic fields of comparable size to great Mesozoic batholiths of the western Americas were Andean-type volcanic fields, where he suggested, "*that a great late Cenozoic batholith, comparable in size and composition to the late Mesozoic batholiths of western North America, has formed beneath the young volcanic pile of the central Andes.*" In many ways it is unfortunate that Hamilton chose the Andes for it is atypical of continental arcs and so, many geologists, also strongly influenced by the supposedly deep Sierran crustal root (Lawson 1936; Bateman et al. 1963; Bateman and Wahrhaftig 1966; Christiansen 1966; Dodge and Bateman 1988), assumed that Cordilleran batholiths were generated in zones of great crustal thickening (Bateman 1992; Ducea 2001; Ducea and Barton 2007; Grove et al. 2008; DeCelles et al. 2009).

One only has to survey continental arcs worldwide to recognize that there are problems in using a thick crust Andean-type model, for, contrary to popular belief, thick sequences of arc rocks erupted and deposited within a subsiding basin are the norm, not volcanoes sitting on high-standing thick crust. Most continental arcs form within subsiding depressions or basins on crust of average or below average thickness (Levi and Aguirre 1981; Hildebrand and Bowring 1984; Busby-

Spera 1988b; Busby 2004, 2012). Modern examples include the Cascades, where the volcanoes sit in a half graben (Williams and McBirney 1979; Mooney and Weaver 1989), the low-standing Alaskan Peninsula (Burk 1965; Fliedner and Klemperer 2000) where volcanoes such as Augustine are partially submerged in Cook Inlet (Power et al. 2010), the Kamchatka Peninsula of easternmost Russia where towering stratovolcanoes sit in huge fault-bounded troughs (Erlich 1968, 1979; Levin et al. 2002a, b), to New Zealand where the Taupo zone sector of the arc is actively extending as calderas and stratocones erupt within it (Houghton et al. 1991; Harrison and White 2006; Downs et al. 2014), and the Central American arc where volcanoes are aligned in a long linear depression (Williams et al. 1964; Williams and McBirney 1969; Burkhart and Self 1985; MacKenzie et al. 2008).

Furthermore, the stratigraphy within pendants and wall rocks of Cordilleran batholiths provides no evidence of thick crust as they too sat at or below sea level during volcanism. The Sierra Nevada was clearly low-standing during magmatism, for it contains marine rocks deposited at about 100 Ma (Nokleberg 1981; Saleeby et al. 2008; Memeti et al. 2010). So was the western Peninsular Ranges arc, where the Santiago Peak and Alisitos volcanics are interbedded with sedimentary rocks containing marine fossils (Fife et al. 1967; Allison 1974; Phillips 1993; Griffith and Hoobs 1993; Wetmore et al. 2005; Busby et al. 2006; Centeno-García et al. 2011). In South America, the 9 km thick Casma arc volcanic rocks, the wall rocks for the younger Coastal batholith of Peru, are dominantly marine (Cobbing 1978, 1985; Atherton et al. 1985) as are many of the thick Jurasso–Cretaceous arc rocks within the Ocoite arc of northern Chile (Levi and Aguirre 1981; Åberg et al. 1984). Even ancient arcs, such as the Paleoproterozoic Great Bear magmatic zone of the Wopmay orogen, were low standing zones of subsidence during magmatism (Hoffman and McGlynn 1977; Hildebrand and Bowring 1984). Where arcs are concerned the Andes are the outlier – simply atypical of modern and ancient arcs.

As stated earlier, the general paradigm for generation of the Santiago Peak–Alisitos arc and the Peninsular Ranges batholith – and in fact all the Cordilleran batholiths of the American Cordillera – has been east-directed subduction beneath the western margin of North America. In what follows, we provide evidence that indicates that at least part of the Santiago Peak–Alisitos arc was constructed by magmatism arising from westerly, not easterly, subduction.

## Polarity of Subduction

As indicated previously, nearly all researchers who have presented models for the origin of the Peninsular Ranges batholith have assumed an eastward-dipping subduction regime. Yet as pointed out by Todd et al. (1988), it was only the presence of scattered occurrences of blueschist-facies metamorphic rocks and ophiolite located to the west of the Peninsular Ranges batholith in the California borderlands which suggested that subduction was eastward. These rocks outcrop in the Sierra de San Andres on the Vizcaino Peninsula and on Cedros Island (Fig. 2). There, a sequence of volcanic and sedimentary rocks, generally interpreted to represent a magmatic arc, active from at least 166 ± 3 Ma until 160 Ma and again during the Cretaceous, sits atop a Late Triassic and mid-Jurassic supra-subduction ophiolitic basement, which in turn, sits structurally above a blueschist-bearing accretionary complex and is separated from it by a serpentinite mélange containing high-grade blocks (Rangin 1978; Kimbrough 1985; Moore 1985, 1986; Kimbrough and Moore 2003; Sedlock 2003). The blocks in the mélange are typically eclogite and amphibolite, with ages in the 170–160 Ma range, and blueschist-facies blocks ranging in age from 115 to 95 Ma (Baldwin and Harrison 1989, 1992). The upper contacts of the blueschist-facies belts are interpreted as normal faults and reflect their probable Late Cretaceous–Paleogene exhumation (Sedlock 1996, 1999). Perhaps 10 km of upper Albian–Cenomanian to Coniacian–Maastrichtian siliciclastic turbidites, known as the Valle Group and described earlier, sit unconformably on the older arc–ophiolite–accretionary complex rocks (Minch et al. 1976; Boles 1986; Busby-Spera and Boles 1986; Sedlock 1993).

While most workers relate the ophiolite–blueschist facies rocks–turbidite basin triad to an eastward-dipping subduction zone and forearc basin related to the Alisitos arc–Peninsular Ranges batholith, the Vizcaino ophiolite is 221 ± 2 Ma, the Cedros Island ophiolite 173 ± 2 Ma, and the arc plutons, 165–135 Ma (Kimbrough and Moore 2003) – all considerably older than the 128–100 Ma Alisitos arc. Given the age difference and the wide and flat Desierto de Vizcaino and the Llano de Magdalena (Fig. 2), both extensive areas without bedrock outcrop, separating the Peninsular Ranges batholith and its wall rocks from the Sierra de San Andres, there is no compelling reason that the two areas have any direct relationship to one another, nor that they were in close proximity during the Early Cretaceous. Other sequences, such as those on Catalina Island and related rocks of the southern California borderlands (Grove et al. 2008), are of Early Cretaceous age in part, but are separated from the batholith by deep water and/or an unknown number of major faults, such as the Oceanside (Abbott and Smith 1989; Crouch and Suppe 1993; Bohannon and Geist 1998), so that there is no direct link to the batholith. Additionally, as documented by Grove et al. (2008), most of the units within the thrust stack on Catalina Island are younger than the age of deformation within the Peninsular Ranges batholith and are generally considered to be part of the Franciscan accretionary complex, which, along with rocks of the Coast Range ophiolite and Great Valley group, were unlikely to have been located west of the Sierran–Peninsular Ranges arc prior to 100 Ma (Wright and Wyld 1997; Hildebrand 2013).

However, because the upper 92–91 Ma Turonian sandstone of the Valle Group is dominated by 100–90 Ma detrital zircon, presumably derived from the La Posta plutons (Kimbrough et al. 2001), one can reasonably argue that rocks of the group were close to the Peninsular Ranges batholith by the Late Cretaceous, but the nature of the basin and its relationship to the Alisitos arc are obscure. Busby-Spera

(1988a) argued that the ophiolite and its overlying volcaniclastic apron on Cedros Island represented a remnant of a back-arc basin of Mid-Jurassic age. Given that arc magmatism there is dated to be as young as 135 Ma (Kimbrough and Moore 2003), it is conceivable in a west-dipping scenario that this magmatism represents an older segment of the Alisitos arc and that the arc migrated eastward due to slab rollback. Alternatively, the 135 Ma plutonic package could be part of a pre-Alisitos arc.

If the subduction polarity wasn't necessarily eastward, then we must examine the region to the east on the other side of the arc. Unfortunately, due to the effects of the opening of the Gulf of California, the relations of the arc to the lower plate are not particularly well exposed in Southern and Baja California; but as Baja is readily restored back to the Mexican mainland (Oskin and Stock 2003), the relationships might be clearer there. In fact, several workers (Tardy et al. 1994; Dickinson and Lawton 2001a; Centeno-García et al. 2008, 2011; Schmidt et al. 2014) suggested that the Alisitos arc formed part of the Guerrero superterrane of the western Mexican mainland.

The Guerrero superterrane is a composite terrane made up of several different terranes that were assembled during the Mesozoic (Centeno-García et al. 2003, 2008) and, along with other amalgamated terranes to the east such as Oaxaquia, collided with North America during the Laramide event at about 75 Ma. The Laramide docking of the arc-bearing superterrane (Tardy et al. 1994; Centeno-García et al. 2011) is documented by a well-developed thin-skinned fold and thrust belt and associated foredeep, located in extreme eastern Mexico along the eastern margin of Oaxaquia, just west of the Gulf of Mexico (Busch and Gavela 1978; Tardy et al. 1992, 1994; Eguiliz de Antuñano et al. 2000; Salinas-Prieto et al. 2000; Nieto-Samaniego et al. 2006; Pérez-Gutiérrez et al. 2009; Hildebrand 2013). Where best exposed at the southern end of the Maya block, a southwest-facing carbonate-dominated platform sitting on basement of the Maya block was drowned during the uppermost Campanian, buried by orogenic flysch during the Maastrichtian–Danian (Fourcade et al. 1994), and overthrust by ultramafic nappes. Rocks of the lower-plate crystalline basement were metamorphosed to eclogite at 76 Ma, which implies that part of the North America margin was subducted to greater than 60 km depth at about that time and exhumed to amphibolite grade levels a million years later (Martens et al. 2012), presumably by slab failure.

Some 25–30 m.y. earlier near the end of the Albian, much of east-central Mexico, such as Oaxaquia, Central and Mixteca terranes, formed a coherent block and was covered by a west-facing Lower Cretaceous carbonate platform (Fig. 12), known as the Guerrero–Morelos platform, or locally the El Doctor platform, in the south and the Sonoran shelf in the north (LaPierre et al. 1992a; Monod et al. 1994; Centeno-García et al. 2008; González-Léon et al. 2008; Martini et al. 2012). In the south, the platform was built upon ~1000 m of Lower Cretaceous red beds, alluvial sandstone and conglomerate with thick evaporite deposits and an older metamorphic basement (Fries 1960). Locally, a suite of Late Jurassic–earliest Cretaceous volcanic and volcaniclastic rocks predated the platform (Monod et al. 1994).

The west-facing carbonate platform was uplifted, eroded, pulled down to deeper water, and buried by orogenic deposits (Fig. 13), known locally as the Mexcala flysch, during the latest Albian–early Cenomanian at about 100 Ma (Monod et al. 2000). During drowning the platform shed carbonate blocks up to 2 m across into the lower parts of the flysch to the west (Monod et al. 1994). This drowning was caused by the attempted subduction of the easterly block and its cover beneath a Lower Cretaceous arc complex, now located in the Zihuatanejo terrane, but which was built upon Triassic–Jurassic basement comprising a Triassic–Jurassic accretionary complex and associated 164–154 Ma Jurassic magmatic rocks (Salinas-Prieto et al. 2000; Bissig et al. 2008; Martini et al. 2010; Centeno-García et al. 2011; Martini and Ferrari 2011). The Lower Cretaceous arc rocks, now folded and cut by plutons, one of which was dated by U–Pb as 105 Ma, are strikingly similar to those of the Alisitos Group in that they are shallow marine sedimentary rocks, volcaniclastic rocks, and a wide variety of subaerial–submarine intermediate composition volcanic rocks with reefal limestone of middle–late Albian age towards the top (Tardy et al. 1992; Centeno-García et al. 2003, 2011). Martini and Ferrari (2011) showed that the carbonate rocks and their basement were folded during the Cenomanian prior to the 94 Ma start of deposition of clastic sedimentation. The results from more detailed detrital zircon studies of sandstone in the area show – in addition to clusters at 106–110 Ma, ~250 Ma, 480–650 Ma, and 1.0–1.3 Ga – strong 160–162 Ma peaks, presumably reflecting the Jurassic basement, and in two younger rocks, huge peaks at 99–97 Ma, which might represent La Posta type intrusions (Centeno-García et al. 2011).

Given that when Peninsular Baja is restored to its pre-Gulf of California paleogeographical position (Fig. 12), the Alistos arc is on strike with, and just north of, the Zihuatanejo terrane and its lower Cretaceous arc, coupled with the striking similarities in Jurassic arc and Jurasso–Triassic accretionary complexes in the basement, their overall stratigraphic packages and settings, as well as their similar ages, they almost certainly represent the same arc complex (Centeno-García et al. 2011). In the Zihuatanejo terrane the relations are clear: the leading edge of a west-facing Albian carbonate platform sitting atop older rocks was pulled beneath a Lower Cretaceous arc and its Jurasso–Triassic basement, at about 100 Ma (Monod et al. 1994), consistent with relations inferred for the Santiago Peak–Alistos arc in Southern and Baja California. The collision marks the closure of an ocean along the western margin of the Cordilleran Ribbon Continent some 20–25 m.y. prior to the Laramide event, which reflects terminal collision of the ribbon continent with North America (Hildebrand 2013, 2014).

Far to the north in Sonora is the Sonoran shelf (Fig. 12), another segment of the west-facing Albian platform or ramp located in western Mexico, this one dominated by carbonate rocks of the Mural Formation

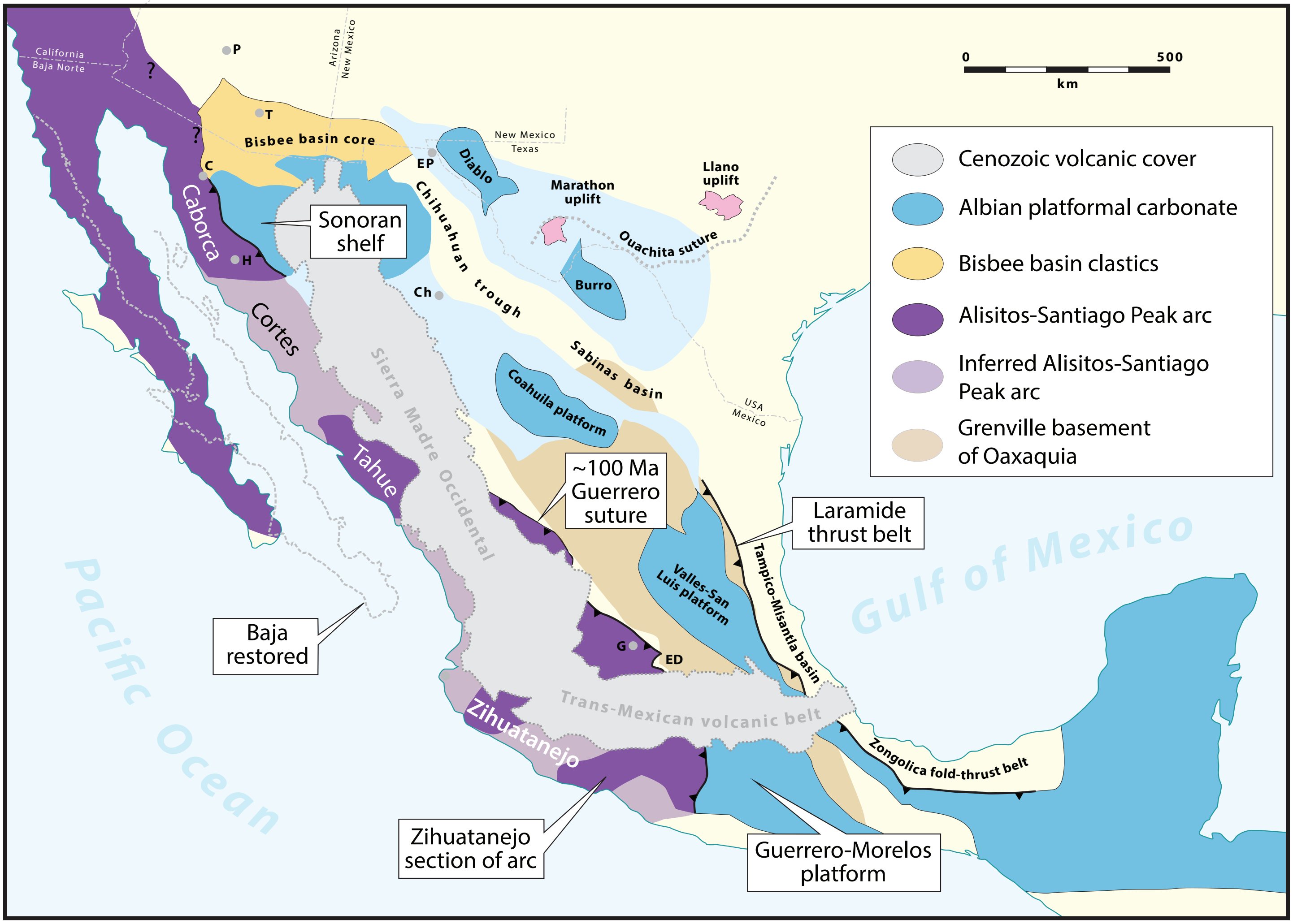

**Figure 12.** Geological sketch map illustrating the extent of the Guerrero–Alisitos–Santiago Peak arc, its terranes, and Albian carbonate platforms to the east. The Laramide thrust belt and related foredeep are located even farther east as shown. ED–El Doctor platform; G–Guanajuato; H–Hermosillo, C–Caborca, T–Tucson, P–Phoenix, EP–El Paso, Ch–Chihuahua. Map data from Dickinson and Lawton (2001a); Martini et al. (2012); Hildebrand (2013); restoration of Baja from Oskin and Stock (2003).

within the Bisbee Basin (Warzeski 1987; Lawton et al. 2004; González-Léon et al. 2008). The shelf was part of a complex, west and southwest-facing passive margin that developed following rifting within the Cordilleran Ribbon Continent during the Late Jurassic (Dickinson and Lawton 2001a, b).

Beneath the rocks of the Bisbee Basin and sitting unconformably atop Jurassic arc rocks, which extend from the Klamath Mountains to southern Arizona and were deformed during a 160 Ma collision, are isoclinally folded Oxfordian to Tithonian marine sedimentary rocks of the Sonoran Cucurpe Formation (Fig. 14), which were largely derived from magmatic rocks of the bimodal Ko Vaya suite (Mauel et al. 2011). Hildebrand (2013) interpreted rocks of the Ko Vaya suite to represent slab failure magmas formed during and immediately following the 160 Ma collision, whereas Dickinson and Lawton (2001b) considered them to be magmatism associated with what they termed the Border Rift – an extensional system extending from the Gulf of Mexico to California.

Rocks of the Cucurpe Formation might correlate with the Tithonian Peñasquitos Formation of the western Peninsular Ranges (Kimbrough et al. 2014a), as both formations have similar basements and contain similar rocks of the same age (Fig. 14). Furthermore, both sequences were deformed between about 145 and 139 Ma and are both unconformably overlain by 130–125 Ma rocks; in the east the Cucurpe is overlain by rocks of the Bisbee margin, and to the west, rocks of the Peñasquitos Formation are overlain by the Santiago Peak volcano-sedimentary sequence (Fig. 14). Kimbrough et al. (2014a) noted that another sequence, the Mariposa Formation of the western Sierra Nevada (Fig. 14), is also of the same age (Snow and Ernst 2008), has a similar detrital zircon profile, and was intruded by 125–120 Ma plutonic rocks of the Sierran batholith (Lackey et al. 2012a, b).

Coarse clastic sedimentation and eruption of bimodal volcanic rocks in the Bisbee basin are commonly thought to have started around 150 Ma, following the Early to Mid-Jurassic

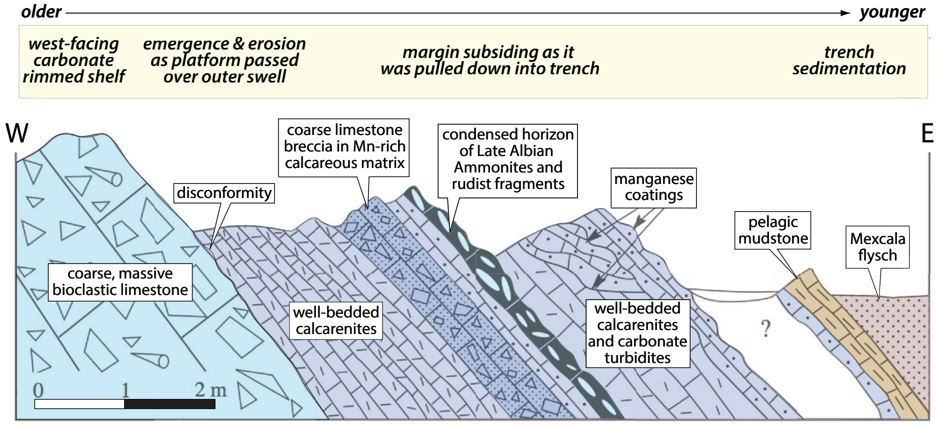

**Figure 13.** Detailed cross section of the uppermost few meters of the west-facing Guerrero–Morelos carbonate platform showing the rapid transition from carbonate shelf to orogenic deposits. Interpretation of stratigraphic units at top. Hoffman (2012) presents an excellent overview of the process of platform foundering at the beginning of orogenesis. Figure modified from Monod et al. (2000).

arc magmatism (Bilodeau et al. 1987; Krebs and Ruiz 1987; Lawton and McMillan 1999; Dickinson and Lawton 2001b), but the oldest sedimentary rocks within the basin were recently shown by detrital zircon studies and dating of intercalated volcanic rocks to have been deposited between 136 Ma and 125 Ma (Peryam et al. 2012). Within the Bisbee Basin, the lowermost clastic rocks have bimodal NE–SW paleocurrents and reflect shelf, lagoonal, tidal flat, and fluvial environments (Klute 1991), but pass upwards into an eastward-transgressive sequence of fining-upwards fluvial to shallow marine deposits (Peryam et al. 2012). The overlying carbonate platform had a well developed reefal rim along the southwest side (González-Léon et al. 2008). Beginning in the Late Albian the platform experienced rapid tectonic subsidence and during the Cenomanian and Turonian was buried by at least 1500 m of clastic sediment of the Cintura/Mojado formations shed in a more or less easterly direction and deposited in a flexural basin (Mack 1987; Gonzalez-Léon and Jacques-Ayala 1988). The most southwestern exposures of Cintura Formation are in excess of 2000 m thick and are overlain gradationally by latest Albian–Early Cenomanian fluvio-deltaic sandstone holding pebbles of quartzite and limestone and overthrust from the southwest by plutonic rocks (Jacques-Ayala 1992; T. Lawton, personal communication 2014).

The tectonic subsidence was caused by west-to-east overthrusting during the Cenomanian when Paleozoic platformal rocks unconformably overlain by Jurassic and Lower Cretaceous volcanic rocks were placed atop the western margin of the carbonate platform (Pubellier et al. 1995). The Cintura Formation is overlain in Sonora by conglomerate of the Cocóspera Formation interbedded with andesitic lava dated by the $^{40}$Ar/$^{39}$Ar method to be 93.3 ± 0.7 Ma (González-León et al. 2011). Anderson et al. (2005) also described the belt in some detail, and based on the age of a little deformed pluton that cut mylonite of the zone, pointed out that the deformation was older than 84 Ma and attributed it to deformation along the Mojave–Sonora megashear.

Taken in its entirety, the evidence in western Mexico suggests that the Alisitos–Santiago Peak arc collided with a west-facing passive margin at about 100 Ma. The polarity of the subduction was clearly westward and the western edge of the passive margin was partially subducted beneath the arc. The basin was apparently a marginal basin open for about 30 m.y. and was of unknown width, although it must have been sufficiently wide to be floored by oceanic crust in order to drive the 100 Ma collision. If we assume that half of the 30 m.y. interval was spreading, then at average spreading and convergence rates of 5 cm/year, the basin would have been about 750 km wide. We call the basin the Arperos–Bisbee Sea, and the collision the Oregonian event, which was the name used by Rangin (1986) for the Albian–Cenomanian deformational event in western Mexico.

Between the two areas around Guanajuato (Fig. 12) is another likely piece of the arc. There, imbricated latest Jurassic and Lower Cretaceous volcanic and plutonic rocks with an uppermost section of calc-alkaline basalt and basaltic andesite, overlain by volcaniclastic rocks and Albian reefal carbonate rocks, sits on an ophiolitic basement (LaPierre et al. 1992b). Pieces of Lower Cretaceous seamounts, presumably off-scraped into the accretionary prism occur locally (Ortiz-Hernández et al. 2003).

Based on the location of the suture, it appears that the basement to the Santiago Peak–Alisitos arc was more extensive and varied than previously thought with the Caborca, Cortes, Tahue and Zihuatanejo terranes all forming part of the basement for the arc (Fig. 12). Uppermost Triassic and Lower Jurassic arc magmatism appears to have occurred along the length of the arc as it is preserved within the arc basement. Therefore, we entertain a model of arc rifting to separate the arc terrane from the western margin of the Cordilleran Ribbon Continent during the Jurassic. Others have noted the presence of Jurassic arc rocks beneath the rifted margin on the ribbon continent (Lawton and McMillan 1999), and Dickinson and Lawton (2001b) called upon slab rollback to create the extension leading to the Bisbee basin.

The idea for two discrete mid–late Cretaceous deformational events in western Mexico has become more popular (for example: Pubellier et al. 1995; Martini and Ferrari 2011; Hildebrand 2013) and here we note that the two events, the ~100 Ma Oregonian and ~75 Ma Laramide, developed on opposite sides of Oaxaquia (Fig. 12). The ~125–105 Ma Sevier deformation of the western US and its hinterland, now located in the Canadian Cordillera (Hildebrand 2014), does not appear to have affected rocks in Mexico.

Late Cretaceous volcanic rocks interbedded with coarse conglomerate

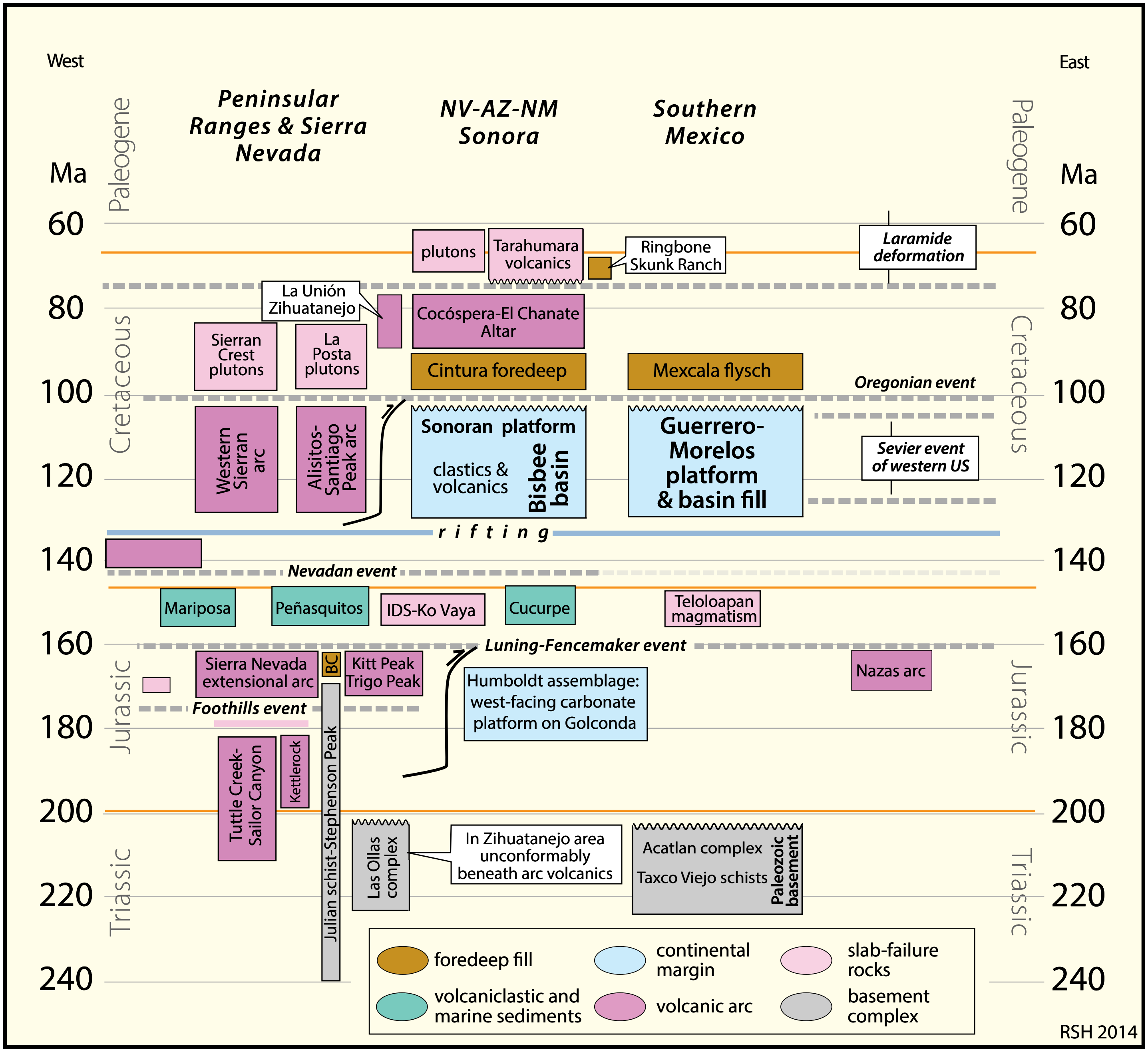

**Figure 14.** Regional correlation chart illustrating temporal relations between many of the rock units and their relationships to regional deformational events. BC–Bedford Canyon Formation.

units that post-date the Oregonian event and predate the Laramide appear to be relatively common within western and central Mexico (Fig. 14). For example, conglomerate of the Cocóspera Formation of Sonora is intercalated with 93 Ma andesitic lava (González-León et al. 2011). Generally considered correlative with the Cocóspera Formation is the upper Cretaceous El Chanate Group, which outcrops just east of Caborca (Fig. 12), and contains thick volcanogenic conglomeratic wedges that were interpreted to have been shed from the west and deposited in an elongate NW-SE thrust-front basin (Jacques-Ayala 1999). Bouldery to cobbly polymictic conglomerate of the Altar Formation, located to the northeast of Caborca in the Sierra El Batamote, is also interbedded with volcanic rocks (Nourse 2001) and contains Turonian-age detrital zircon (T. Lawton, personal communication 2014). To the south in the Zihuatanejo terrane, and sitting unconformably upon folded rocks of the older Albian limestone and volcanic rocks are coarse volcanogenic conglomerate and sandstone layers intercalated with tuff beds and andesitic lava flows and breccia of the La Unión and Zihuatanejo formations, dated to be Late Cenomanian to Santonian in age (Martini et al. 2010; Martini and Ferrari 2011). These Late Cretaceous volcanic rocks, mostly andesite to rhyolite, might represent a younger period of arc magmatism erupted on

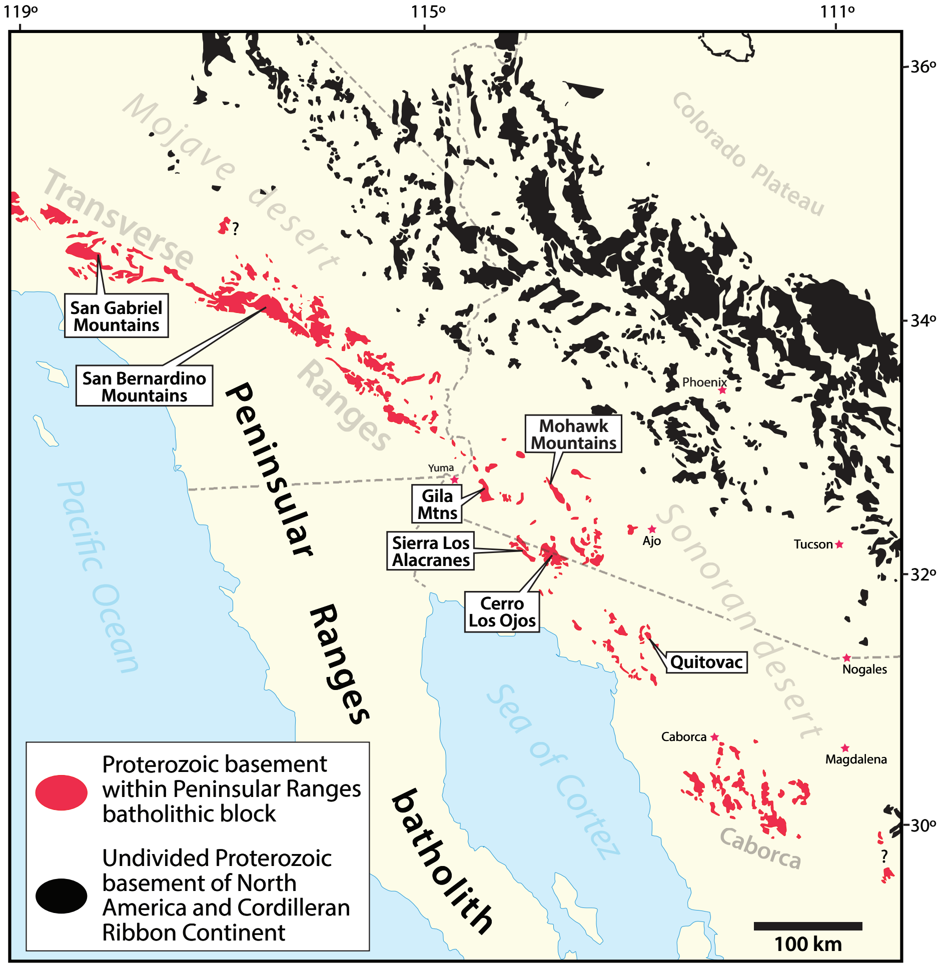

**Figure 15.** Sketch map modified from Kistler et al. (2014) showing distribution of Proterozoic rocks, locations of rocks in Figure 17, and likely basement rocks in the Peninsular Ranges batholithic block.

the amalgamated Guerrero–Oaxaquia block and generated by westerly subduction prior to the terminal Laramide collision. The coarse conglomerate might be debris shed from the exhumed Oregonian collision zone or be alluvial fans on the flanks of volcanoes, or both.

Caborca terrane – located just to the west of the suture, the Sonora platform (Fig. 12) and the thrust belt – contains distinctive Neoproterozoic and Paleozoic strata that are a detailed match for strata found today in eastern California–western Nevada (Stewart 2005) and in the San Bernardino Mountains near Los Angeles (Cameron 1982; Stewart et al. 1984). Crystalline basement is also exposed within the terrane west of the thrust belt in Sonora, where it comprises 1725–1696 Ma orthogneiss, tabular granitoid bodies (Nourse et al. 2005), and anorthositic complexes dated at around 1100 Ma (Espinoza et al. 2003). In the San Bernardino Mountains the basement to the metasedimentary section is 1750 ± 15 Ma (Silver 1971). In fact, the basement west of the presumed suture contrasts sharply with other Proterozoic basement provinces of the southwestern US, and is termed the Mojave basement province (Bennett and DePaolo 1987; Wooden and Miller 1990). These rocks form a band of similar Proterozoic rocks from the Caborca terrane northwestward through southwest Arizona and the Transverse Ranges of California (Fig. 15). They probably represent the more easterly basement to the now dismembered arc.

Fragments of the northeast-vergent fold and thrust belt separating the arc rocks and their basement from the Albian platformal rocks may continue to the north in the Big Maria Mountains (Hamilton 1982) and the Clark, Ivanpah, and Mescal mountains (Walker et al. 1995) of eastern California, where strongly tectonized stratigraphic sections, similar to those of the southwestern US continental margin, occur with Mesozoic volcanic and plutonic rocks. Cross-cutting thrusts, younger than those of the 125–105 Ma Sevier fold-thrust belt in southern Nevada and eastern California (Pavlis et al. 2014), are of approximately the right age and orientation to have been formed during the 100 Ma collision. The collisional belt also likely continues up along the eastern side of, or even into, the Sierra Nevada, which probably led to its present juxtaposition nearly orthogonal to structures and facies in central Nevada; but that takes us far afield, so additional discussion of this interesting topic is withheld for a subsequent contribution.

Nevertheless, pieces of the presumed North American passive margin are included within the arc and, along with other Neoproterozoic–Lower Paleozoic sequences in the basement, likely accumulated on the southwestern continental edge of North America as that margin has long been known to be truncated and missing its passive margin (Hamilton and Myers 1966; Burchfiel and Davis 1972). When, and precisely where, the pieces were torn off North America is open to speculation, but apparently fragments were incorporated within the Cordilleran Ribbon Continent, only to be rifted off during the Late Jurassic and return some 30–40 m.y. later. When considered together, all the evidence indicates that subduction was westward beneath the Alisitos arc, occurred within a broad marginal sea, and that the lower plate during the collision was located well to the east and contained a west-facing passive margin capped by an Albian carbonate platform.

As arc magmatism in the Santiago Peak–Alisitos shut down at 100 Ma during the collision, and the rocks were rapidly deformed, it was the active pre-collisional arc. The central area of the arc underwent extreme exhumation, uplift, and erosion during and immediately following La Posta magmatism, which is atypical for magmatic arcs, so something unique happened during the collision that led to the emplacement of the voluminous La Posta suite and simultaneous exhumation characteristic of the region.

If arcs are not zones of crustal thickening why did the eastern Peninsular Ranges batholith have such intense exhumation and uplift? We suggest that the attempted subduction of the eastern block beneath the western arc effectively doubled the thickness of the crust and that due to the buoyancy contrast between subducting oceanic lithosphere and the difficulty to subduct continental lithosphere of the lower eastern plate, the lower oceanic portion of the slab broke off and sank into the mantle allowing the collision zone to rise. Next we look at the process of slab failure and show how it can generate not only the exhumation, but also the post-collisional La Posta magmatism and other features.

## Slab Failure

Because the continents are very old and oceanic lithosphere young by comparison, it is obvious that every collision that entails the closure of an ocean basin wide enough to drive collision, must involve break-off of the subducting slab, for the alternatives are for continents to be subducted or for slabs to dangle off continental margins into the mantle. Neither is observed. Therefore, slab failure, or break-off as it is sometimes called, is an integral component of plate tectonics and a natural consequence of subduction (Roeder 1973; Price and Audley-Charles 1987; Sacks and Secor 1990; Davies and von Blanckenburg 1995; Davies 2002; Atherton and Ghani 2002; Cloos et al. 2005).

Over 40 years ago, seismologists suspected that when the edges of large continental masses are partially subducted, their buoyancy leads to failure of the subducting slab (McKenzie 1969; Isacks and Molnar 1969). This is because the buoyancy forces resisting the subduction of continental lithosphere are as large as those pulling oceanic lithosphere downward (Cloos et al. 2005). Eventually, the greater density of the oceanic lithosphere causes the lower plate to break, predominantly by viscous necking (Duretz et al. 2012) at its weakest point, and sink into the mantle.

Once the subducting slab fails and the lower plate is freed of its oceanic anchor, rocks of the partially subducted continental margin rise due to buoyancy forces (Duretz et al. 2011). The failure also allows asthenosphere to upwell through the tear, melt adiabatically, and rise into the collision zone, where it interacts especially with subcontinental lithosphere and crust of the upper plate. The resulting magmas, which form linear arrays above tears in the descending slab, are upwellings flowing through the breach in the slab (Macera et al. 2008). They commonly overlap the terminal stages of deformation. If the magmas intrude the upper plate, they may form a linear belt atop or alongside the old arc and appear temporally continuous with the older magmatism, and so be readily confused with it. Magmas might also intrude rocks of the foredeep and/or the shortened passive margin of the lower plate, or both (Hoffman 1987; Hildebrand and Bowring 1999; Hildebrand et al. 2010).

There is now a burgeoning literature on the effects of slab failure, ranging from currently active to Precambrian (Hildebrand and Bowring 1999; Teng et al. 2000). The effects of slab failure are important, diverse, and may be responsible for features such as rapid uplift (Chatelain et al. 1992), syncollisional magmatism (Davies and von Blanckenburg 1995; Keskin 2003; Macera et al. 2008), tomographic gaps in the descending slab (Wortel and Spakman 1992), thick-skinned foreland deformation (Cloos et al. 2005), seismic discontinuities (Wortel and Spakman 1992), crustal recycling (Hildebrand and Bowring 1999), transitory pulses of mafic magmatism (Ferrari 2004) doubly vergent orogens (Regard et al. 2008), plateau uplift (Rodgers et al. 2002), ultra-high pressure exhumation (Anderson et al. 1991; Babist et al. 2006; Xu et al. 2010), changes in plate motion (Austerman et al. 2011); subhorizontal swarms of deep earthquakes (Chen and Brudzinski 2011), lateral shifts in foredeep sedimentation (van der Meulen et al. 1998), opening of small ocean basins (Carminati et al. 1998), switchover from foredeep flysch to orogenic molasse (Sinclair 1997; Wilmsen et al. 2009), and porphyry copper and other mineralization (Solomon 1990; de Boorder et al. 1998; Cloos et al. 2005; Hildebrand 2009).

Several factors are important in slab failure and govern where and when during the collision the slab will rupture. First, the age of the subducting lithosphere is perhaps most important because young lithosphere is weaker and therefore break-off will be fast, commonly less than 1 m.y. after initial collision (Duretz et al. 2012), and will occur at shallow levels, whereas with older, thicker and stronger lithosphere, break-off is slower and the continental edge is subducted deeper into the mantle. The depth of break-off largely controls the width of the orogen, for it is the rebound of the partially subducted continent that will lead to the region of intense uplift and exhumation (Duretz et al. 2011, 2012; Duretz and Gerya 2013). Thus, shallow break-off creates narrow orogens, lower-grade metamorphism, and intense, rapid and higher rates of exhumation, whereas deep break-off creates broad orogens with higher grades of metamorphism and slow, more subdued rebound (Duretz et al. 2011). In the case of deep failure the subducted margin might be sufficiently buoyant that it initially rises to the Moho, where it might stall until the over-thickened crust collapses by extension and/or denuded by erosion (Walsh and Hacker 2004).

The depth of break-off likely also controls the volume of slab failure magmatism because in shallow failure the asthenosphere upwells to shallower depths, which generates greater volumes of melt due to adiabatic melting (McKenzie and Bickle 1988). Additionally, during shallow failure the upwelling asthenosphere, say at 35–50 km depth, creates an advective heat source capable of generating melts in the lithospheric mantle, the asthenospheric mantle and the crust (van de Zedde and Wortel 2001). Thus, shallow break-off will create larger quantities of magma and they are likely to be compositionally varied. Furthermore, because the asthenospheric mantle source region is highly variable (Menzies et al. 1987; Foley 1992), and because the rising magmas can assimilate between 10% and 75% crust-derived materials during their rise through the crust (McDowell et al. 1996; Housh and McMahon 2000;

McMahon 2000, 2001; Chung et al. 2003), the resultant magmas can be heterogeneous, ranging from pure asthenospheric melts, mixtures involving lithospheric mantle melts, to complex crustal melts and, of course, mixtures of the three (e.g. Hart et al. 2004).

When the break-off is located beneath the arc, or nearly so, upwelling asthenosphere rises into the region of little or no lithospheric mantle, and the resulting magmas might look very much like those of an arc, but where the break-off occurs adjacent to the arc the magmas might be quite different in composition because the asthenosphere would impinge first on the subcontinental lithospheric mantle. And given that those mantle regions have different properties, such as composition, depending on their age (Jordan 1978; Pearson and Nowell 2002; Poupinet and Shapiro 2009), magmas created in those areas might have different compositions from place to place and orogen to orogen. Magmatism might start out reflecting melting within enriched lithospheric mantle and quickly revert to asthenospheric melts as the lithosphere is thermally thinned and transected by deeper level melts (Perry et al. 1987). Additionally, given that the margin breaks off at depth beneath and more or less parallel to the arc, it might be common for the asthenosphere to rise, at least in part, beneath the transition from arc to continental lithosphere, which would generate additional compositional variations, and might even appear as a smooth transition between two entirely different magma types.

In Southern and Baja California, the shutdown of arc magmatism at ~100 Ma marked the collision and, within 1–2 m.y. of collision, the earliest plutonic complexes of the 99–86 Ma La Posta suite were emplaced (Kimbrough et al. 2001; Premo et al. 2014b). The magmatism was especially voluminous and magmas appear to have been emplaced during a period of immediate exhumation close to and overlapping with the upper plate arc (Fig. 16). They are contemporaneous with deposition of thick Cenomanian–Turonian clastic successions to the west, which involved a rapid change from flysch-type sedimentation to coarse cobbly and bouldery molasse during the early Cenomanian (Kimbrough et al. 2001). These are all characteristics of shallow break-off and so suggest that the oceanic lithosphere was not particularly old, but based on thermomechanical models, older than about 30 million years at the time (Duretz et al. 2011).

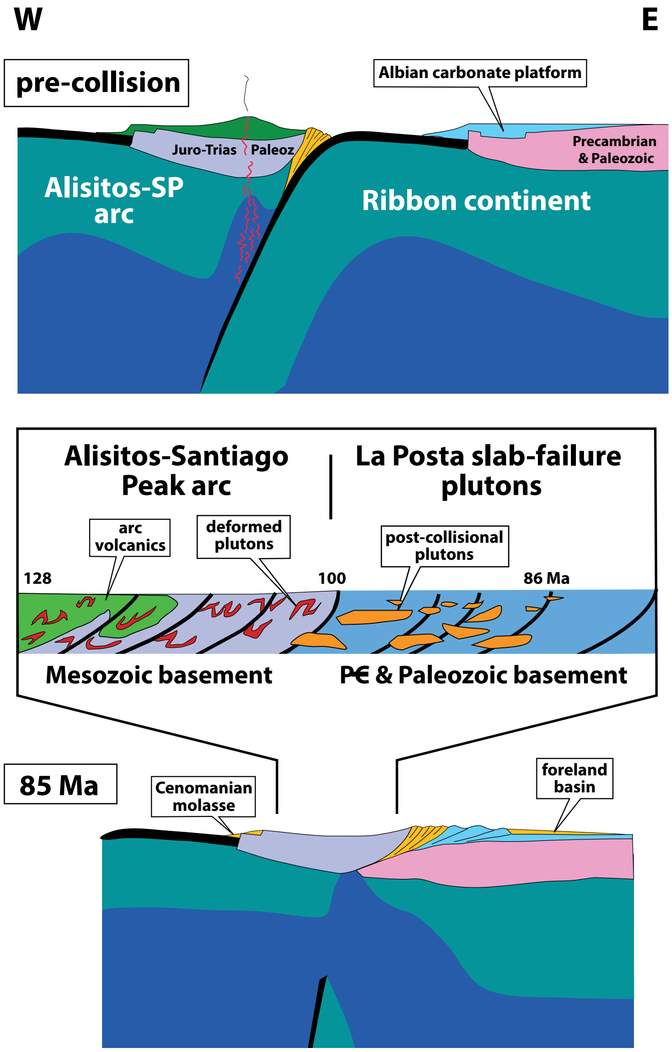

**Figure 16.** Tectonic model showing the development of the Alisitos–Santiago Peak arc above a westward-dipping subduction zone and its collision with the western margin of the Cordilleran Ribbon Continent and its west-facing Albian carbonate platform as discussed in the text. The collision was followed by slab failure of the lower plate and emplacement of the La Posta plutons during a period of major exhumation.

## Exhumation and Origin of the Doubly Vergent Fan Structure

Once the subducting oceanic slab fails, the leading edge of the lower plate is no longer being pulled down beneath the upper plate, and due to buoyancy forces, will rise, typically at a rapid rate, limited only by the erosion rate (Burbank 2002) and strength of the lithosphere (Avouac and Burov 1996). At the same time, asthenospheric mantle is streaming upward through the tear and creating buoyant melts that will also rise into the collision zone, the exact location depending on how and where the descending plate failed. For example if the tear is at or near the oceanic–continent interface, then diachronous tearing (Wortel and Spakman 2000; Schildgen et al. 2014), or perhaps basal traction (Alvarez 2010), would cause continued convergence, either or both of which would pull the subducting slab over the rising asthenospheric welt and cause slab failure magmas to rise just inboard of the tear. Similarly, re-entrants and promontories in the lower plate might fail at different places along strike so that the slab failure magmas might span tectonic boundaries in the resultant orogen. Also, changes in the subduction regime can happen abruptly along strike and have huge impacts on the form of deformation and magmatism (Ely and Sandiford 2009).

In a somewhat similar fashion, the leading edge of the lower plate is pulled beneath the overriding plate and how far depends on the buoyancy contrast and strength of the plate. As stated earlier, younger lithosphere will break more quickly, in less than 1 m.y., and in those cases the continental edge isn't subducted deeply but instead is barely tucked beneath the arc. In the case of shallow break off, as soon as the slab fails it rises and immediately begins to exhume the overriding plate. Thus, the time between initial collision and initiation of exhumation and magmatism due to slab failure is very short.

The rapid response to slab failure is important but given that the lower plate typically represents a formerly thinned section of continental lithosphere, it is unlikely to rebound to sea level but instead will have a carapace or veneer of upper plate rocks atop it. Depending on the crustal thickness, strength profile, and perhaps rate of exhumation of the upper plate as governed by rainfall (Hoffman and Grotzinger 1993), it might get lifted gently to form a broad dome, or alternatively it might fail and there will be a major fault in the upper plate separating the hinterland from the relict arc. In some instances a bivergent orogen, such as the Alps, might form (Regard et al. 2008).

Following exhumation, uplift and erosion, one should find a zone of higher grade upper plate rocks between the upper plate arc rocks and the lower plate. The grade should rise gradually towards the hinterland in the lower plate, then increase rapidly at the suture as the base of the upper plate is encountered. In the case of a faulted upper plate, the grade should remain high, perhaps decreasing gently due to the thinner lower plate, until the fault is crossed, where the grade will drop precipitously in the upper plate, which was never buried.

If one assumes that subduction prior to collision was westward, then the Sierra de San Pedro Mártir cross-section (Fig. 4) of the Peninsular Ranges batholith displays the features described above that are characteristic of slab failure with a faulted upper plate. In this case the leading edge of the eastern block was partially subducted beneath the Alisitos arc and slab failure occurred at 100 Ma. Once the slab failed, magmas rising from the upwelling asthenosphere rose into the crust to produce the La Posta suite. Although the plutons intruded both eastern and western sectors, they were mostly emplaced into the deeper eastern sector. The fan structure might be a root zone (Roeder 1973).

Due to the release of the downward pull of the oceanic lithosphere, and perhaps fueled by upwelling asthenosphere and rising magma, the orogenic root began its buoyant upheaval, lifting the upper plate on its back. However, the upper plate was simply not strong enough to withstand the forces so it failed more or less above the distal edge of the lower plate. As the dynamically rising hot hinterland was elevated it spread laterally over the Alisitos arc and perhaps eastward as well. In this interpretation, the western part of the doubly vergent fan structure marks the approximate western limit of the lower plate at depth. Good seismic profiles should show the upper plate within the hinterland as a fairly thin sheet sitting above a gently inclined to broadly warped, reflector representing the collisional suture.

The uplift, exhumation, and consequent erosion also created huge volumes of coarse debris, much of which was shed to the windward, wet side of the rising orogenic welt, which in this case would have been westward. And that is what is observed as flysch sedimentation to the west was abruptly swamped during the early Campanian by voluminous coarse debris (Kimbrough et al. 2001). This is similar to the transition from flysch to molasse in the Alpine belt, which is thought to have been caused by slab failure (Sinclair 1997).

In many ways, parts of the Peninsular Ranges orogen are similar to the Alps of Europe, in that both orogens are doubly vergent with a metamorphosed crystalline core and much lower grade thrust sheets on the external flanks. The main differences are the amount of magmatism and the width of the orogen, which could be directly related to the depth of breakoff. The Main Mártir thrust, which placed amphibolite-grade rocks of the arc and its basement westward over lower grade arc rocks, is more or less an equivalent structure to the Insubric Line, an antithetic thrust fault, which placed amphibolite-grade rocks of the upper plate over the Southern Alpine nappes to the south.

In the preceding sections we developed a coherent, actualistic, and testable model that explains all of the critical observations, which the current long-lived eastward-dipping subduction models fail to do. In our model, the westward-dipping subduction led to partial subduction of the eastern block and its west-facing passive margin beneath the arc, which caused its young oceanic lithosphere to break off and generate slab failure magmatism of the La Posta suite within 1 m.y. of the collision. Rebound of the eastern, partially subducted plate caused rapid uplift and exhumation during the emplacement of the plutons.

## Detrital Zircon

Our recognition that basement to the Santiago Peak–Alisitos arc rifted from rocks to the east at about 139–136 Ma, and that it was composed of a wide variety of Jurasso–Triassic rocks, as well as a nearly complete section of Paleozoic and Neoproterozoic sedimentary rocks built on Precambrian crystalline basement, provides a ready outboard, or offshore, source for a wide detrital zircon spectrum in sedimentary rocks of the arc complex and precludes that they must have been derived directly from North America as argued by some researchers (Gehrels et al. 2002; Kimbrough et al. 2006, 2014a). This conclusion, coupled with the likelihood that fragments of Laurentia such as the Antler platform of the Great Basin region and Caborca terrane in Sonora (Ketner 1986; Gastil et al. 1991; Stewart 2005; Hildebrand 2009, 2013; Premo et al. 2010) were probably derived from the southwest corner of Laurentia in what is the present day Mexico region and incorporated within the Cordilleran Ribbon Continent, possibly during the transition from Pangea B to A (Irving 1977, 2004; Kent and Muttoni 2003), serves to complicate correlations and detrital zircon studies. Terranes derived from the southwest corner of North America should contain North American flora and fauna, but also large quantities of Grenville age zircon reflecting their proximity to that belt, which was rich in Grenvillian basement (Hoffman 1989).

Also, it appears as though the western Sierra Nevada batholith has a remarkably similar history to the Santiago Peak–Alisitos arc, including an older arc complex in the west, and compositionally zoned, post-deformational, plutonic complexes, such as the Tuolumne, Whitney, John Muir, and Sonora, of the Sierran Crest magmatic event (Coleman and Glazner 1998) to the east. The Snow Lake pendant (Fig. 17), located along the north edge of the Tuolumne intrusive complex in Yosemite National Park is yet another fragment of the distinctive Neoproterozoic–Early Paleozoic sequence found in the Death Valley and Caborca areas (Stewart 1970, 2005; Lahren et al. 1990; Memeti et al. 2010) and, like the Peninsular Ranges, it represents part of the basement to the arc. The original location of the sections remains uncertain. We now look a bit more closely at the Sierra Nevada to ascertain if there are features there that might inform our understanding of the Peninsular Ranges batholith and related rocks.

## Comparison with Other Cordilleran Batholiths

Just over a decade ago Ducea (2001) proposed an eastward-directed subduction model for the origin of Californian Cordilleran batholiths to explain what he thought was a period of unusually high magmatic flux, from 100–85 Ma, within the Sierra Nevada. In his model, eastward directed retroarc, thin-skinned thrusting in the Great Basin area was balanced by westward underthrusting of middle to lower crust, which as a result was shoved beneath the Sierran arc, melted to produce the 100–85 Ma magmatism, and all the excess material, or restite, sinking into the mantle. Others soon expanded on the model (Ducea and Barton 2007; DeCelles et al. 2009), whereas some workers, mindful of a likely sedimentary component to the magmatism, proposed that large volumes of crustal material were subducted from the west beneath the Peninsular Ranges in order to thicken the crust (Todd et al. 1988; Grove et al. 2008; Miggins et al. 2014; Premo and Morton 2014).

Hildebrand (2013) pointed out: (1) that it is difficult, if not impossible, to get the requisite 400 km of North American cratonic lithosphere beneath the Sierra Nevada–Peninsular Ranges batholiths because it is simply too buoyant unless attached to negatively buoyant oceanic lithosphere; (2) that even if it was possible to get the crust beneath them, by Ducea's (2001) own admission there is no obvious mechanism to melt such a large volume of continental crust; (3) that because the bulk composition of the batholiths is so close to that of bulk middle and lower crust (Ducea 2002; Rudnick and Gao 2003), there would be very little restite to drip into the mantle, which means that the crust should be very much thicker than observed; (4) because the thrusting took place at the scale of the lithosphere, the Ducea model provided no actualistic mechanism to dispose of the sub-continental lithospheric mantle; and (5) that the so-called flare-up may not be beyond the bounds of magmatic flux in young arcs.

Ducea (2001) also noted that since it took time for the isotherms to rebound after crustal thickening, the melting event, however it was caused, postdated the thickening by ~15–25 m.y. However, such an early thickening is countermanded by the deposition of shallow marine sedimentary rocks at about 100 Ma within both the Sierran and Alisitos–Santiago Peak arc terranes. As these rocks were deposited immediately prior to the regional deformation and within a couple of million years of the emplacement of the post-deformational plutons, there is no evidence of crustal thickening within the arc prior to the ~100 Ma deformational event.

As touched upon in the early part of this contribution, the major Cordilleran batholiths of North America are clearly composite bodies that share significant similarities. The Sierra Nevada has long been known to be composed of two halves: an older western sector and a younger eastern sector separated by an apparent break in the lithosphere, as defined by geochemistry, magnetic susceptibility, age, radiometric and stable isotopes, wall rock provenance, and basement types (Nokleberg 1983; Kistler 1990, 1993; Chen and Tilton 1991; Bateman et al. 1991; Coleman and Glazner 1998; Saleeby et al. 2008; Lackey et al. 2008, 2012a, 2012b; Chapman et al. 2012). Just as with the Peninsular Ranges batholith, the western sector of the Sierra Nevada represents an ~125–100 Ma arc (Bateman 1992) constructed upon crust assembled mainly during the Jurassic, whereas the eastern half contains large compositionally zoned tonalite–granodiorite–granite complexes, such as the Tuolumne, Whitney, John Muir, Domelands, and Sonora (Fig. 17), emplaced during the 98–86 Ma Sierran Crest magmatic event (Coleman and Glazner 1998; Saleeby et al. 2008). And just like the Peninsular Ranges batholith, rocks of the Sierra Nevada contain evidence of an ~103–100 Ma deformational event that postdated all known sedimentary and volcanic wall rocks within the western arc (Peck 1980; Nokleberg and Kistler 1980; Bateman et al. 1983; Saleeby et al. 1990; Bateman 1992; Wood 1997; Memeti et al. 2010; Hildebrand 2013) yet predated, or was partly coeval with, the compositionally zoned plutonic complexes of the Sierran Crest magmatic event (Greene and Schweickert 1995; Coleman and Glazner 1998; Davis et al. 2012). The plutons were emplaced more or less simultaneously with development of mylonitic shear zones, a rapid increase in cooling rates between about 90–87 Ma, and increased sedimentation in the basin to the west during the Turonian (Mansfield 1979; Renne et al. 1993; Tobisch et al. 1995). Thus, by analogy with the Peninsular Ranges batholith, we suggest that the western half of the Sierran batholith was an arc generated by westward subduction, and that the arc collided at ~103 Ma with the western margin of the Cordilleran Ribbon Continent. Slab failure of the partially subducted eastern block led to voluminous magmatism of the Sierran Crest magmatic event.

There is support for the general slab failure model in Sierran xenoliths, which also provide feedback that can be applied to the Peninsular Ranges batholith. First, ultramafic xenoliths collected from much younger volcanic rocks (Fig. 18) suggest that the xenoliths are dominantly residual cumulates remaining after extraction of partial melts from both upper mantle and subcontinental lithosphere at depths of at least 32–18 kb (Mukhopadhyay and Manton 1994; Chin et al. 2012), consistent with upwelling mantle and adiabatic melting resulting from slab failure. Ducea and Saleeby (1998) showed that the cumu-

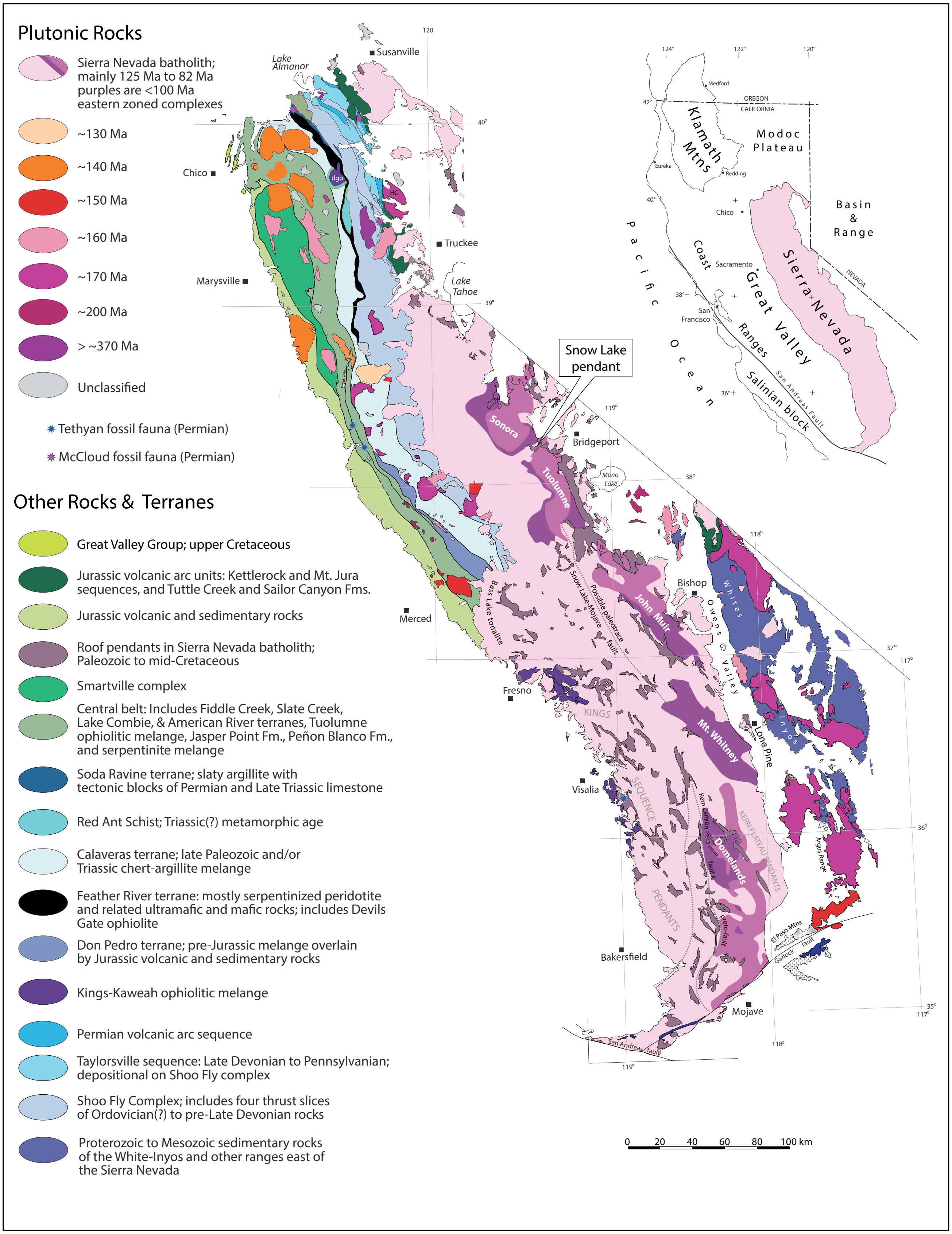

**Figure 17.** Generalized geological map of the Sierra Nevada batholith and environs, showing the basement terranes, location of the Snow Lake pendant, and the distribution of major plutonic complexes of the post 100 Ma Sierran Crest magmatic suite (modified from Irwin and Wooden (2001) with additional data from Dunne et al. (1978), Saleeby et al. (1978), Bateman (1992), and Saleeby and Busby-Spera (1993). Distribution of post 100 Ma suite modified from Van Buer and Miller (2010).

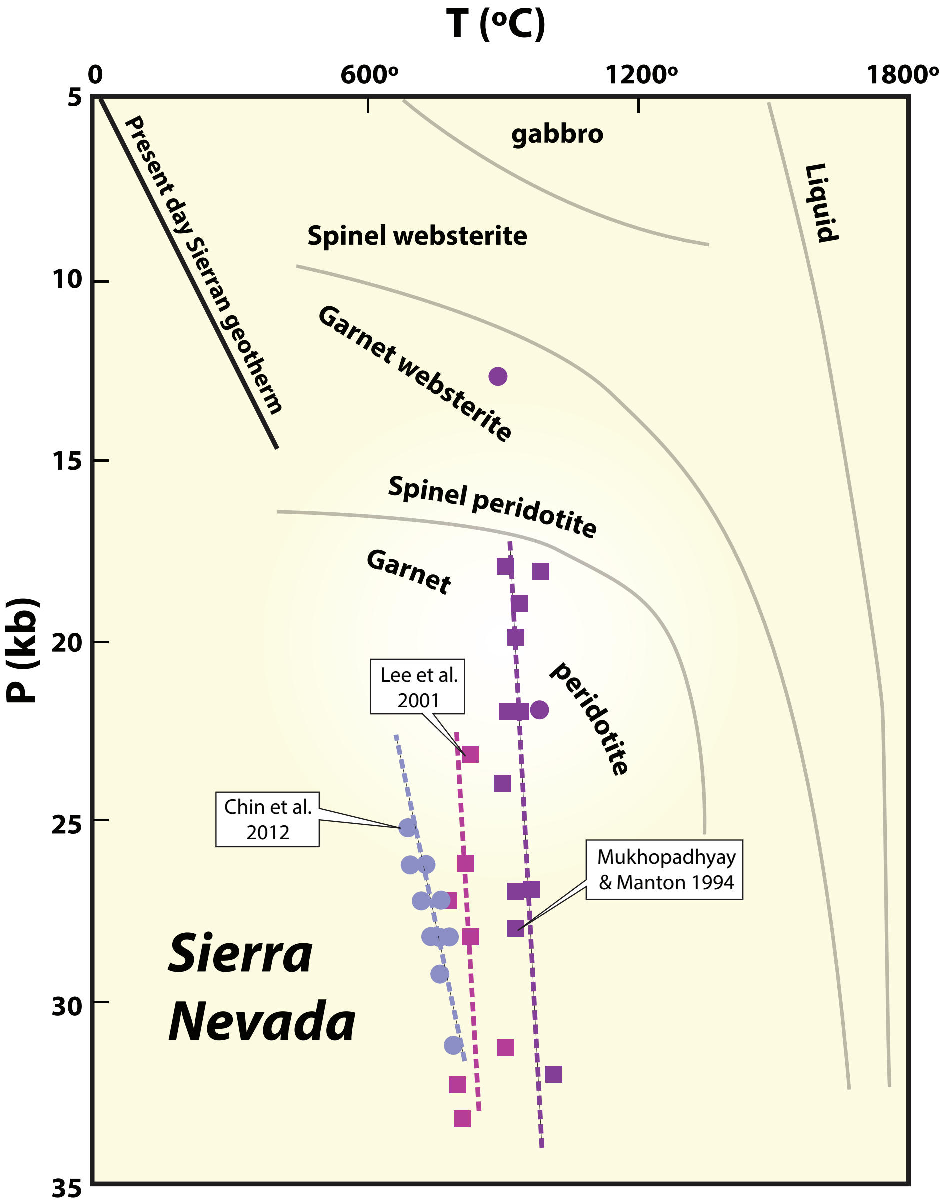

**Figure 18**. *P–T* grid illustrating the final equilibrium conditions calculated for various groups of mantle xenoliths from the Sierra Nevada. Although the arrays are artifacts of the different reaction kinetics of the geothermometers and geobarometers, the points represent minimum *P* values (Chin et al. 2012). These high pressures (~3 GPa) support the model presented here in that the La Posta and Sierran Crest magmatic suites resulted from melting at great depth caused by slab failure, upwelling of asthenosphere, and melting within the garnet stability field.

late rocks are the same age as Sierran granitoid magmatism. The idea of upwelling mantle and adiabatic melting is supported by the detailed work of Lee et al. (2001), who also studied Sierran mantle xenoliths and found evidence for a cool subcontinental lithosphere of Proterozoic age underplated by hot asthenosphere during the Mesozoic.

Second, our model for westward-dipping subduction of the western margin of the Cordilleran Ribbon Continent beneath the arc readily resolves the difficulties of Chin et al. (2013) when trying to interpret granulitic quartzite xenoliths from a Miocene diatreme in the central Sierra Nevada. They were baffled because their extensive data from the quartzite xenoliths – *T* = 700–800ºC, *P* = 7–10 kb, ~103 Ma mean metamorphic age from U–Pb analyses in zircon, Proterozoic and Archean U–Pb crystallization ages for the cores of detrital zircon, and Hf isotopic ratios like those from Proterozoic basement of the eastern Sierra Nevada – appeared to indicate that rocks of the North American passive margin were transported deep beneath the arc and metamorphosed close to 100 Ma; yet they had no viable mechanism for getting them there in an eastward-directed subduction model. The presence of the quartzite xenoliths, their ages and isotopic characteristics thus provide an unexpected test and confirmation of our westward-dipping subduction model.

Because of the paradigm that the Sierran batholith was built on the western margin of North America, other researchers used the eclogite-facies quartzite xenoliths, with their North American isotopic signatures, as evidence that the sub-batholithic crust was at least 70 km thick and was simply thickened North American crust (Ducea and Saleeby 1998; Ducea 2001). They also used the presence of garnet peridotite xenoliths to suggest that the mantle lithosphere was at ~120 km depth.

In our model, the western margin – whether you believe it was North America or the ribbon continent – was subducted beneath the arc (Fig. 14), which readily accounts for the quartzite xenoliths, the eclogite-facies metamorphism and their isotopic signatures. It also provides a more actualistic method of getting mantle lithosphere to the inferred depths and, given that the xenoliths are restite or cumulate from removal of melt along an adiabatic geotherm from ~3.5–1.7 GPa (Mukhopadhyay and Manton 1994), they confirm the concept of mantle rising through the torn slab and melting adiabatically to produce the slab failure magmas. This was corroborated by two other detailed studies of peridotite xenoliths (Fig. 18), the first by Lee et al. (2001), who, as mentioned, found two types of xenoliths with contrasting thermal histories and concluded that hot asthenosphere and cold Proterozoic lithospheric mantle "*were suddenly juxtaposed, a feature consistent with the aftermath of rapid lithospheric removal or sudden intrusion of asthenospheric mantle into the lithosphere*" during the Mesozoic. The second by Chin et al. (2012), showed that peridotite underwent shallow melt depletion at 1–2 GPa and was re-fertilized at depths of about 3 GPa, which could readily be accomplished by taking partially subducting depleted lithosphere then re-fertilizing it by upwelling asthenosphere. Thus, the quartzite and peridotite xenoliths, as well as their features and histories – so difficult to explain in static eastward subduction models – are readily accounted for in an actualistic westward subduction–collision–slab failure model.

Similar types of xenoliths are known from the Pamirs and Tibetan Plateau where they are generally interpreted to represent fragments of subducted continental crust (Hacker et al. 2000, 2005; Ducea et al. 2003). Detailed study of samples from the Pamir found much older detrital zircon that appears to have had a Gondwanan, as opposed to Indian, source and so suggests a subduction polarity (Hacker et al. 2005), just as do the Sierran examples.

As is well known, the western Sierran arc has a basement comprising numerous Jurassic and Paleozoic terranes (Saleeby 1981; Irwin and Wooden 2001; Hildebrand 2013). Late Jurassic sedimentary rocks of the Mariposa Formation (Fig. 14), commonly interpreted to represent forearc deposits to a more easterly arc are part of this basement (Snow and Ernst 2008) and are consistent with similar age rocks containing comparable detrital zircon suites along the west side of the Peninsular Ranges batholith (Kimbrough et al. 2014a) and in Sonora (Mauel et al. 2011).

The Coast plutonic complex of British Columbia is another composite batholith built of two blocks: 190–110 Ma to the east and 160–100 Ma to the west (Gehrels et al. 2009). A west-vergent fold-thrust belt, that developed around 100 Ma (Rubin et al. 1990; Haeussler 1992), places high-grade rocks of the eastern belt over lower grade rocks of the Gravina–Dezadeash–Nutzotin belt to form a thrust stack that is of higher metamorphic grade upwards (Lynch 1992, 1995; Journeay and Friedman 1993; Crawford et al. 2000; McClelland and Mattinson 2000). Although the deformation is about the same age, the polarity is the reverse of the more southerly batholiths. A group of post-deformational plutons (Gehrels et al. 2009) are likely slab failure bodies.

In this contribution we have shown how the Peninsular Ranges batholith comprises two distinct periods of magmatism – separated by a deformational event – that are simply and logically explained by a period of arc magmatism followed by an arc–continent collision, which caused rapid shutdown of the arc, thickening of the subjacent crust as the continental edge was partially subducted, and consequent failure of the westward-dipping slab to produce slab failure magmas (Fig. 16). The consilience of so many independent lines of evidence, from isotopic to structural data, stratigraphy to plate kinematics, mantle xenoliths and xenocrystic zircon to rapid exhumation gives us great confidence in our overall model for westward-dipping subduction beneath the 130–100 Ma Alisitos–Santiago Peak and Sierra Nevadan arc terranes. Not only does the model tie together many disparate bits of geology, it also places them within a modern and actualistic plate tectonic framework.

## Petrogenesis

Given that the Cordilleran batholiths described here are composed of two compositionally distinct magmatic suites separated by a period of deformation, it might be enlightening to look briefly at their petrogenesis. Both suites would seem to involve partial melts of asthenosphere and variable amounts of mantle lithosphere and crust, yet they are quite different in composition. Here we present a few ideas and constraints on their petrogenesis.

The presence of basaltic lavas and gabbroic intrusions, coupled with their overall calcic nature (Fig. 8a, b), within the Santiago Peak–Santa Ana arc indicate that mafic melts were ultimately responsible for the magmatism in the arc, although there appear to be no primary mantle melts present there today. Recently, the most detailed studies to date on the Santiago Peak–Santa Ana arc concluded that the arc was built upon oceanic crust (Clausen et al. 2014), or a heterogeneous Jurassic basement deposited at or near a continental margin (Herzig and Kimbrough 2014). The Santa Ana plutons have a continuous compositional range from gabbro to granite, with 47%–77% $SiO_2$ (Fig. 8) typical of arcs, yet Clausen et al. (2014) suggested that the mafic magmas rising from the mantle into a lower crust dominated by gabbro/amphibolite created the spectrum of melts by partial melting, magma mixing and fractional crystallization. The main problem with a lower crustal scenario, which they recognized, is that the overall process would create huge volumes of high-density ultramafic restite in the lowermost crust for which there is no geophysical, or other, evidence.

Based on comparison with the La Posta plutons, they suggested that there is something peculiar about the composition of plutons within the Santa Ana suite in that they have initial Sr ratios lower than 0.704 and $SiO_2$ contents > 55%, but they compared apples to oranges because they contrasted them with the slab failure-type plutons (Clausen et al. 2014). If they had compared them to other arc suites of the western US they would have found them to be rather typical. For example, the western, or arc portion, of the Sierra Nevada contains plutons, such as the multiply folded sheets of the Stokes Mountain complex (Fig. 1), with the same characteristics (Clemens Knott 1992). Furthermore, nearly all the Quaternary volcanic rocks of the Cascades from 51°N to 41°N have $^{87}Sr/^{86}Sr$ lower than 0.704 independent of $SiO_2$ content and amount of contamination by varied continental crust and mantle lithosphere (Hildreth 2007). It is the slab failure plutons that are markedly different from the arc bodies as seen on our various geochemical and isotopic figures.

Overall, there can be little doubt that batholiths and associated siliceous volcanic rocks are generated in continental crust, for in volcanic arcs built on oceanic crust there are no batholiths or plutonic complexes like those observed in western North America, (Waters 1948; Bateman 1981; Whalen 1985). One has only to study the differences in magmatism in the Kurile–Kamchatka and Aleutian–Alaska Peninsula arcs where the transition between the two crustal types is readily observed. On continental crust, mag-

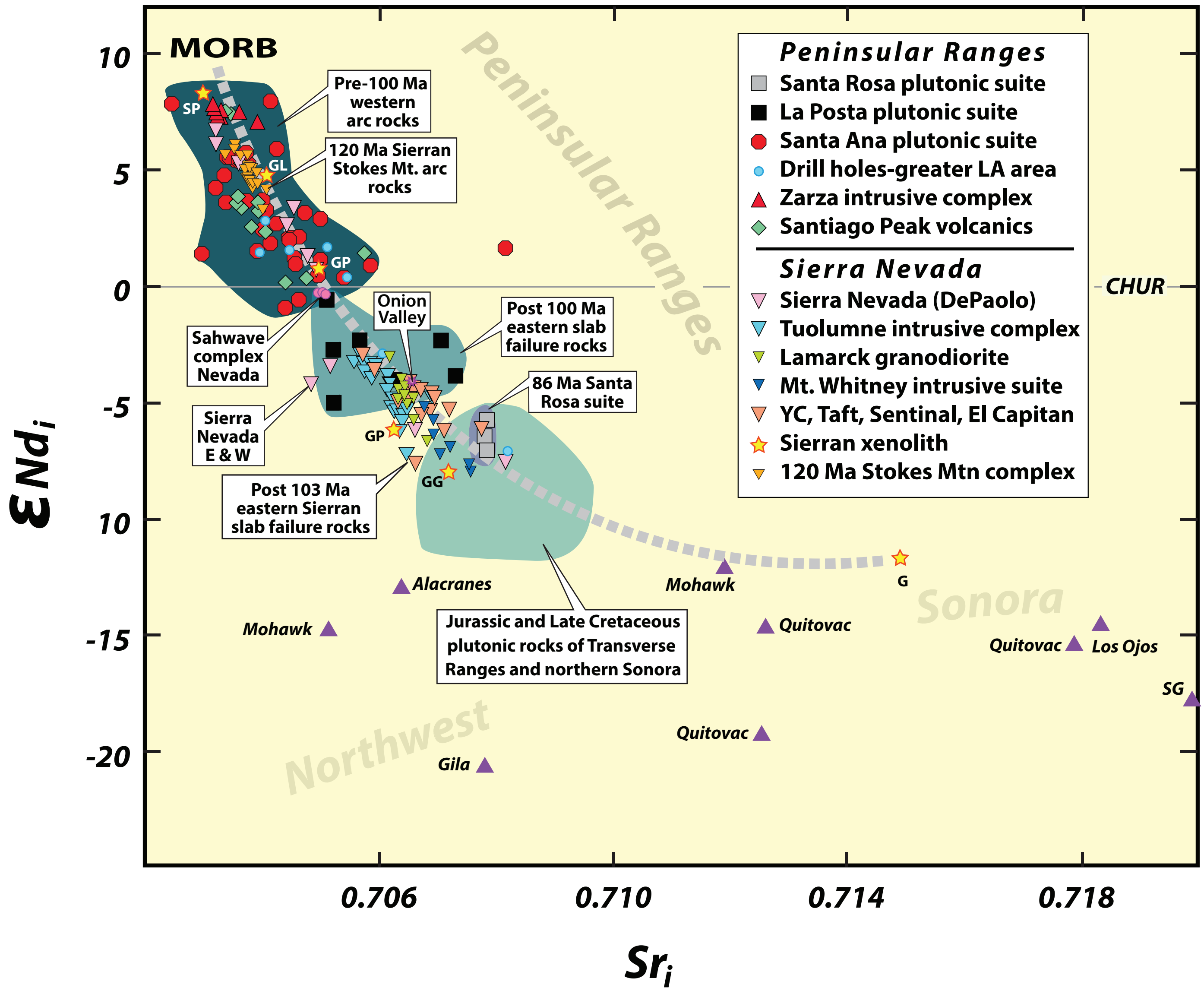

**Figure 19.** εNd versus $Sr_{initial}$ of various suites within the Peninsular Ranges batholith showing the evolved nature of the plutons and their similarities to Mesozoic rocks of the Transverse Ranges; eastern, post 103 Ma plutons of the Sierra Nevada (inverted triangles), and likely basement rocks of the northwest Caborca terrane (purple triangles). Modified from Premo et al. (2014b). Peninsular Ranges samples from drill holes in greater Los Angeles area from Premo et al. (2014a); Zarza intrusive complex, a Santa Ana arc pluton in Baja, from Tate et al. (1999); Santiago Peak volcanics from Herzig and Kimbrough (2014); Sierran xenoliths: SP–spinel peridotite; GP–garnet peridotite; GG–garnet granulite; G–granulite. 120 Ma Stokes Mountain plutons of western Sierran arc from Clemens Knott (1992); Sierran xenolith data from Domenick et al. (1983); post 103 Ma plutons of eastern Sierra Nevada: Sierra Nevada from DePaolo (1981); Tuolumne intrusive suite from Memeti (2009); 94 Ma Lamarck granodiorite from Coleman et al. (1992); 88–83 Ma Mt. Whitney intrusive suite from Hirt (2007); 103–95 Ma Yosemite Creek (YC), Taft, El Capitan, and Sentinal from Ratajeski et al. (2001); Onion Valley, a 92 Ma hornblende gabbroic sill complex, from Sisson et al. (1996); 93–89 Ma Sahwave intrusive suite–a post 100 Ma zoned complex, located in western Nevada, and similar in composition, zoning and petrography to Sierran Crest plutons, from Van Buer and Miller (2010).

mas are richer in silica and incompatible elements, intermediate–siliceous ignimbrites are common, and large composite batholiths are emplaced into the volcanic suprastructure (Hildebrand and Bowring 1984).

Crustal melts were generated early on within the Santiago Peak arc as indicated by early eruption of voluminous quartz porphyritic siliceous tuff that predated the andesitic eruptions (Herzig and Kimbrough 2014). Given that the immediate crust beneath the arc was Jurassic, it is not surprising that plutons assimilating such young crust have low initial Sr (Fig. 19). However, Santa Ana–Santiago Peak arc magmatism exhibits an initial $\varepsilon_{Nd}$ range of +8.2 to –0.6 and depleted mantle model ages ($T_{DM}$) ranging from 0.31 to 1.03 Ga and are clearly not directly

DMM-derived magmas. Thus, we see the Santiago Peak–Santa Ana arc to be a rather typical arc suite (Fig. 11d).

The La Posta plutons have more evolved Nd, Sr, Pb and O isotopic signatures than the Santa Ana suite (Figs. 19, 20, 21) and clearly involved crustal contamination. Overall, the Pb isotopic dataset appears to be a mixing trend between a more primitive, less radiogenic end-member, represented by the lowest $^{207}$Pb/$^{204}$Pb and $^{208}$Pb/$^{204}$Pb samples forming the Santa Ana suite, and the consistently most radiogenic or evolved samples of the Santa Rosa suite (Fig. 20). Elevated $^{207}$Pb/$^{204}$Pb signatures, relative to DMM and especially the most radiogenic end-member Santa Rosa suite, resulted from decay of the almost extinct $^{235}$U parent of $^{207}$Pb, a mostly Archean process. Thus, these $^{207}$Pb/$^{204}$Pb signatures indicate very long-lived source differences and substantiate input from an ancient upper crustal component, in both the La Posta and Santa Ana suites. Although input from ancient crust within the Santa Ana suite may have been volumetrically minor, the observed $^{207}$Pb/$^{204}$Pb signatures are incompatible with derivation solely from juvenile DMM-like sources within an isolated intra-oceanic arc setting.

Initial Pb–Sr and Nd ratios from the Proterozoic basement west of the suture zone within the Caborca terrane (Iriondo et al. 2004; Farmer et al. 2005; Nourse et al. 2005) are a good fit for the continental crustal component of the La Posta plutonic rocks (Kistler et al. 2014). SHRIMP analyses documented xenocrystic cores of Proterozoic zircon within La Posta plutons that also support the probability that the Proterozoic terranes or sedimentary rocks derived from them could have been the crustal component in the plutons (Kistler et al. 2014). This fits well with recently acquired data from plutons on Searl Ridge (Fig. 3) that show, based on detrital zircon grains and Pb–Sr–Nd isotopic data, a strong involvement of older crust, likely Proterozoic (Premo and Morton 2014).

Hafnium data from both Jurassic and Cretaceous plutons that cut the Jurassic basement suggest that, in addition to the primitive mantle component, at least three additional components are required: (1) a combined Proterozoic–Paleozoic–Mesozoic metasedimentary component; (2) a Neoproterozoic constituent; and (3) an element with a model age of about 2300 Ma (Shaw et al. 2014). When the Hf model ages are combined with the overall low δ$^{18}$O isotope data (Fig. 21) from the Santa Ana suite and their low initial Sr ratios the best fit for a crustal source is a large ion lithophile element-depleted lower crust of Neoproterozoic age because the low δ$^{18}$O values rule out a metasedimentary source (Shaw et al. 2014).

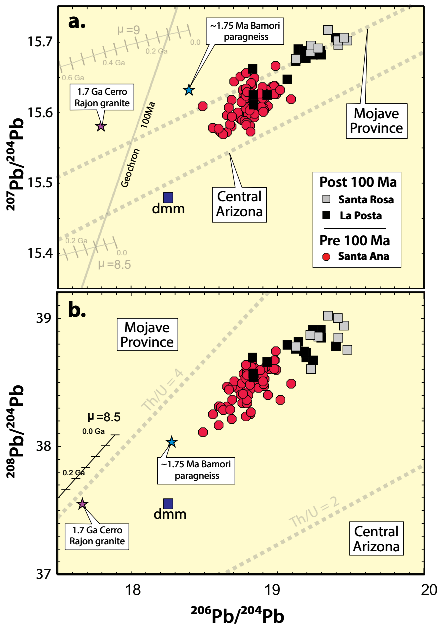

**Figure 20.** Plots of whole rock (a) $^{207}$Pb/$^{204}$Pb; and (b) $^{208}$Pb/$^{204}$Pb vs. $^{206}$Pb/$^{204}$Pb for Peninsular Ranges batholith plutonic groups compared to Proterozoic basement of the Mojave province and central Arizona and two basement samples from the Caborca region from Farmer et al. (2005) and model Th/U of 4 and 2 for 1.7 Ga reservoirs from Iriondo et al. (2004). Single stage reference growth curves for $^{238}$U/$^{204}$Pb ratios (μ) of 8.5 and 9, a $^{232}$Th/$^{204}$Pb ratio of 40.5 and the geochron were calculated using 4.5 Ga for the age of the Earth and Canyon Diablo troilite (Tatsumoto et al. 1973) for initial values.

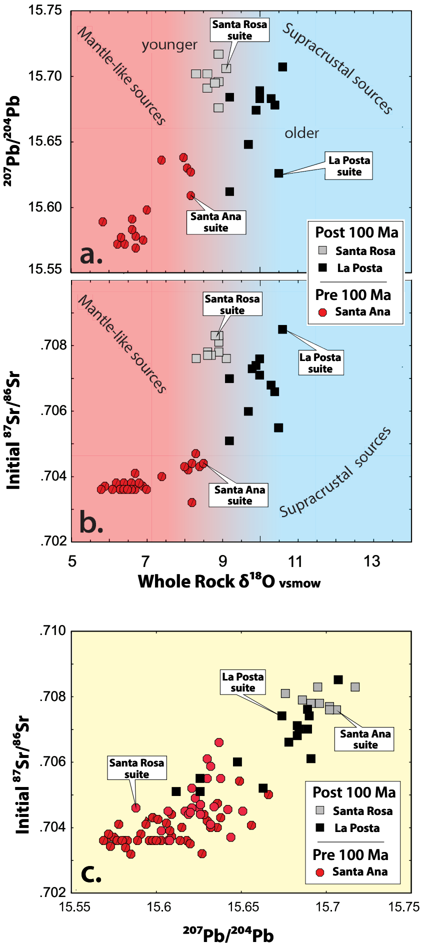

**Figure 21.** Plots of (a) $^{207}$Pb/$^{204}$Pb; and (b) initial $^{87}$Sr/$^{86}$Sr vs. δ$^{18}$O (VSMOW)(‰); and (c) initial $^{87}$Sr/$^{86}$Sr vs. $^{207}$Pb/$^{204}$Pb for Peninsular Ranges batholith plutonic groups. Isotopic data from Kistler et al. (2003, 2014).

An important point to remember is that, based both on models (Reiners et al. 1995) and experiments (Watson 1982), large changes in trace element content and isotopic compositions can take place with very little change in major element chemistry when mantle basalt is interacting with continental crust, especially when hybridization is incomplete. We compared the 0.2 Ma Kuanyinshan basalt (8.4–5.8% MgO) from Taiwan with the La Posta plutons on Figure 11c. As can be seen, the trace elements are similar yet major elements differ widely. This suggests to us that the rocks from Taiwan spent little time in contact with crust prior to eruption, whereas the presumably much larger volumes of La Posta magma were able to assimilate much greater volumes of crustal material, but that nearly all of the transfer of trace elements took place very early on with very small amounts of partial melting. This early hybridization favours increasing asymmetry of Sr and Nd isotopic ratios because the diffusion rates for Sr are faster than those

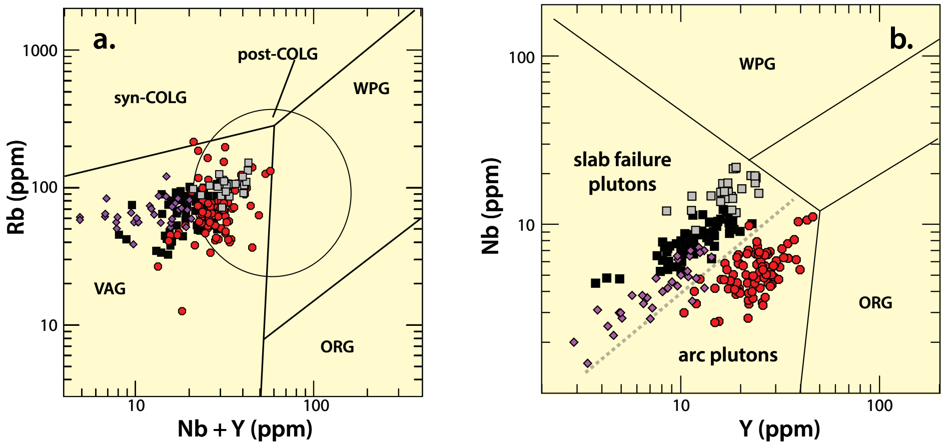

**Figure 22.** (a) Rb vs. Y + Nb; and (b) Nb vs. Y plots for Peninsular Ranges batholith plutonic groups with fields from Pearce (1996). In (b), we divided the former volcanic arc plus collisional granite field of Pearce et al. (1984) into arc and slab failure fields, based on data presented here.

for Nd (Lesher 1994). Thus, there is little doubt that rocks of the Santa Ana suite had significant crustal input. And given the even more evolved isotopes in the La Posta rocks, there can be little doubt that they too involved a significant crustal component.

The main question concerns the origin of the mafic component rising into the crust from the mantle. The rare earth element (REE) concentrations of the two suites are different as originally noted by Gromet and Silver (1987), who suggested that rocks of the Santa Ana arc were derived from partial melting of plagioclase-rich sources whereas La Posta rocks were derived from garnet-bearing assemblages. They also pointed out that generation of La Posta rocks involved a higher $\delta^{18}$O source. Silver et al. (1979) noted that the extremely heavy nature of the oxygen in the La Posta plutons (Fig. 21a, b) required that they had a prior history of access to surface waters. As the La Posta plutons were emplaced into the mid and lower crust, an unlikely source region for surface fluids, the source of fluids was more likely to have been within the mantle source region. As the Santa Ana and La Posta plutons do not have the same oxygen signature they must have had different mantle sources.

In the Sierra Nevada, deep-seated plutons contain abundant evidence for young supracrustal contamination, even in gabbroic plutons, based on high $\delta^{18}$O in zircon values (Lackey et al. 2005). These, along with similar values in La Posta rocks (Fig. 21), might indicate that parts of the leading edge of the subducted plate melted or at least dehydrated to produce sufficient water to contaminate the mantle melts before they ever reached the upper plate crust. Later melts of the Santa Rosa suite have lower $\delta^{18}$O values (Fig. 21), which suggest that the source region was depleted in the fluid phase by about 86 Ma.

Mafic and ultramafic xenoliths in the Sierra Nevada shed some light on the mantle melts involved in slab failure, for the xenoliths, dated to be the same age as the plutons of the eastern slab failure plutons, have similar Nd and Sr isotopic values along with elevated $\delta^{18}$O, and are arguably cumulates left behind after extraction of melts (Ducea and Saleeby 1998; Lackey et al. 2005). As the xenoliths provide minimum pressure bounds (Chin et al. 2012), they clearly were formed within the garnet peridotite field (Fig. 18), and as La Posta plutons have REE patterns of residual garnet (Gromet and Silver 1987), it is reasonable to assume that the slab failure basalt magma originated from rising asthenosphere at deeper levels, say in the garnet stability field (Grove et al. 2013), than the precursors to typical arc magmas, which appear to be formed at shallower levels by melting in the plagioclase and spinel stability fields (Till et al. 2012).

We cannot evaluate whether or not subcontinental mantle was involved in slab failure magmatism, but it is possible that it was. Given that both Nd and Sr isotopes and trace element patterns within the plutons are similar to early lithospheric mantle melts of the Rio Grande rift (Perry et al. 1987) or even oceanic islands (Sisson et al. 2002) we cannot separate them on the basis of isotopic composition. It might be that only the earliest La Posta magmas involved a lithospheric mantle component, but dating is not yet sufficient to evaluate this possibility.

## Geochemical Identification of Slab Failure-Related Granitoid Magmas

On the Rb–Y + Nb diagram of Pearce (1996), all samples from the Peninsular Ranges batholith plot in the volcanic arc granite (VAG) field within which almost all the Santa Ana and about half of the La Posta samples fall in the overlapping fields of VAG and post-collisional granites (Fig. 22a). On the Nb–Y diagram of Pearce et al. (1984), all samples plot in the VAG plus syn-collisional granite field; however, due to differences in Nb/Y between the Santa Ana and La Posta suites (Fig. 10c), there is quite good separation between these two groups on this plot, though not into the fields defined by Pearce et al. (1984). In our opinion these tectonomagmatic diagrams cannot be reliably employed for the geochemical identification of slab failure versus normal arc-type granitoid magmas. However, there is the possibility based on our few examples, that volcanic arc granite and slab-failure granite can be distinguished as on Figure 22b.

Although we firmly believe that the best indicator of slab-failure magmatism is its post-collisional timing, we tried to discriminate between arc and slab-failure magmas by utilizing the differences in trace element concentrations shown on histograms (Fig. 10). We did this empirically by observing the separation of trace element concentrations to arrive at values of La/Yb, Gd/Yb, Nb/Y, and Sr/Y that separate the largest numbers of pre- and post-deformational samples.

As can be seen from Figure 23, the pre- and post-deformational rocks of the Peninsular Ranges batholith fall predominantly into two discrete groups on all three plots. We

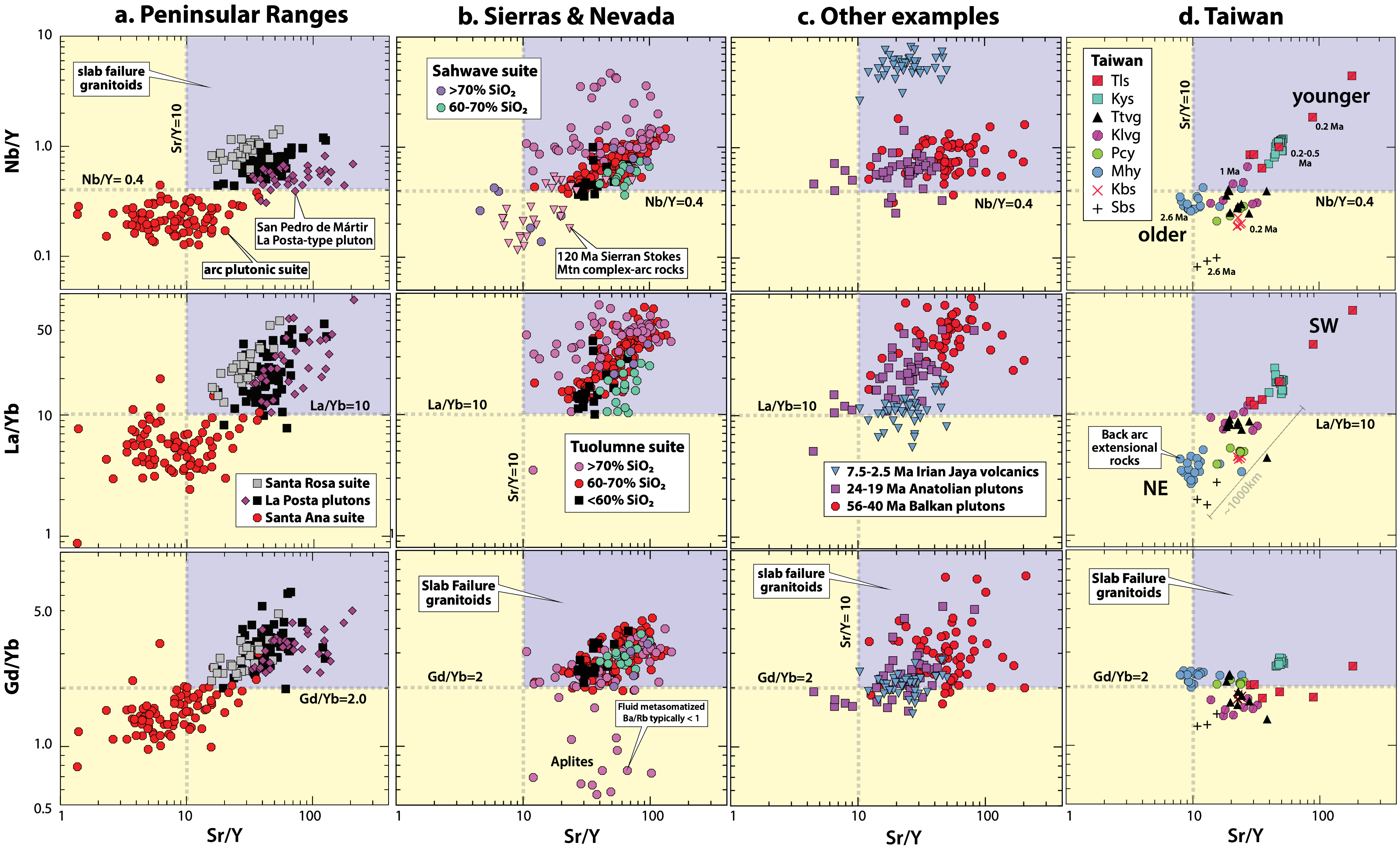

**Figure 23.** (a) Felsic (>60% $SiO_2$) Peninsular Ranges Batholith plutonic samples plotted on Nb/Y, La/Yb, and Gd/Yb vs. Sr/Y diagrams. Dashed lines are ratio values obtained from histograms (Figure 10b, c, and d) that separate most Santa Ana arc-type plutonic samples from La Posta–Santa Rosa slab failure plutonic rocks. Analyses from the Sierra San Pedro Mártir pluton, a La Posta-type pluton in Baja California, are also plotted using data from Gastil et al. (2014). (b) Samples from the 94–84 Ma Tuolumne intrusive complex of the Sierra Nevada from Memeti (2009) and 93–89 Ma Sahwave intrusive suite–a post 100 Ma zoned complex, located in western Nevada, and similar in composition, zoning and petrography to Sierran Crest plutons, from Van Buer and Miller (2010). (c) Analyses from 7.5–2.5 Ma post-collisional magmatism in Irian Jaya from McMahon (2000, 2001); 24–19 Ma post-collisional plutonic rocks from western Anatolia, Turkey (Altunkaynak et al. 2012); and analyses from the 56–40 Ma post-collisional Rhodope Massif of southern Bulgaria–northern Greece (Marchev et al. 2013). (d) Samples from a 1000 km-long swath of 2.5–0.2 Ma volcanoes extending northeastward from northern Taiwan along the Asian continental margin (Wang et al. 2004).

were encouraged by the differences in trace element ratios and so plotted a few more suites in order to see if the discrimination based on the Peninsular Ranges worked for other post-collisional magmatic suites inferred to have formed by slab failure magmatism.

We plotted post-Sierran arc plutons of the well-studied Tuolumne intrusive complex on the same figure (Fig. 23), along with 120 Ma rocks of the Stokes Mountain complex, representative of arc magmatism in the westernmost Sierran batholith (Clemens Knott 1992). Modern and complete analyses of the older Sierran rocks are scarce, and even the data set from the Stokes Mountain complex does not include complete REE analyses. Nevertheless, samples from the post 103 Ma Tuolumne intrusive complex, inferred here to be a result of slab failure, fall mostly within our proposed slab failure field, whereas the bulk of the arc rocks do not. Both Nd and Sr isotopic compositions from the Tuolumne and other post-deformational plutons of the eastern Sierra Nevada are nearly identical to those of the La Posta–Santa Rosa suite (Fig. 19), whereas Stokes Mountain samples have isotopic compositions that plot with the Santiago Peak–Santa Ana arc rocks (Fig. 19). Rocks of the Sahwave complex (Van Buer and Miller 2010), a Tuolumne-like intrusive complex of similar age located in northwestern Nevada, also plot within our proposed slab failure fields. We note that rocks with greater than 70% $SiO_2$ may have significant interaction with a volatile component and do not plot within the slab failure field.

We also plotted (Fig. 23) samples from Irian Jaya, where 7.5–2.5 Ma magmatic rocks are interpreted to have formed as the result of collision of the northern margin of Australia with the south-facing 20–9 Ma Marimumi arc (Cloos et al. 2005). The rocks are dominantly intermediate calc-alkaline, high-K shoshonitic and syenitic with relatively unradiogenic Nd and moderately radiogenic Sr isotopic compositions (Housh and McMahon 2000) broadly similar to those of the La Posta suite, but with lower $\varepsilon_{Nd}$ reflecting the Archean basement. The rocks shown in the plot are dominantly andesite whereas most of the other suites are dominated by samples with > 60% $SiO_2$, which might explain why the Irian Jaya samples cluster near the bottom of the slab-failure field on two of the plots.

Samples from western Anatolia, where 24–19 Ma magmatism formed following the collision of the Sakarya and Anatolide–Tauride blocks (Altunkaynak et al. 2012), also fall within the slab failure field on our discrimination diagrams (Fig. 23) and have similar Nd and Sr isotopic compositions to the La Posta suite. Also within the Alpine belt, and plotted on Figure 23, likely slab-failure magmatism occurred in the Macedonian–Rhodope–North Aegean zone of the southern European Balkans, where Early–Middle Eocene magmatism was bookended by Late Cretaceous arc magmatism and Oligocene extensional magmatism (Marchev et al. 2013). They list Nd and Sr isotopic compositions similar to the other examples cited here.

Our last example (Fig. 23) of post-collisional magmatism is also the youngest and while one would think it therefore the simplest, they would be mistaken. Volcanic rocks ranging in age from 2.5 Ma to 0.2 Ma occur sporadically in a linear band extending from northern Taiwan for about 1000 km along the Asian margin. According to Wang et al. (2004), from whom this description was extracted, the oldest magmas, from Mienhuayu and Sekibisho (MHY and SBS) have: (1) Mg contents of ~6–8%; (2) the highest $^{143}Nd/^{144}Nd$ and relatively elevated $^{87}Sr/^{86}Sr$; and (3) were derived from asthenospheric sources that were fluxed by slab fluids during opening of the Okinawa back-arc basin. In contrast, the youngest rocks, Tsaolingshan (TLS) and Kuanyinshan (KYS), which were both erupted on the northwestern part of the island of Taiwan at about 0.2 Ma have: (1) Mg0 contents of about 15%; (2) the lowest Nd and highest Sr isotopic compositions; (3) model Nd ages falling between 2.5 and 2.0 Ga, which suggest derivation in part from Proterozoic domains in the subcontinental lithospheric mantle (SCLM) or the crust; and (4) Kuanyinshan rocks typically have Ba/Rb <1, indicating significant fluid metasomatism. Remarkably, these young highly magnesian basaltic magmas, which appear to have resulted from very small degrees of partial melting of metasomatized SCLM, have trace element concentrations nearly identical to those of the seemingly much more voluminous La Posta suite (Fig. 11), perhaps providing a real world case of early assimilation of trace elements during partial assimilation.

It is important to understand that these are not universal discrimination plots, for some arc suites, such as the Bodie Hills of eastern California (John et al. 2012; du Bray et al. 2013), which sit atop the eastern Sierran slab-failure rocks, likely scavenged sufficient subjacent crustal material so that they too would plot in the upper right on all these plots. Even the bimodal Plio–Pleistocene volcanic rocks of the Aurora Volcanic field, located in the extensional Basin and Range province just north of Mono Lake, have similar geochemical signatures that also suggest involvement of plutonic rocks of the Sierra Nevada (Kingdon et al. 2014).

## Criteria for Identification of Slab Failure-Related Plutonic Rocks

We showed earlier in the paper that the batholith was likely the upper plate in a collision with an Albian carbonate platform located to the east and that the western edge of the eastern continental margin was pulled beneath the arc. The timing of the collision was ~100 Ma and following collision, or perhaps in part overlapping it, major magmatism of the La Posta suite took place over the length of the batholith. It is the timing of magmatism during and directly after collision, coupled with the strong exhumation, that provides the most compelling evidence that the La Posta plutons are slab-failure bodies, not the geochemistry. That is not to say that our discrimination diagrams do not work, for they do seem to separate slab-failure magmas from arc rocks in the cases that we investigated. However, it must be noted that early slab-failure magmas might be more arc-like as the asthenospheric melts interact with the subcontinental lithospheric mantle. Following slab failure in many collisional orogens, a new subduction zone commonly starts up, but with opposite polarity. The new arc may form atop the pre-collisional arc and the post-collisional slab-failure magmas to form a complex amalgamation of deformed and little deformed magmatic rocks. This, coupled with coincidental opening of a marginal basin, such as the Okinawa trough, behind the Ryukyu arc during collision, can make a mockery of simplistic models and serves as a cautionary tale.

## Some Implications of Our Model

1. Lee et al. (2007) employed geochemical data from the Peninsular Ranges batholith to examine linkages between arc magmatism and Phanerozoic continental crust formation. They concluded that refinement into a felsic crust occurred after oceanic arc accretion during 'the continental arc stage' when an accretion-thickened crustal and lithospheric column was thermally reworked by emplacement of subduction-generated basaltic magmas. There are several problems with their model. First, the Santiago Peak–Alisitos arc was not a primitive arc built on oceanic crust, for it contains far too large a volume of felsic rocks, and its basement, where exposed, comprises abundant Jurassic orthogneiss and Paleozoic metasedimentary rock. Second, there is no evidence that the La Posta suite was derived from subduction of oceanic lithosphere, and third, the crustal materials involved were likely the older Proterozoic–Paleozoic basement of the batholith as demonstrated by xenocrystic cores in zircon grains and Pb–Sr–Nd isotopes (Premo and Morton 2014; Kistler et al. 2014), augmented by fluids and possibly melts from the subducted continental margin.

   In our model, the thermal event that refined mantle materials into more evolved continental crust was directly related to shallow slab failure and consequent upwelling of asthenosphere, which was the advective heat source responsible for the major, short-lived, and focused thermal pulse required to drive the crustal melting and reworking process. Because every collision should have a slab-failure component, this mechanism adds significantly to our understanding of how continental crust formed, grew, and was recycled over Earth history (Hildebrand and Bowring 1999). A possible check on our hypothesis would be to investigate whether major pulses or peaks in crust formation during Earth history postdate major ocean-closure events, such as supercontinent amalgamation. A recent study of $\delta^{18}$O in zircon on a worldwide basis suggests that subduction of sediment and surficially weathered rocks during collisions has led to a long-term record of supercontinent amalgamation as documented by the heavy nature of the $\delta^{18}$O of zircon (Spencer et al. 2014).
2. Geologists studying the geochemical characteristics of plutonic and volcanic associations with high Sr/Y and La/Yb values have generated an abundant literature over the last 20 years as they attempted to classify and understand the petrogenesis and tectonomagmatic implications of rocks such as adakite (Defant and Drummond 1990; Sajona et al. 2000; Macpherson et al. 2006; Moyen 2009), Archean tonalite–trondhjemite–granodiorite (TTG) suites (Martin 1986, 1987, 1994; Smithies 2000; Kamber et al. 2002; Whalen et al. 2004), Archean sanukitoid suites (Whalen et al. 2004; Martin et al. 2005, 2009) and adakitic granite (Wang et al. 2007; Whalen et al. 2010). To our knowledge, only one of the published petrogenetic models for these various igneous suites link them to possible slab failure (Whalen et al. 2010), yet they are similar chemically to the La Posta suite, as well as Cenozoic examples, such as northernmost Taiwan, where comparable magmas were erupted as the exhumed mountain belt collapsed within a few m.y. of collision (Chung et al. 2001; Wang et al. 2002, 2004) and Tibet, where enigmatic magmatism accompanied uplift and exhumation (Turner et al. 1993, 1996; Mahéo et al. 2002; Kohn and Parkinson 2002). These two examples of probable slab failure magmatism might typify the shallow and deep break-off end members respectively, as reflected in their orogenic width, proximity to the suture, and differences in timing relative to the collision. That said, the mantle and crust are sufficiently heterogeneous that it is likely that no discrimination plot can be unfailingly diagnostic.
3. We believe that our model for the Peninsular Ranges batholith is generally applicable to other orogenic belts, and so 'paired' plutonic belts (Tulloch and Kimbrough 2003) consisting of arc-related magmatism, followed by post-tectonic slab failure type plutonism, could represent substantive evidence for the presence of major tectonic sutures in much more deeply eroded terranes, much as do remnants of suprasubduction ophiolites preserved in less denuded terranes. It is worth emphasizing that in cases of deep break-off that slab-failure magmatism may occur a significant distance from the suture and long after the initial collision.
4. In an attempt to reconcile juxtaposed basement blocks and their cover, such as the abrupt northeastern edge of the Caborca terrane in Sonora, Silver and Anderson (1974) hypothesized that Late Jurassic sinistral motion along a major strike-slip fault, which they termed the Mojave–Sonora megashear, separated rocks of Caborca from similar rocks in the Death Valley region. Our rifting and collisional model presents a viable alternative to the Mojave–Sonora megashear hypothesis (Anderson and Silver 2005) because in our model lithological units, considered to be offset along the megashear, may have originally formed more coherent blocks that were separated by rifting and break-up leading to widening of the Bisbee–Arperos sea. When the sea closed, some 30 m.y. later, those fragmented blocks, such as Caborca, simply did not return to their original locations; but instead were accreted farther south.
5. Previously, paleogeographic reconstructions of the pre-160 Ma Jurassic arc of the Klamath Moun-

tains and northern Sierra required it to bifurcate southeast to head into southern Arizona and southwest to Baja California. Our model simplifies the paleogeography in that the Jurassic arc of Baja was rifted from the eastern strand at about 139–130 Ma as the Bisbee margin formed.

**6.** Another peculiarity that might be resolved by our model, or at least partially so, is the Klamath Mountains block, which contains many similar rock packages as the Sierra Nevada, including a Jurassic arc that is generally correlated with the northern Sierran rocks (Irwin and Wooden 2001), but lacks the Sierran Cretaceous arc and slab failure magmatism. Because the western Klamaths were deformed during the ~145 Ma Nevadan event, it thus seems likely that it was separated from both rocks to the east and the Sierran block during the 139–130 Ma rifting event.

**7.** We now recognize that the Bisbee–Arperos sea had an eastern boundary that trended more or less southeast from southwest Arizona to southern Mexico (Fig. 12) yet Dickinson and Lawton (2001b) suggested that the Bisbee basin formed part of what they termed the Border rift system, which was an intracontinental rift extending from the Gulf of Mexico northwest through the Sabinas basin and Chihuahua trough to at least the Bisbee basin (Fig. 12). If active at the same time they likely formed oceanic margins on both the eastern and western sides of the Oaxaquian terrane. Closure of the Arperos–Bisbee sea on the west occurred during the Oregonian event at about 100 Ma and an unnamed sea – but possibly the last vestiges of the Panthalassic ocean – formerly located along the eastern margin of Oaxaquia, vanished during the Laramide event at about 75 Ma.

**8.** An unresolved question is what caused the Bisbee–Arperos sea to open? Presumably, it was subduction reversal following the deformation of the Nevadan collisional event responsible for the strong deformation of the Cucurpe–Peñasquitos–Mariposa rocks. This situation would have been analogous to Taiwan where the Okinawa trough opened as the result of collision, slab failure and subduction reversal (Viallon et al. 1986; Teng et al. 2000) or variations on this theme as seen in numerous other examples (McCabe 1984; Wallace et al. 2009). If it was a marginal sea then there should have been an arc behind which the sea could open. However, there was little time between the deformation of the Cucurpe–Peñasquitos–Mariposa rocks, bracketed to be 145–139 Ma, and the deposition of the unconformably overlying rocks of the Bisbee basin dated to be 136–125 Ma (Mauel et al. 2011; Peryam et al. 2012; Kimbrough et al. 2014a). Perhaps the 141–135 Ma volcanic and plutonic rocks of the Vizcaino Peninsula (Kimbrough and Moore 2003) represent a remnant of the arc, as might the swarm of 143–140 Ma plutons in the western Sierra Nevada (Irwin and Wooden 2001; Day and Bickford 2004). In any case, possible arc rocks of this age are not particularly common. If the basin opened as a marginal sea then there was also an unidentified event that caused the subduction to step into the basin and reverse polarity to dip westward. Whether this was the attempted subduction of an oceanic plateau or a collision of terranes is unknown but a reasonable candidate might be the proposed arc–arc collision between the Alisitos and Santiago Peak blocks (Alsleben et al. 2008; Schmidt et al. 2014). They described a narrow SW-vergent 110–108 Ma fold-thrust belt, which extends southward from the Agua Blanca fault through at least the northern Baja Peninsula (Fig. 2). The proposed suture placed the Santiago Peak block atop the Alisitos block (Alsleben et al. 2008). However, given the likely large-scale meridional migration of outboard Cordilleran terranes, it is also possible that the arc rocks are now located far to the north.

**9.** The model proposed here, that many Cordilleran batholiths are composed of two magmatic phases, arc and slab failure, might be used to reconstruct widely separated terranes. For example, within the American Cordillera there are two batholithic terranes recognized as out-of-place orphans: the Salinian block (Ross 1978), located just west of the San Andreas fault in central California; and the Coastal batholith of Peru with its Arequipa–Antofalla basement (Loewy et al. 2004). In our accompanying contribution (Hildebrand and Whalen 2014: this volume) we briefly describe the geology of those terranes, hypothesize that the two were formerly joined, and that the high-grade Salinian block with its 100–82 Ma plutons formed the opposing block to the dominantly lower grade, mainly Albian, arc complex of the Coastal batholith.

**10.** A major unanswered question is where is the arc that is inferred to lie to the east of the Franciscan mélange, Coast Ranges ophiolite, and Great Valley Group? Based on deformation (Hildebrand 2013) and detrital zircon (Wright and Wyld 2007), it seems clear that those rocks were not adjacent to the Sierra Nevada prior to the 100 Ma collision. A possible candidate is the Xolapa terrane of southern Mexico, which contains Late Jurassic and Early Cretaceous plutons (Herrmann et al. 1994; Ducea et al. 2004), yet has long been known to lack a forearc and accretionary complex (Karig et al. 1978).

**11.** Arcs appear on their face to be very simple elements, and during subduction probably are relatively so, at least at a regional scale. However, appearances are often deceiving, and as arcs commonly collide with other tectonic elements, the subducting slab tears off to allow different magmas to rise into or adjacent to the arc, and new oppositely dipping subduction can start up very quickly, typically within a million years, to create a complex and commonly confusing magmatic tableau (Dewey 2005; Huang et al. 2006; van Staal et al. 2007; Hildebrand et al. 2010). Furthermore, as these events take place at continental margins and within ribbon continents, the possibility that these complex arc-bearing terranes might be torn apart by rifts and/or strike-slip faults and strewn laterally along the margin, only to have new arcs built atop them, must be considered. On a world covered by moving plates, simplicity is not necessarily correct.

## CONCLUSIONS

1. The Peninsular Ranges batholith is a composite batholith comprising a western arc complex, the Santiago Peak–Alistos–Guerrero arc, that formed between 128–100 Ma on Jurassic, Paleozoic and Precambrian crust dominantly above a westward-dipping subduction zone, and a 99–86 Ma suite of post-deformational plutons that were emplaced after the arc collided with a composite terrane located to the east.
2. The basement within the arc complex appears to have rifted from the Cordilleran Ribbon Continent between about 139 and 130 Ma.
3. The Santiago Peak–Alistos–Guerrero arc collided at about 100 Ma with a Lower Cretaceous passive margin, located to the east and topped by a west-facing Albian carbonate platform terrace, which was pulled into the trench, buried by orogenic flysch, and overthrust by exotic allochthons containing slices of the arc and its basement. This platform is intermittently exposed from Caborca, where it is known as the Sonoran shelf, to Zihuatanejo, where it is known as the Guerrero–Morelos platform.
4. During the short-lived collision, the oceanic lithosphere of the lower plate was relatively young so broke off at shallow depths and sank into the mantle, which allowed asthenosphere to rise through the tear to shallow depths, adiabatically melt, and enter the overlying lithospheric mantle and lower crust where it formed composite plutonic complexes of the 99–86 Ma La Posta suite. The shallow break-off created a narrow orogen because little of the lower plate was subducted.
5. Plutons of the La Posta suite were emplaced during a period of major exhumation, which reflects the rebound of the lower plate following slab break-off.
6. The switchover from flysch to molasse in basins to the west of the batholith occurred during the early Cenomanian and it reflected the rapid uplift and erosion of the rising orogenic welt following slab failure.
7. Shallow slab break-off during the 100 Ma collision provides a simple and actualistic model that ties together the voluminous magmatism of the La Posta suite, the narrow orogen, and its rapid exhumation.
8. Although they have similar compositions and are ultimately derived from asthenospheric source material, slab-failure magmatism appears to form at greater depths than does arc magmatism and is governed by melting in the presence of garnet as opposed to mantle-derived magmas of arcs, which appear to form in the spinel–plagioclase regime.
9. We note similar relations in other Cordilleran batholiths such as the Sierra Nevada and suggest that paired batholiths might generally represent both pre-collisional arc and syn- to post-collisional slab failure magmatism.
10. Arcs are dominantly extensional and are not regions of thickened crust unless they are built on older collisional terranes.
11. Arcs are not generally deformed unless they collide with another block. It is collision and attempted subduction of the lower plate that thickens the crust.

## ACKNOWLEDGEMENTS

We are pleased to present this paper on batholiths in the Paul F. Hoffman volume, for while many think of Paul for Snowball Earth or United Plates of America, most are unaware that he mapped a 2º sheet in the northern Great Bear batholith of Wopmay orogen in the mid-1970s, and it was that work which provided the stimulus for the senior author to study the magmatic rocks there for his dissertation. Connections often run deep in geology and Paul held the prestigious Sturgis Hooper chair at Harvard University for 15 years whereas another Canadian, Reginald A. Daly, author of *Igneous Rocks and their Origin* and who recognized that batholiths were emplaced in mountain belts, was Sturgis Hooper Professor from 1912–1942.

Dave Kimbrough, Keegan Schmidt, Helge Alsleben, Paul Wetmore, Wayne Premo, and Vicki Langenheim generously shared important preprints with us as we wrote the initial draft of this paper before publication of GSA Memoir 211 on the Peninsular Ranges batholith. We are especially grateful to Schmidt and Langenheim, as well as Jade Star Lackey, who provided vector versions of their figures so that we could readily modify them to suit our needs and include them here. Ongoing discussions with Tim Lawton clarified many questions on the geology of Sonora and the southwestern US. Doug Morton helped locate geochemical samples so that we were able to remove samples collected from contact or highly altered zones. We thank C-T. Lee for helping us better understand the ins and outs of the Sierran mantle xenoliths. Keegan Schmidt, Doug Morton, and Tim Lawton reviewed earlier versions of the manuscript. Reviews by A. Zagorevski and J.B Murphy were helpful. The senior author especially thanks Sam Bowring for 30+ years of stimulating discussions about arcs and batholithic terranes. This is more self-funded research. NRCan contribution 20140247.

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**Received September 2014**
**Accepted as revised September 2014**
**First published on the web**
**October 2014**