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ARTICLE

The mid-Cretaceous Peninsular Ranges orogeny: a new slant on Cordilleran tectonics? I: Mexico to Nevada[1]

Robert S. Hildebrand and Joseph B. Whalen

Abstract: The Peninsular Ranges orogeny occurred during the mid-Cretaceous at ~100 Ma and affected rocks from southern Mexico to Alaska. The event resulted from the closing of an Early Cretaceous marine arc trough, named the Bisbee–Arperos seaway in Mexico and Arizona, and the Cinko Lake arc trough in the Sierra Nevada. The trough was an ocean that formed after the Late Jurassic – Early Cretaceous Nevadan orogeny and associated post-collisional magmatism. It was open for ~40 million years and closed by westward subduction. Here, we focus initially on the most complete cross section, located in southwestern Mexico, where a west-facing Albian carbonate platform, with subjacent siliciclastic rocks built on the western margin of North America, was pulled down into a trench at 100 Ma, buried in hemipelagic mud and Cenomanian flysch, then overthrust from the west by rocks of the 140–100 Ma Santiago Peak – Alisitos arc and its substrate, the Guerrero Superterrane, which collectively document westerly subduction. This tectonically thickened collision zone was exhumed and intruded by 99–84 Ma distinctive post-collisional tonalite–granodiorite plutonic complexes, all with Sr/Y > 20, Sm/Yb > 2.5, Nb/Y > 0.4, and La/Yb > 10. These geochemical features are typical of slab failure, not arc magmas. The post-collisional plutons, previously considered to represent arc flare-ups, were derived from melting of the descending slab following arc-continent collision. Remnants of the arc, basin, related east-vergent 100 Ma thrusts, flexural foredeep, and 99–84 Ma slab failure plutons are traced from the Peninsular Ranges, through the Mojave Desert to the Sierra Nevada where similar rocks, relations, and ages occur. Along the western, back-arc, side of the orogen after collision and slab break-off, but during exhumation, east-dipping reverse faults with >10 km of east-side up movement shed 100–85 Ma plutonic and other debris westward from the hinterland into troughs such as the Valle and Great Valley. We extend our synthesis northward, from west-central Nevada to Alaska, in Part II.

Key words: orogeny, North American Cordillera, arc magmatism, arc-continent collision, slab failure magmatism, Peninsular Ranges orogeny.

Résumé : L'orogenèse des chaînes péninsulaires s'est produite durant le Crétacé moyen, vers 100 Ma, et a touché des roches allant du sud du Mexique à l'Alaska. Elle est le résultat de la fermeture d'une fosse d'arc marine d'âge crétacé précoce, appelée le bras de mer Bisbee–Arperos au Mexique et en Arizona et la fosse de l'arc de Cinko Lake dans les Sierra Nevada. La fosse était un océan formé après l'orogenèse névadienne d'âge jurassique tardif à crétacé précoce et le magmatisme post-collision associé. Elle est demeurée ouverte pendant ~40 millions d'années et s'est refermée par subduction vers l'ouest. Nous nous concentrons dans un premier temps sur la coupe la plus complète, située dans le sud-ouest du Mexique, où une plateforme carbonatée albienne faisant face à l'ouest, avec des roches silicoclastiques sous-jacentes accumulées sur la marge occidentale de l'Amérique du Nord, a été attirée dans une fosse à 100 Ma, ensevelie par des boues hémipélagiques et un flysch cénomanien, puis charriée vers l'est par des roches de l'arc de Santiago Peak – Alisitos de 140–100 Ma et son substrat, le superterrane de Guerrero, qui documentent collectivement une subduction vers l'ouest. Cette zone de collision épaissie tectoniquement a été exhumée et recoupée par des complexes plutoniques à tonalites-granodiorites post-collision distinctifs de 99–84 Ma qui présentent tous des rapports Sr/Y > 20, Sm/Yb > 2,5, Nb/Y > 0,4 et La/Yb > 10. Ces caractéristiques géochimiques sont typiques des magmas de rupture de plaque et non des magmas d'arc. Les plutons post-collision, auparavant considérés représenter des sursauts de magmatisme d'arc, sont dérivés de la fusion de la plaque descendante dans la foulée de la collision arc-continent. Des restes de l'arc, du bassin, de chevauchements vers l'est reliés de 100 Ma, de l'avant-fosse formée par flexion et de plutons associés à la rupture de la plaque de 99–84 Ma peuvent être suivis des chaînes péninsulaires au désert du Mojave et jusque dans les Sierra Nevada, où de roches, relations et âges semblables sont observés. Le long du côté ouest d'arrière-arc de l'orogène après la collision et la rupture de la plaque, mais durant l'exhumation, des failles inverses à pendage vers l'est montrant >10 km de déplacement du bloc est vers le haut ont évacué vers l'ouest des débris plutoniques de 100–85 Ma et d'autres débris de l'arrière-pays jusque dans des fosses comme la Valle et la Grande vallée. Dans la deuxième partie, nous élargissons notre synthèse vers le nord, du centre-ouest du Nevada jusqu'en Alaska. [Traduit par la Rédaction]

Mots-clés : orogenèse, cordillère nord-américaine, magmatisme d'arc, collision arc-continent, magmatisme de rupture de plaque, orogenèse des chaînes péninsulaires.

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> *It ain't what you know that gets you into trouble. It's what you know for sure that just ain't so.*
>
> —Mark Twain

Introduction

In 1969, Warren Hamilton published two seminal papers in which he inferred — based in part on the Cenozoic volcanic belt of the Andes — that thousands of kilometres of oceanic lithosphere were swept against, and subducted beneath, western North America to generate the great Mesozoic batholithic belt and the ensimatic and chaotic Franciscan Formation (Hamilton 1969*a*, 1969*b*). At about the same time, Dickinson (1970) noted the similarity of ages across California and so linked strongly deformed rocks of the high-pressure, low-temperature Franciscan complex with sedimentary rocks of the Great Valley Group and plutons of the Sierran-Klamath batholith as a trench fill – forearc basin – arc batholith tectonic association (Fig. 1). This concept quickly evolved into a more generalized hypothesis in which the trench fill – forearc basin – batholithic assemblage, interpreted to be the products of eastward subduction beneath western Laurentia, had an associated fold-thrust belt, located well to the east, with mostly westerly dipping thrust faults developed in heated retro-arc crust, and an adjacent, but even more easterly, foreland basin (Burchfiel and Davis 1972; Armstrong and Dick 1974; Dickinson 1976). A half century later, the essence of this model is still in vogue and rarely challenged, so the notion of eastward subduction beneath North America — especially for the great batholithic belts of the Sierra Nevada, Peninsular Ranges, and Coast plutonic complex — has become a formidable paradigm.

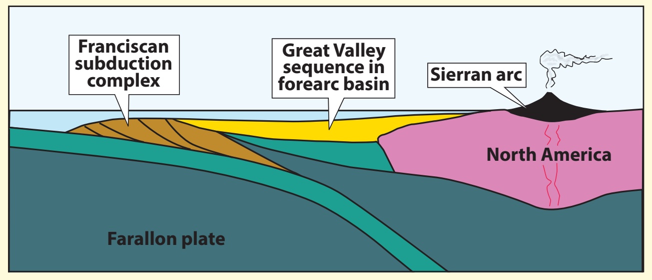
Although several contributions have challenged this paradigm (Moores 1970; Mattauer et al. 1983; Chamberlain and Lambert 1985; Lambert and Chamberlain 1988; Johnston 2008; Hildebrand 2009, 2013; Hildebrand and Whalen 2014*a*, 2014*b*, 2017; Hildebrand et al. 2018), they were, in many cases, broad syntheses covering several orogenies through time and so these ideas failed to generate traction within the Cordilleran community. In the aftermath of the recent kerfuffle about the polarity of subduction in the northern Cordillera (Sigloch and Mihalynuk 2020; Pavlis et al. 2020*a*, 2020*b*), it seemed to us worthwhile and timely to describe a little known, mid-Cretaceous orogeny that can be traced along the length of the North American Cordillera from southern Mexico to Alaska, and perhaps beyond, as it provides evidence on the polarity of subduction in the northern Cordillera. We call it the Peninsular Ranges orogeny after the region where we first recognized it and because the most-complete cross sections of the orogen are exposed there and in adjacent Mexico.

Although we have argued that other orogenies within the Cordillera involved eastward-facing arcs, we focus on the Peninsular Ranges orogen because it entailed several of the world's most impressive Cordilleran type batholiths, which, for over 50 years, have been taken as proof-positive evidence for eastward subduction beneath North America. We approach the overall geology of the orogen from south to north, and our goal is to demonstrate why we find the long-ingrained hypothesis for eastward subduction flawed and untenable.

The Peninsular Ranges orogen in its type area

In Southern and Baja California, the largely chaparral-covered mountains expose remnants of the Early Cretaceous Santiago Peak – Alisitos arc terrane, comprising shallow-marine clastic and carbonate sedimentary rocks, deep-water turbiditic fan deposits, basaltic to rhyolitic volcanic rocks, and 128–99 Ma calcic, epizonal intrusions ranging from gabbro to granite (Allison 1974; White and Busby-Spera 1987; Almazán-Vásquez 1988*a*, 1988*b*; Johnson et al. 2003; Wetmore et al. 2005; Busby et al. 2006; Herzig and Kimbrough 2014; Clausen et al. 2014; Morris et al. 2019). In California, the basement to the volcano-sedimentary cover is dominantly composed of metamorphosed and deformed Jurassic to Triassic metaturbidites, migmatitic schists, gneisses, and granodioritic plutons, but farther south on the Baja Peninsula of Mexico, carbonates and quartzites of Paleozoic age also occur (Shaw et al. 2003; Todd 2004; Gastil and Miller 1981; Gastil et al. 1991; Gastil 1993). Near San Diego, an uppermost Jurassic succession of marine volcaniclastic rocks, collectively named the Peñasquitos Formation, was folded, in places even overturned, prior to deposition of the Santiago Peak rocks (Kimbrough et al. 2014). To the south in Baja California (Fig. 2), arc successions overstep several subterrane boundaries within the Guerrero superterrane (Centeno-García et al. 2008), and after Cenozoic opening of the Gulf of California is restored, form a continuous lithostratigraphic unit onto the mainland in Zihuatanejo (Centeno-García et al. 2011; Duque-Trujillo et al. 2015). Thus, the arc formed atop and intruded rocks of the Guerrero superterrane as noted by Dickinson and Lawton (2001*a*).

Fig. 1. Cartoon illustrating the fundamental western triad of the Sierran paradigm. [Colour online.]



The intrusions, dated at 128–99 Ma (Todd et al. 2003; Wetmore et al. 2005; Premo et al. 2014; Shaw et al. 2014), were informally termed the Escondido plutons (Clausen et al. 2014) whereas we called the same bodies, the Santa Ana suite (Hildebrand and Whalen 2014*b*). These plutons are both normally and reversely zoned, isotropic to foliated, locally protomylonitic, sheeted intrusive complexes, varying in composition from tonalite through quartz diorite and granodiorite to leucomonzogranite, locally with abundant wall rock screens and mafic inclusions, and containing varying proportions of mafic enclaves (Todd et al. 2003; Todd 2004).

Morton et al. (2014) noted that the westernmost intrusions are isotropic whereas those farther east are foliated, so that there is a megascopically visible deformation gradient from west to east, especially evident in enclaves. In the east, cumulate layering in gabbroic plutons is now mostly steeply dipping; intrusive contacts are folded, in many places isoclinally, along with their wall rocks. The mineral foliation is steep and commonly transects external contacts, and dykes of one pluton within another are isoclinally folded (Todd and Shaw 1979).

In Baja California, large pre-100 Ma plutons are also strongly deformed with concordant contacts, transecting cleavage, and folded wallrocks (Murray 1979; Johnson et al. 1999, 2003). Some bodies there were recumbently folded (Johnson et al. 2002). Overall, the data provide compelling evidence that intrusions of the Santiago Peak – Alisitos arc are complexly folded sills or sheets (Hildebrand and Whalen 2014*b*).

Age of deformation

Premo and Morton (2014) examined a variety of rocks in the Peninsular Ranges where they found and dated zircon in a pre- to syn-metamorphic diorite dyke, which yielded an age of 103.3 ± 0.7 Ma. They also dated zircon in a post-metamorphic pegmatite dyke to be 97.53 ± 0.18 Ma, which they interpreted to have been

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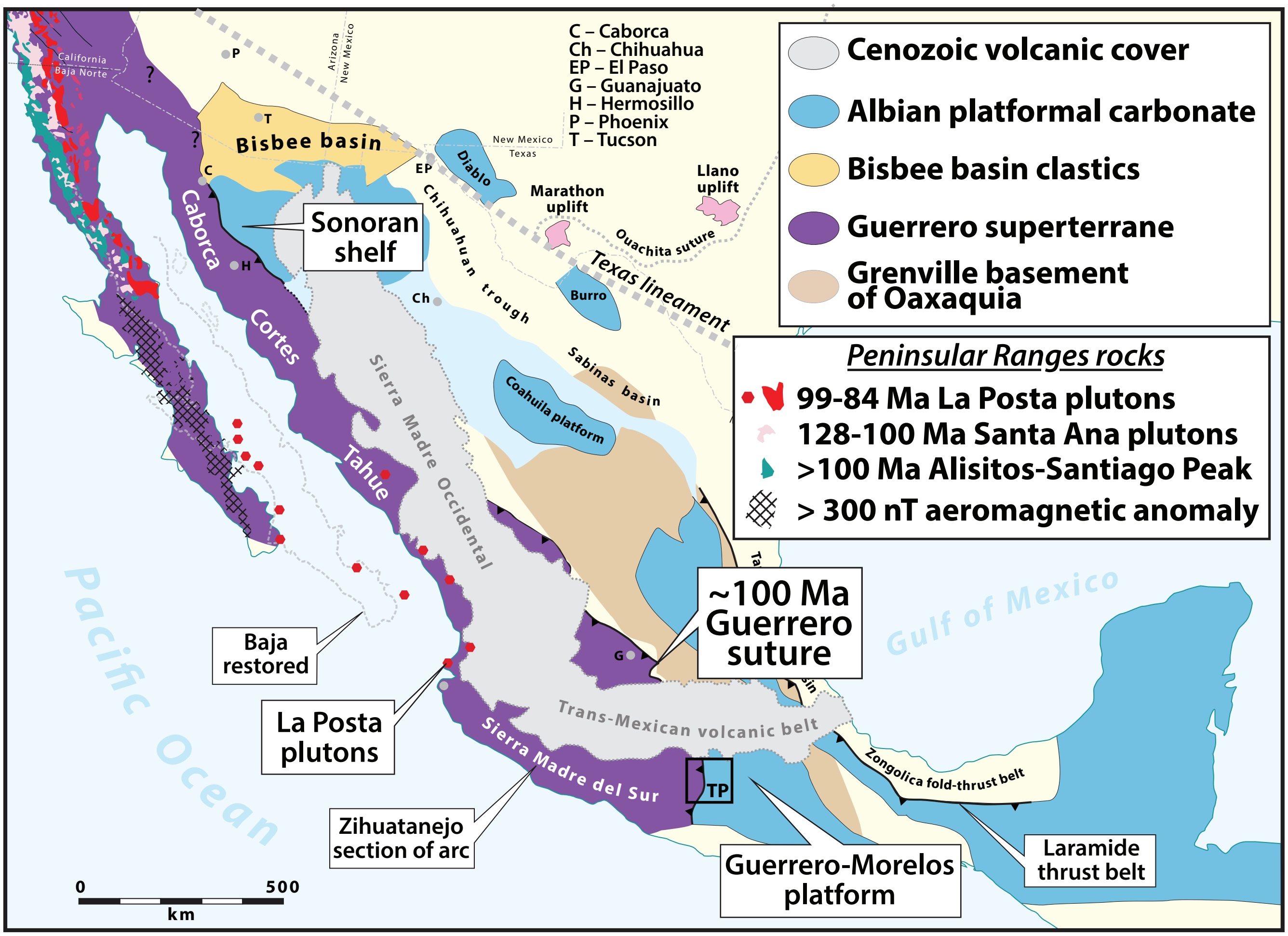
Fig. 2. Sketch map illustrating key geological units of the Peninsular Ranges batholith and Aptian–Albian volcano-sedimentary rocks of the Alisitos – Santiago Peak arc, various terranes of the Guerrero superterrane, and Albian carbonate platforms, mostly located west of the younger Laramide suture and its related fold-and-thrust belt. The Peninsular Ranges batholith continues the length of Baja California, as indicated by a conspicuous aeromagnetic anomaly (Langenheim et al. 2014), but the batholith is buried by younger volcanic rocks south of the state line. Red dots represent drilled and dated core from La Posta plutons (Duque-Trujillo et al. 2015). Rocks of similar age and lithology to those of the Peninsular Ranges batholith crop out in Zihuatanejo (Centeno-García et al. 2011). Westward-facing Albian carbonate banks of the Sonora and Guerrero–Moreles platforms were pulled westward beneath rocks of the Guerrero superterrane at 100 Ma during closure of the Bisbee–Arperos seaway. Box labeled "TP" shows location of Fig. 5. [Colour online.]



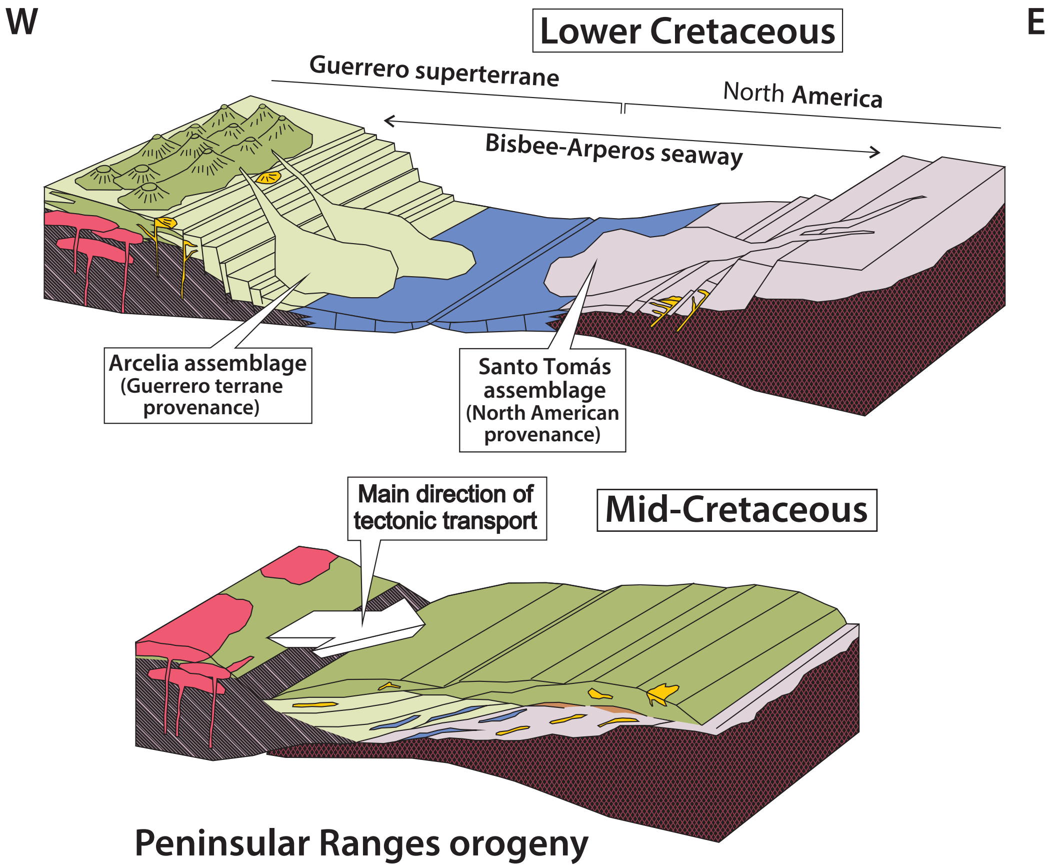
emplaced soon after metamorphism. Additionally, they dated more than 30 hornblende separates and determined that metamorphism took place at or before 100.1 ± 0.6 Ma. These age data are consistent with data collected farther south in the Sierra de San Pedro Mártir of Baja California, where the age of the deformation is tightly constrained by plutons. There, 100 Ma gabbro, as well as a 101 Ma gabbro–tonalite–trondhjemite body, are compositionally linked to the arc, strongly deformed, and folded (Johnson et al. 2002; Alsleben et al. 2008; Schmidt et al. 2009) whereas the post-deformational Sierra San Pedro de Mártir intrusive complex yields U–Pb zircon ages as old as 96 Ma (Gastil et al. 2014; Ortega-Rivera et al. 1997). Thus, we consider the deformational age of the arc rocks to be tightly constrained at 100 Ma, roughly coincident with the Albian–Cenomanian boundary (Cohen et al. 2013).

Bisbee–Arperos seaway

The Santiago Peak – Alisitos arc developed along the western margin of an elongate trough or seaway, termed the Bisbee–Arperos seaway, after the transborder Bisbee basin and the Arperos basin farther south, which we interpret to have been parts of the same basin (Hildebrand and Whalen 2014*b*). The Bisbee–Arperos basin developed during rifting of the western part of North America following the ~153 Ma Nevadan orogeny and a younger Early Cretaceous event, possibly as young as about 140 Ma.

In southern Arizona, coarse clastic sedimentation and eruption of bimodal volcanic rocks in the Bisbee basin were traditionally considered to have started at around 150 Ma, following Early to mid-Jurassic arc magmatism (Bilodeau et al. 1987; Krebs and Ruiz 1987; Lawton and McMillan 1999; Dickinson and Lawton 2001*b*). However, 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 and 125 Ma (Peryam et al. 2012). Within the Bisbee Basin, the lowermost clastic rocks have bimodal northeast–southwest paleocurrents and reflect shelf, lagoonal, tidal flat, and fluvial environments (Klute 1991), but pass stratigraphically upwards into an eastward-transgressive sequence of fining-upwards fluvial to shallow marine deposits (Peryam et al. 2012). A recent stratigraphic, detrital

Fig. 3. Block diagram modified from Martini et al. (2014) illustrating the dual nature of sedimentation within the Bisbee–Arperos seaway of southern Mexico and the 100 Ma collision between the Guerrero superterrane and North America. Where sufficient data exist, these relations are consistent from southern Mexico to Alaska. [Colour online.]



zircon, and provenance study of the basal siliciclastic unit in the basin, the Morita Formation, determined maximum depositional ages (MDAs) for the lower part of the unit to range from 131 to 125 Ma depending on the location (González-León et al. 2020). The overlying carbonate platform, known in northern Mexico as the Sonoran shelf, had a well-developed reefal rim or ramp along its southwest side (González-Léon et al. 2008).

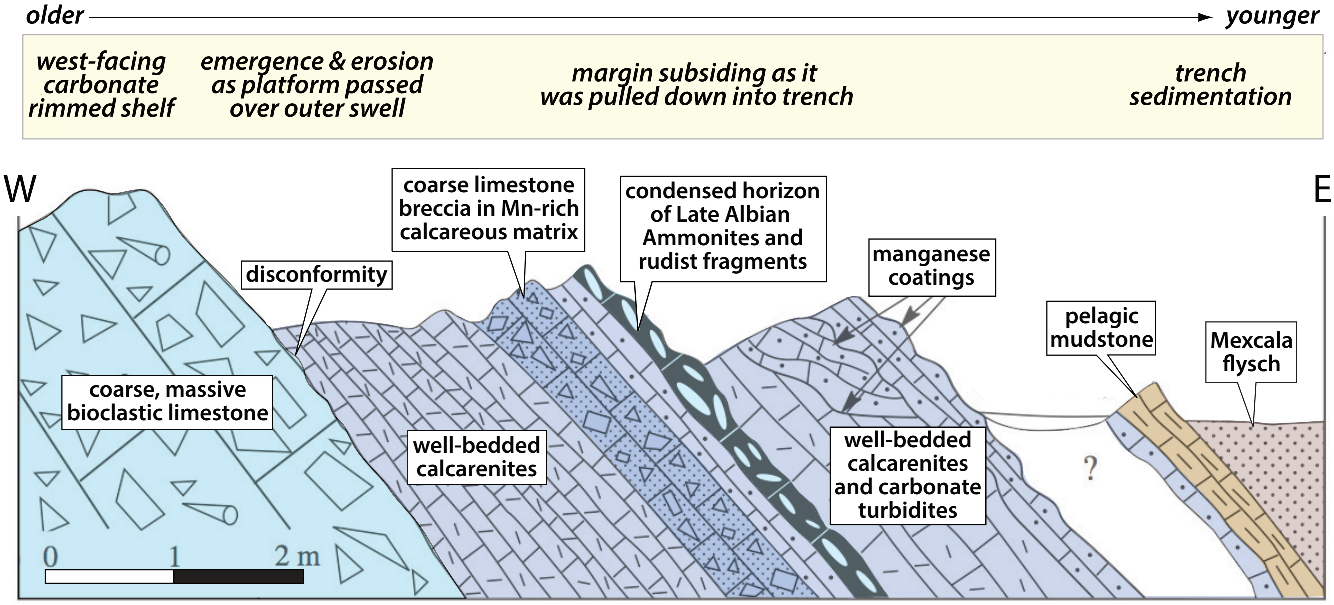
In Sonora, the rocks of the Bisbee Basin sit unconformably atop deformed Jurassic arc rocks and isoclinally folded, Oxfordian to Tithonian, marine clastic rocks of the Cucurpe Formation, which were largely derived from post-160 Ma plutonic rocks of the bimodal Ko Vaya suite (Mauel et al. 2011; Lawton et al. 2020). We interpret rocks of the Cucurpe Formation to be consanguineous with the Tithonian Peñasquitos Formation of the western Peninsular Ranges near San Diego (Kimbrough et al. 2014), as both formations have similar basements and contain comparable rocks of the same age. Furthermore, both successions were deformed between about 145 and 139 Ma and are both unconformably overlain by 130–125 Ma rocks. In the east, the Curcurpe Formation 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 arc complex. Kimbrough et al. (2014) noted that another succession, the Mariposa Formation of the western Sierra Nevada, 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 westernmost Sierran batholith (Lackey et al. 2012*a*, 2012*b*).

Farther south, much of east-central Mexico, such as Oaxaquia, Central, and Mixteca terranes (Ortega-Gutiérrez et al. 1995; Centeno-García 2005; Keppie et al. 2012), formed a coherent block and was covered by a westward-thickening siliciclastic prism capped by a west-facing Albian carbonate platform (Fig. 2), known as the Guerrero–Morelos platform in southern Mexico as well as the Valles – San Luis and El Doctor platform in central Mexico (Lapierre et al. 1992; Monod et al. 1994; Centeno-García et al. 2008; Martini et al. 2012). The platform was built upon about 1000 m of Lower Cretaceous red beds, alluvial sandstone, and conglomerate with thick evaporite deposits and an older metamorphic basement (Fries 1960).

Martini et al. (2014) demonstrated that calcareous and siliciclastic metaturbidites of the eastern Santo Tomás assemblage, deposited on easterly derived submarine fans within the basin, were exclusively derived from North American sources, such as Oaxaquia and the Acatlán and Taray complexes, and were sedimentologically disconnected from mafic to intermediate volcanic sources in the arc to the west (Fig. 3).

The western margin of the Arperos Basin, now preserved in eastward-vergent thrust sheets, is represented by the Arcelia and Arperos assemblages, which comprise Aptian volcaniclastic metaturbidites derived from the west, and are intercalated with intraplate and oceanic basalts (Tardy et al. 1994; Martini et al. 2012). Overall, the basin shows a clear provenance asymmetry with sediments derived from the Guerrero terrane and its carapace of arc rocks to the west and mainland-derived sediments to the east (Fig. 3), so that the Bisbee–Arperos seaway separated the Guerrero superterrane and its arc from the Lower Cretaceous passive margin of North America (Martini et al. 2014; Hildebrand and Whalen 2014*b*).

Fig. 4. Detailed cross section of the uppermost few metres of the west-facing Guerrero–Morelos carbonate platform showing the rapid transition from carbonate shelf to orogenic deposits near Concordia, Estado de Guerrero. Hoffman (2012) presents an excellent overview of the process of platform foundering at the beginning of orogenesis. Figure modified from Monod et al. (2000). For location of section, see Fig. 5. [Colour online.]



Closure of the Bisbee–Arperos seaway and arc-continent collision

Perhaps the best cross section of the orogen in southern and central Mexico is that of the Sierra Madre del Sur, located south of the Trans Mexico volcanic belt (Fig. 2). There, beginning in the late Albian, upward growth of the west-facing carbonate platform stopped, as marked by a disconformity atop massive bioclastic carbonate and below a few metres of well-laminated beds of detrital carbonate, breccias, condensed horizons rich in Albian faunal debris, and ultimately by hemipelagic shale overlain by Mexcala flysch (Monod et al. 2000). The disconformity, as well as the rapid tectonic subsidence and burial of the carbonate platform by hemipelite and orogenic flysch, are easily explained by transport of the platform over the outer bulge to a trench, where it was eroded; then, as the platform was pulled into the trench, it was covered by a thin veneer of hemipelagic mud deposited on the starved outer-trench slope, only to be overwhelmed by trench-fill turbidites upon arrival in the trench axis (Fig. 4). Easterly vergent thrust faults inverted the basin and thrust basinal facies rocks and basement of the Guerrero superterrane onto the North American margin, where it originated prior to rifting and formation of the basin (Fig. 3).

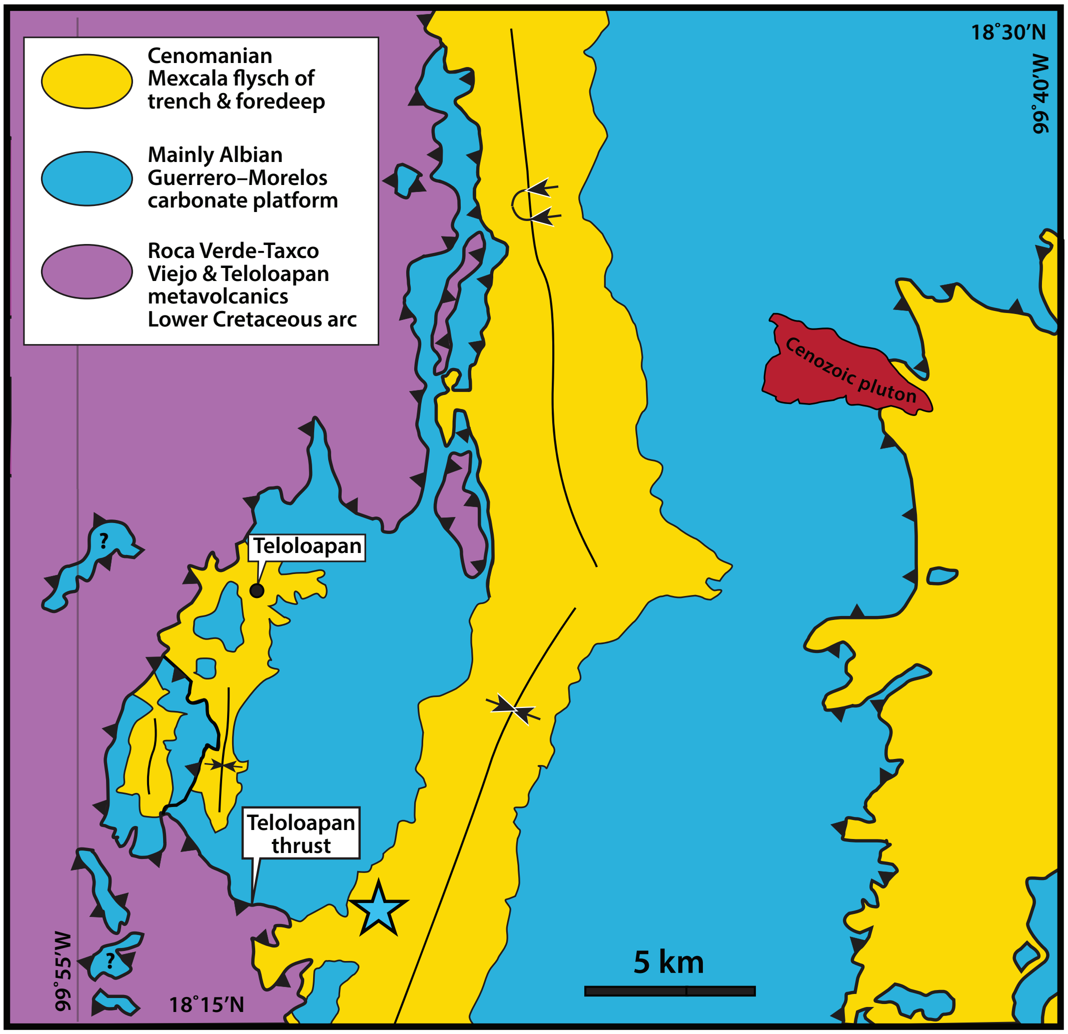
To the west of the carbonate platform, several kilometres of calc-alkaline and tholeiitic metavolcanic and metasedimentary rocks of various arc assemblages within the Guerrero superterrane (Centeno-García et al. 2008), including, from west to east, the Zihuatanejo, Arcelia, Taxco – Taxco Viejo, and Teloloapan assemblages, have U–Pb ages and prominent age peaks ranging from 141 to 124 Ma (Talavera-Mendoza et al. 2007; Campa-Uranga et al. 2012), the same age as the passive margin succession on the eastern side of the Bisbee–Arperos trough. The easternmost units of the Teloloapan terrane were thrust over the west-facing, dominantly Albian Guerrero–Morelos carbonate platform and its synorogenic cover of Cenomanian Mexcala flysch (Fig. 5) at about 100 Ma. Some researchers (Mendoza and Suastegui 2000; Guerrero-Suasegui 2004; Talavera-Mendoza et al. 2007) argued that the easternmost Teloloapan metavolcanics, which are penetratively deformed and recumbently folded, but at relatively low metamorphic grade, were overlain by a different, but much lesser deformed, carbonate platform just west of the Guerrero–Morelos platform and place the suture along its eastern boundary. Here we note that because both carbonate platformal successions formed during the Albian and are overlain by similar Cenomanian clastic successions, we interpret them as formerly continuous units dismembered by thrust faults. We locate the suture along the Teloloapan thrust (Fig. 5), which places the older volcanic successions eastward over the Albian carbonate platform and its overlying orogenic Mexcala flysch as originally envisioned by Campa and Coney (1983).

In the north, the Sonoran platform was buried by at least 1500 m of westerly derived Cenomanian and Turonian flysch, termed the Cintura and Mojado formations, and deposited in a flexural foredeep (Mack 1987; González-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 with sparse pebbles of quartzite and limestone, and overthrust from the southwest by plutonic rocks (Jacques-Ayala 1992; T. Lawton, personal communication 2014). Lawton et al. (2020) established the temporal correlation between the Mojado and Cintura formations by U–Pb studies of detrital zircons and ash beds, which aid in understanding the nature of the foredeep as far to the east as El Paso, Texas.

The tectonic subsidence was caused by downward flexure of the lithosphere when the leading edge of the North American margin was subducted beneath the Guerrero superterrane and its Lower Cretaceous arc carapace (Pubellier et al. 1995; Martini et al. 2014). The Cintura Formation is overlain in Sonora by conglomerate of the Cocóspera Formation interbedded with andesitic lava dated by ^{40}Ar/^{39}Ar as 93.3 ± 0.7 Ma (González-León et al. 2011). Anderson et al. (2005) also described the thrust belt in some detail and, based on the age of a pluton that cuts mylonites of the zone, determined that the deformation was older than 84 Ma.

Taken in its entirety, the evidence in western Mexico suggests that the Alisitos – Santiago Peak arc, and its basement, collided with a west-facing passive margin at about 100 Ma during the

Fig. 5. Geological sketch map showing relations near Teloloapan, west-central Mexico, illustrating metavolcanic and metasedimentary rocks of the Roca Verde, Taxco–Viejo, and Teloloapan arc assemblages thrust over the west-facing Guerrero–Morelos carbonate platform and its overlying syntectonic cover of Mexcala flysch along the Teloloapan thrust. Modified from Cabral-Cano et al. (2000). Detailed section at Concordia (Fig. 4) marked by star. See Fig. 2 for location of figure. [Colour online.]



Peninsular Ranges orogeny. The polarity of subduction was clearly westward and the western edge of the North American passive margin was partially subducted beneath the arc. The basin was apparently a linear trough of unknown width that was open for at least 30 million years, but it must have been sufficiently wide to be floored by oceanic crust to drive the 100 Ma collision. If we assume that half of the 30 million year timespan was spreading, then at moderate spreading and convergence rates of 5 cm/year (Müller et al. 2008), the basin would have been about 750 km wide: about three-quarters the maximum width of the Sea of Japan.

Post-collisional plutonism and exhumation of the orogenic hinterland

Soon after collision and terminal closure of the basin, seemingly within a million years, the collisional hinterland was intruded by a voluminous suite of post-collisional 99–86 Ma mesozonal to catazonal plutons (Fig. 6). The bodies were intruded during a period of rapid exhumation when rocks at depths of 15–23 km were brought to the surface in less than 10 million years by detachment faulting and collapse (Krummenacher et al. 1975; Ortega-Rivera et al. 1997; Ortega-Rivera 2003; Miggins et al. 2014). Rapid exhumation is also documented by abundant coarse plutonic debris of the Valle Formation, such as boulder beds containing clasts up to 2.5 m in diameter, as well as abundant 100–90 Ma detrital zircons deposited during the Cenomanian–Turonian, in a basin located to the west of the collision zone (Kimbrough et al. 2001). As this basin was located west of the former arc and collision zone, that is, on the opposite side of the arc from the trench, it cannot have been a forearc basin. The debris was probably shed from reverse fault scarps, some with 3–4 kbar of 100–86 Ma exhumation across them, that bounded the hinterland belt to the west (Schmidt and Paterson 2002; Schmidt et al 2014; see also Supplementary Fig. S1[2]).

The post-collisional intrusions form a group of gregarious plutons, collectively termed the La Posta suite, after a compositionally zoned intrusive complex that spans the international border (Walawender et al. 1990). The plutons are mesozonal to catazonal, range in age from 99 to 86 Ma (Premo et al. 2014), possibly

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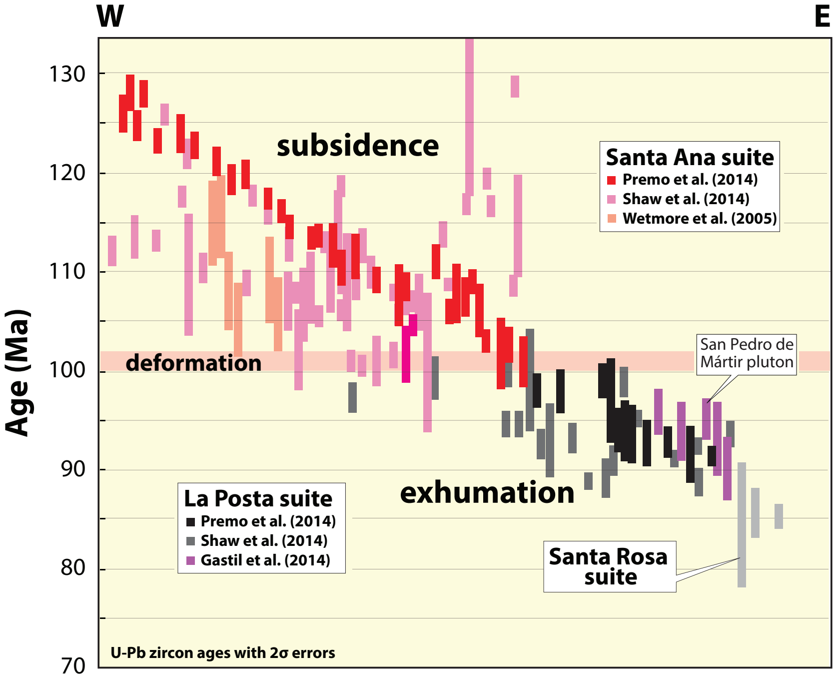
[2] Supplementary data are available with the article at https://doi.org/10.1139/cjes-2020-0154.

Fig. 6. U–Pb zircon ages with 2σ errors for the Peninsular Ranges batholith plotted versus general longitude. Modified from Premo et al. (2014) 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, because most researchers recognized that the western Santa Ana arc suite did not migrate with time (Silver and Chappell 1988; Shaw et al. 2014). [Colour online.]



young eastward (Ortega-Rivera 2003), and are dominated by large, concentrically zoned complexes comprising biotite–hornblende-bearing, tonalitic marginal phases grading inward over several decametres to granodiorite and cored by granite, in places containing both biotite and muscovite (Hill 1984; Silver and Chappell 1988; Walawender et al. 1990). A diagnostic characteristic of the bodies in the field is the presence of euhedral titanite (Silver and Chappell 1988).

The plutons were emplaced mostly to the east of the Santiago Peak – Alisitos arc, although a few intrude the easternmost arc plutons. Thus, there are two, side-by-side intrusive suites, the arc-related Escondido / Santa Ana and the post-collisional La Posta. Plutons of the Escondido / Santa Ana arc suite are mainly epizonal and compositionally more variable, ranging from gabbro to granite, than the younger, post-collisional La Posta plutons, which are dominantly granodioritic to tonalitic.

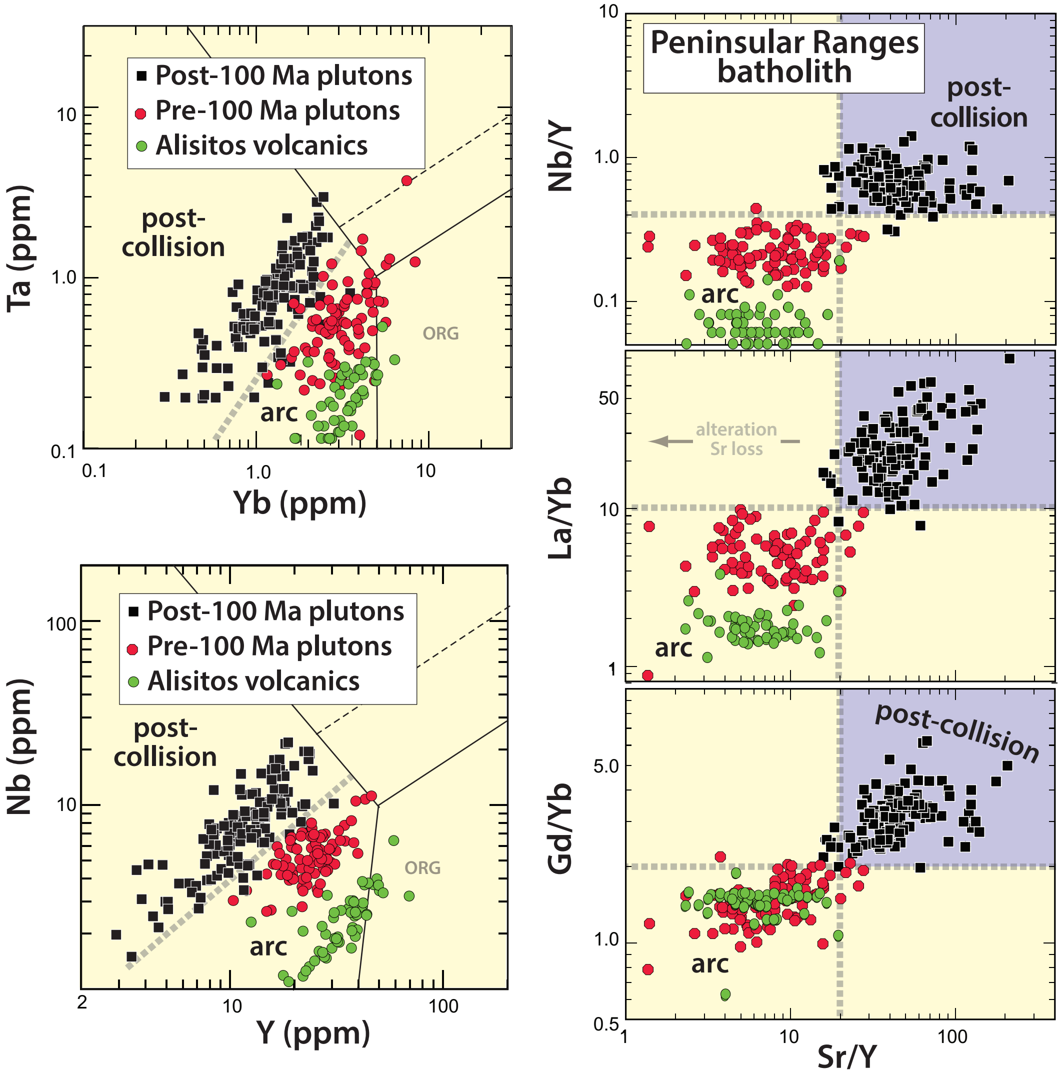
These two different intrusive suites, each with different ages, depth of emplacement, and composition have been recognized for some time (Buddington 1927; Larsen 1948; Silver et al. 1979; Silver and Chappell 1988; Gromet and Silver 1987; Gastil et al. 1975, 1990; Kimbrough et al. 2001; Tulloch and Kimbrough 2003; Ortega-Rivera 2003). Most researchers agree that the older Santiago Peak – Alisitos rocks represents a magmatic arc, but also infer that the younger La Posta magmatism represented a continuation of arc magmatism, despite development of numerous models that invoke closure of back-arc basins and collisions just prior to their emplacement (Silver and Chappell 1988; Gastil et al. 1981; Gromet and Silver 1987; Todd et al. 1988; Walawender et al. 1990; Busby et al. 1998; Johnson et al. 1999; Ortega-Rivera 2003; Schmidt et al. 2014).

Kimbrough et al. (2001) tied together many critical elements, including 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 they attributed the La Posta suite to a transient episode of high-flux magmatism. Tulloch and Kimbrough (2003) expanded 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 mainland arc during slab-flattening, which shut off normal arc magmatism and generated the burst of La Posta magmatism. In a more recent contribution, Centeno-García et al. (2011, p. 1793) noted the strong ties between the history of Baja California and the Guerrero composite terrane of mainland Mexico and so speculated that the arc was separated from the continent by a marginal basin, which closed "when the Early Cretaceous Alisitos fringing arc underthrust the Mexican continental margin and the crust was greatly thickened" also without explaining how the arc ended up on the lower plate and the continental margin on the upper.

Hildebrand and Whalen (2014*b*) examined recent inductively coupled plasma – mass spectrometry geochemical data and, to resolve the tectonomagmatic difficulties, proposed that the two plutonic suites were emplaced in two different tectonic regimes separated by a 100 Ma arc-continent collision. The collision resulted from the closure of the Bisbee–Arperos seaway, which had formed along the western North America margin at about 140 Ma (Fig. 4). That the plutons were emplaced during rapid exhumation suggested to us that the post-collisional bodies formed by some mechanism related to slab break-off (Sacks and Secor 1990; Davies and von Blanckenburg 1995). It is the depth of break-off that 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).

The process of arc-continent collision and slab failure, or break-off, involves the pulling of the leading edge of the continent beneath the arc. When the competing buoyancy forces

Fig. 7. Plutonic samples with SiO_2 >60% from the Peninsular Ranges batholith plotted on five discrimination diagrams modified from Hildebrand and Whalen (2014*b*, 2017) and Whalen and Hildebrand (2019). The Nb vs. Y and Ta vs. Yb discrimination diagrams were modified from Pearce et al. (1984) by addition of fields for post-collisional and arc plutons based empirically on samples from the Peninsular Ranges batholith. ORG, within-plate granite. Alisitos volcanic arc data are generally more mafic and are from Morris et al. (2019). [Colour online.]



between the oceanic and continental lithosphere are overcome, the sinking slab tears from the lower continental plate and sinks into the mantle. Unless the tear is diachronous, the collision stops at this time, the trench dies, and the continental margin, now free of its oceanic anchor, rapidly rises thereby generating extreme exhumation rates in the collision belt. Well-understood ongoing arc-collision belts, such as Taiwan, provide a timeline of 4–5 million years for arc-continent collision in the south, slab break-off, collapse of the mountain belt in the northern part of the island, and initiation of oppositely directed subduction beneath the Ryukyu arc (Viallon et al. 1986; Suppe 1987; Lallemand et al. 2001; Huang et al. 2006; Teng 1996). In the case of the Peninsular Ranges orogen, the short time from initial collision of the arc, which had relatively thin crust, as documented by the presence of intercalated marine sedimentary rocks in the arc, to slab break-off — as well as other severe problems discussed by Hildebrand (2013, p. 82) — preclude crustal thickening by arc magmas and melting of underthrust cratonic crust, both of which are integral components to the cyclic arc model of DeCelles et al. (2009).

The recognition that the two magmatic suites were emplaced in contrasting tectonic settings led to the construction of a variety of geochemical discrimination diagrams (Fig. 7) that provide evidence for the distinction between arc and post-collisional plutons, and are especially useful where the geology is difficult, obscure, or incomplete. These discrimination diagrams were verified with Cenozoic arc and post-collisional rocks where the tectonic setting is independently known (Hildebrand and Whalen 2017; Hildebrand et al. 2018). We also devised a protocol for their use (Whalen and Hildebrand 2019), and then tested their usability with multiply deformed and metamorphosed volcanic and plutonic rocks in the Paleozoic Taconic orogen (Hildebrand and Whalen 2020). We discuss our model for the petrogenesis of these rocks following a description of the Sierra Nevada where additional data from plutons in a similar tectonomagmatic regime helps to unravel their petrogenesis.

As we describe parts of the orogen farther north, it is important to keep in mind that the best exposed cross section of the orogen is in Mexico and not all of the more northerly cross sections are as complete, or obvious, as they are complicated by

Fig. 8. Similarities along strike within the Peninsular Ranges orogen, from Mexico to Alaska, of major sedimentological, magmatotectonic, and tectonic packages arranged from west to east, along with their age constraints, where known. Note the coeval nature of most units along strike. The absence of a foreland basin north of the Lewis and Clark line in Idaho/Montana is attributed to uplift and erosion during the younger Laramide orogeny.

West → East

North ↑ South

Location	Western retroarc debris 99-83 Ma	Back-arc Reverse faults	Arc terrane 130-100 Ma	Syn-arc basin 140-100 Ma	Age of Collision	Metamorphic hinterland	Post-collision plutonism 99-84 Ma	Easterly vergent fold-thrust belt ~100 Ma	Foredeep <100 Ma
Mainland Alaska	McHugh complex	Yes	133-98 Ma Chisana	Kahiltna	103-97 Ma	amphibolite	94-88 Ma Tok-Tetlin Gardiner Crk. ?	yes	unknown
Insular Alaska	Queen Charlotte Group	Yes	Muir-Chichagof suite & Gravina	Gravina	105-95 Ma	amphibolite granulite	95-90 Ma Moth Bay & many others	yes	unknown
Coast Plutonic belt, BC	Nainaimo Group	Yes	Gambier Group Firvale & Desire plutonic suites	Gambier Group	101-97 Ma	amphibolite granulite	Ecstall & many others 99-85 Ma	yes	unknown
Cascades	Cascade River Skagit gneiss ?	NR	Chiwaukum schist	Nooksack	108-96 Ma	amphibolite	Many plutons 96-89 Ma	unknown	unknown
Idaho & Montana	unknown	NR	Little Goose Hazard Creek 120-108 Ma	unknown	100-91 Ma	amphibolite	Atlanta lobe Payette-Rat Cr. 98-84 Ma	Yes	Flint Crk. basin Frontier Fm. Bighorn basin
Nevada/UT	unknown	NR	King Lear 125-123 Ma	Newark Canyon ?	101-96 Ma	amphibolite	Many plutons 98-84 Ma	Sevier fold & thrust belt: Pavant & Nebo thrusts	Frontier Sanpete Dakota Mancos Indianola
Sierra Nevada	Eastern Great Valley Group	NR	western arc terrane & Cinko Lake arc	Cinko Lake trough	103-98 Ma	amphibolite	Sierran Crest 99-84 Ma		
Mojave Desert	unknown	NR	Delfonte volcanics 100.5±2 Ma	not recognized	100.5-98 Ma	amphibolite	Teutonia & others 98-85 Ma	New York Mtns Mezcals-Spring & Muddy Mtns	Willow Tank Baseline etc
Peninsular Ranges Mexico & USA	Valle Gp	Yes	128-100 Ma Santiago Peak & Alisitos	Bisbee-Arperos trough	103-98 Ma	amphibolite	La Posta 99-84 Ma	Yes	Cintura Mojada Mexcala

Laramide overprint

BC–British Columbia | UT–Utah | NR–Not Recognized | Crk–Creek

younger orogenic events, intrusions, or cover. Nevertheless, we find that along strike, sufficient components of the orogen exist to ascertain that it is continuous and coeval from Mexico to Alaska (Fig. 8). In most locations, several of the following features exist and collectively constitute a rationale for correlation and continuity along strike.

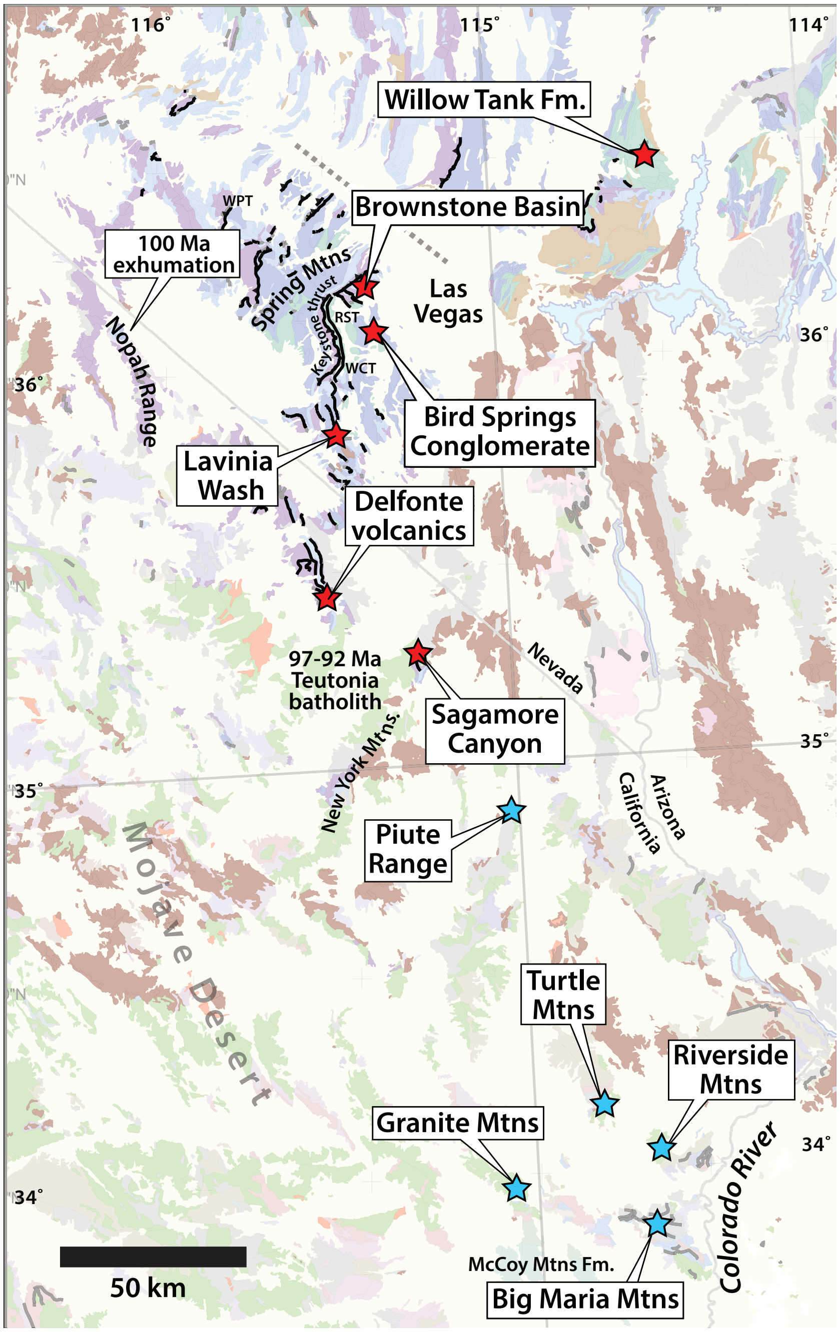
1. The occurrence of an Early Cretaceous trough, 140–100 Ma, comprising volcano-sedimentary arc successions formed on a substrate of Jurassic orogenic rocks, commonly atop Paleozoic cover.
2. A >100 Ma arc with magmatism that overlaps temporally with sedimentation in the trough and is located along the western margin of it.
3. Sedimentation within the trough that deposited different age debris adjacent to opposite sides of the basin.
4. The consilience of deformation of the volcano-sedimentary arc successions, shutdown of arc magmatism, eastward-verging thrusting, and formation of an orogenic foredeep — all at about 100 Ma.
5. Post-deformational plutons, with compositions distinct from arc plutons, and ranging in age from 99 to 84 Ma, were emplaced into an orogenic hinterland during rapid exhumation.
6. Reverse faults, typically with 6–10 km of east side up separation, formed along the western margin of the orogenic hinterland.
7. Sedimentary rocks, most commonly Cenomanian to Santonian, containing abundant post-collisional plutonic debris were shed westward into the back-arc region during exhumation of the hinterland to the east.

Whereas the trough opened along a largely Jurassic accretionary margin, it contained a wide variety of rocks ranging in age from Precambrian to Cretaceous and grouped in many ways from area to area. In some places, such as Mexico, the Guerrero terrane refers to the westernmost outboard terrane, but in other places along strike, rocks had not been grouped into older terranes and groups, or were previously part of named terranes, but were dismembered and now occur on both sides of the trough. For example, in the Canadian Cordillera, the more easterly Intermontane and westerly Insular superterranes collided during the Jurassic, but rifting during opening of the seaway at 140–135 Ma, did not occur at precisely the same location(s) as the previous suture, so although the western block was dominated by rocks of the Insular terrane, it could contain fragments of Intermontane terrane and form a new western composite terrane. The lack of recognition of this 100 Ma suture zone led to some implausible models involving reversed basins and large-magnitude strike-slip faults (Monger et al. 1994; Gehrels et al. 2009). By recognizing the existence of the Early Cretaceous seaway, we resolve these types of problems to some degree, but the problem of previously defined terranes occurring on opposite sides of the basin is an artifact of problems inherent in the existing nomenclature. To resolve these issues, we refer to all of the rocks on the outboard arc-bearing block, which appear to have formed a continuous ribbon continent, as the Peninsular Ranges composite terrane, although we still utilize the original names wherever reasonable to do so, such as with local basement-cover relations.

Mojave Desert sector

The thrust belt in Sonora can be traced northward to about the United States border where it is transected by a segment of the younger, and somewhat sinuous, Laramide orogen, which trends nearly east–west across southern Arizona and California (Hildebrand 2015). To the north, the 80–70 Ma post-deformational intrusions of the Laramide are progressively less common (Fig. 9) and the 100–85 Ma post-deformational plutons reappear to the

Fig. 9. Map modified from Wells (2016) and Hildebrand and Whalen (2017) on a geological base provided by Sue Beard (US Geological Survey) showing the location of sites near Las Vegas, Nevada, with evidence for 100 Ma thrusting as red stars, and location of 100–85 Ma plutons described in text as blue stars. WCT, Wilson Cliffs thrust; RST, Red Springs thrust; WPT, Wheeler Pass thrust. [Colour online.]



north of the Laramide McCoy Mountains Formation, and to the west within California in the Big Maria Mountains, where a 86 Ma granodiorite was folded during the Laramide orogeny (Hamilton 1964; Stone 2006). Just to the north in the Turtle and Riverside mountains, several intrusions are in the 100–85 Ma range (Allen et al. 1995). One granodioritic pluton, in the Granite Mountains, just north of Palen Pass, is undated, but cuts Jurassic rocks and generally contains a mylonitic foliation with a mineral lineation (Stone and Kelly 1989) so is likely another member of the 100–84 Ma suite. Near the northern end of the Piute Range, the 85 ± 7 Ma East Piute body is weakly to strongly peraluminous, undeformed to mylonitic, and predates the Laramide deformation (Fletcher and Karlstrom 1990; Miller et al. 1990).

Some researchers recognized the lithological similarities of the 100–84 Ma Mojave plutons (for example, Allen et al. 1995) with those of the Sierra Nevada and Peninsular Ranges batholiths and wondered why they were so far out of line with those belts. Faults or tears in the subducting plate might be responsible for apparent jumps across strike.

The mid-Cretaceous thrust belt of the US Cordillera, commonly referred to as the Sevier fold-thrust belt (Armstrong 1968), reappears in the New York Mountains of California (Burchfiel and Davis 1977), where highly strained metavolcanic rocks range in age from 98.4 to 97.6 Ma, whereas associated metasedimentary rocks of Sagamore Canyon (Fig. 9) have MDAs of 98 Ma (Wells 2016). Thrust faults cut the volcanic rocks and are cut by 90.4 ±

0.8 Ma Mid Hills monzogranite, which is one of several plutons of the 98–90 Ma Teutonia batholith (Beckerman et al., 1982; Miller et al. 2007; Haxel and Miller 2007; Wells 2016).

In the Mezcal Range to the northwest, a sequence of 100.5 ± 2 Ma basaltic lavas and epiclastic rocks overlain by plagioclase porphyritic ignimbrites and lavas known as the Delfonte volcanics (Fig. 9), was detached, folded, and transported eastward on thrust faults (Fleck et al. 1994; Walker et al. 1995) prior to the emplacement of the Teutonia batholith. Other allochthons in the area carry deformed plutons dated between 150 and 140 Ma (Walker et al. 1995).

In the southern Spring Mountains just southwest of Las Vegas (Page et al. 2005), nonmarine sedimentary and volcaniclastic rocks of the Lavinia Wash sequence (Fig. 9), interpreted as synorogenic deposits by Carr (1980), lie structurally below the contact thrust plate. A rhyolitic boulder in conglomerate of the Lavinia Wash sequence was dated at 98.0 Ma, and plagioclase within an ignimbrite in the sequence yielded a ^{40}Ar/^{39}Ar age of 99.0 ± 0.4 Ma (Fleck and Carr 1990). Two different ages of thrusts are well mapped and described in the area of the Spring Mountains, Nevada (Burchfiel et al. 1974, 1998; Axen 1987; Walker et al. 1995; Page et al. 2005), where the spectacularly exposed Keystone thrust is a classic example of a younger and “out-of-sequence” thrust (Longwell 1926; Davis 1973; Burchfiel et al. 1998).

A conglomerate unit within Brownstone Basin (Fig. 9), sits structurally beneath the Red Spring thrust and contains cobbles and pebbles apparently derived from the Wheeler Pass thrust plate to the west (Axen 1987), as well as detrital zircons as young as 103–102 Ma (Wells 2016). The Wheeler Pass thrust sheet itself (Fig. 9), where exposed in the Spring Mountains, contains evidence for exhumation during the Late Jurassic (Giallorenzo 2013), which perhaps reflects the Nevadan event; however, zircon (U–Th)/He thermochronology from the thrust sheet, where exposed in the Nopah Range to the southwest (Fig. 9), shows that exhumation started there at ~100 Ma (Giallorenzo 2013).

In both the Caborca region of Sonora and the Spring Mountains – Death Valley area west of Las Vegas, distinctive Neoproterozoic and Cambrian sedimentary rocks, such as the Noonday Dolomite, Johnnie Formation, and Stirling Quartzite, unknown from autochthonous North America, were transported eastward in allochthons, although they were originally hypothesized to be offset by the enigmatic Mojave–Sonora megashear (Stewart 2005). The Neoproterozoic successions, as well as 150–140 Ma plutons, and the 100.5 Ma Delfonte volcanics, were likely situated at or near the leading edge of the arc terrane during basin closure. However, without Lower Cretaceous cover on the eastern North American block, precisely which thrust fault marks the suture is not obvious.

Northeast of Las Vegas (Fig. 9), the upper Albian to Cenomanian Willow Tank Formation and Baseline Conglomerate, interpreted as synorogenic foreland deposits, rest unconformably on Middle Jurassic Aztec sandstone in the Valley of Fire region, and were dated as 98–96 Ma (Fleck 1970; Bohannon 1983; Bonde 2008; Pape et al. 2011). More recent studies of detrital zircons from these and other local formations — as well as zircons from plutons and volcanic rocks — bracket deformation from 102 to 96 Ma (Troyer et al. 2006; Bonde et al. 2012; Wells 2016).

Farther north in east-central Nevada, eastward-vergent thrust faults within the Garden Valley thrust system (Bartley and Gleason 1990), part of the Central Nevada fold and thrust system (Speed et al. 1988; Long 2015), are cut by the ~98 Ma Lincoln stock and the ~86 Ma Troy granite (Taylor et al. 2000). Basinal sedimentary rocks of the westerly derived Newark Canyon Formation are exposed within the Central Nevada fold and thrust belt in east-central Nevada and were deposited from about 106 Ma until just after 99 Ma (Di Fiori et al. 2020). The rocks could be a remnant of the through-going pre-collisional seaway as they appear to be too old to be part of the foredeep succession. The Nevada data are consistent with folds and thrusts active at about 100 Ma in eastern Nevada, but the northward continuation of the Sevier fold-thrust belt from the Las Vegas area lies farther east in Utah and will be examined after descriptions and discussion of the Sierra Nevada arc.

The Sierra Nevada

The geology of the Sierra Nevada is similar to the Peninsular Ranges in that it has a 130–100 Ma volcano-plutonic arc complex, built largely on Jurassic to Paleozoic basement, and situated west of a 100–82 Ma suite of dominantly granodioritic–tonalitic intrusions. One fundamental difference is located in the western Sierran foothills where at least three different arc terranes (Supplementary Fig. S2[2]), younging westward and each accreted during the Jurassic, serve to document westerly subduction, because arcs are the upper plate in collisions (Brown et al. 2011; Hildebrand 2013). Each accretionary event was followed by an interval of post-collisional plutonism that spanned several adjacent terranes (Supplementary Fig. S2[2]), which is typical for slab failure magmatism (Hildebrand and Whalen 2017).

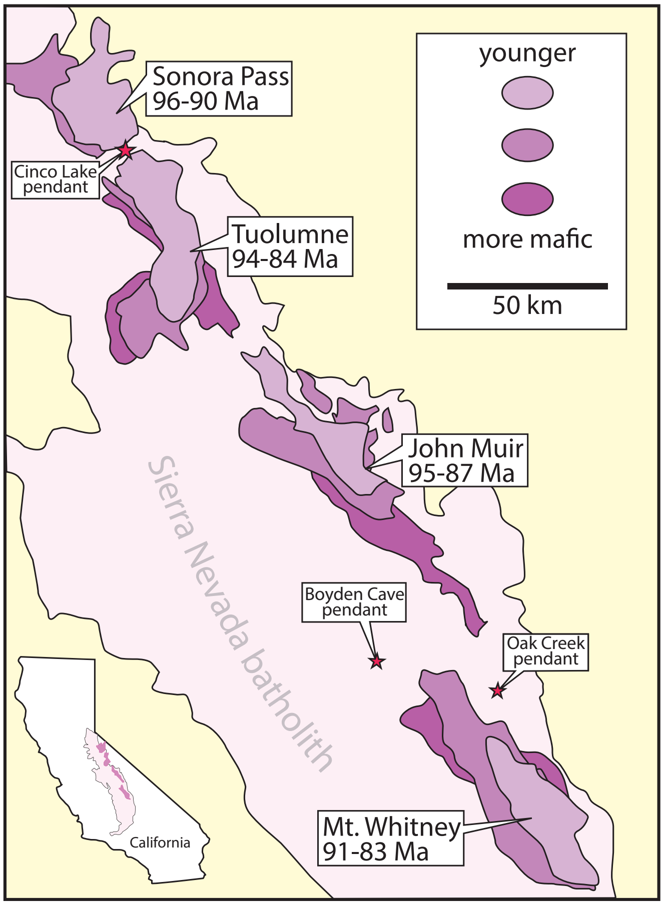
Early Cretaceous arc rocks are less abundant in the Sierra Nevada than in the Peninsular Ranges batholith, but many intrusive rocks of that age exist and are widely distributed (Bateman 1992). Perhaps the best-studied example of Early Cretaceous plutonic rocks was by Clemons-Knott, who mapped a group of ~120 Ma ring complexes, known as the Stokes Mountain complex, and produced geochemical analyses and isotopic data (Clemens-Knott 1992; Clemens-Knott and Saleeby 1999). Other examples of 130–100 Ma rocks occur as roof pendants within the batholith.

Saleeby et al. (1990) described the geology of the Boyden Cave and Oak Creek pendants (Fig. 10; Supplementary Fig. S3[2]), both located in Sequoia – Kings Canyon National Park. In the Boydon Cave pendant, a variety of <110 Ma metavolcanic and metasedimentary rocks — as well as Paleozoic and Jurassic metasedimentary rocks — are intruded by a number of highly strained 103 Ma hypabyssal intrusions and by post-deformational plutons at about 100 Ma. The Oak Creek pendant, located to the west on the Sierran Crest, comprises Jurassic metavolcanic rocks overlain with angular unconformity by deformed and metamorphosed <110 Ma basaltic to rhyolitic tuff, breccia, and lava, cut by hypabyssal sills, and intruded by plutons dated at 106–105 Ma. Chen and Moore (1982) obtained a slightly discordant U–Pb age on zircon of 103–100 Ma from an leucogranite body that cuts the sequence.

Memeti et al. (2010), in trying to define the location of the cryptic Snow Lake shear zone of Lahren and Schweickert (1989), collected and analyzed detrital zircons from several pendants, two of which are applicable to our study. The first is at Cinko Lake, located to the northeast of the Snow Lake pendant, where a sequence of metavolcanic and metasedimentary rocks, folded about northwest axes, have MDAs of 103 Ma; were intruded by a 101.8 ± 0.2 Ma pluton, also metamorphosed and deformed; and cut by the voluminous post-deformational 94–84 Ma Tuolumne intrusive complex and the 96 Ma Kinney Lakes granodiorite of the Sonoran Pass intrusive complex (Fig. 11). Just a few kilometres to the southeast and along the eastern contact of the Tuolumne complex, Cao et al. (2015) obtained an MDA of 117.4 ± 2 Ma from volcanogenic sandstones cut by a 97.4 ± 0.4 Ma pluton. Deformed metasedimentary rocks in both the Strawberry Mine and Cinko Lakes pendants produced U–Pb zircon age peaks of 117, 116, 112, 108, 103, 99, and 96 Ma, consistent with local Aptian–Albion arc sources (Memeti et al. 2010). We call the magmatic and related sedimentary rocks the Cinko Lake arc trough after dated exposures at Cinko Lake.

Farther south in the Mineral King pendant (Supplementary Fig. S3[2]), Sisson and Moore (2013) report U–Pb zircon ages for metarhyolitic tuffs and andesitic lavas of 111–102 Ma, with older metarhyolites and siliceous sills ranging back to 140 Ma. They also reported that a 98 Ma granodiorite cuts vertical metasedimentary rocks, which are also cut by isoclinally folded aplites, one of which produced a U–Pb zircon age of about 98 Ma.

Fig. 10. Sketch map showing four post-collisional centered complexes of the Sierra Nevada. These are only a few of the post-collisional plutons. See Supplementary Fig. S3[2] for a more detailed view of the southern sector of the batholith. Location of Fig. 11, Cinco Lake pendant, as well as location of Boyden Cave and Oak Creek pendants, are starred. Modified from Davis et al. (2012). [Colour online.]



Near the southern end of the batholith, where it outcrops along the Kern Canyon fault (Supplementary Fig. S3[2]), the Erskine Canyon sequence comprises 105–102 Ma siliceous ignimbrites and subordinate intermediate lava flows, along with associated hypabyssal rocks (Saleeby et al. 2008). These authors also document several plutons with ages ranging from 105 to 103 Ma cropping out to the west and a 98 Ma granodiorite to the east. Even farther south, in the Tehachepi Mountains, Wood (1997) mapped and dated by U–Pb zircon methods, several isoclinally and recumbently folded gabbroic, dioritic, and tonalitic plutons of the Tehachapi intrusive complex, which yielded ages of about 100 Ma, and sit close to the Oaks metavolcanics (Supplementary Fig. S3[2]) dated at 103 Ma (Chapman 2012). Thus, widespread pendants within the main Sierran block consistently contain evidence for the existence of Early Cretaceous volcanic and epiclastic rocks that were deformed at about 100 Ma prior to emplacement of post-deformational plutons as old as 98–96 Ma.

In the northern Sierra (Supplementary Fig. S3[2]), northwest of Lake Tahoe, Lower to Upper Jurassic metavolcanic and metasedimentary rocks of the Eastern Mesozoic belt (Christe and Hannah 1990) are unconformably overlain by a sequence of Barremenian prehnite–pumpellyite grade metasedimentary and metavolcanic rocks collectively known as the Evans Peak sequence (Christe 2011). Lower units in the sequence comprise chert-pebble conglomerate and quartzose sandstones, which are overlain by coarse-grained plagioclase-rich sandstone, tuffaceous shales, green siliceous tuff, volcanic cobbly conglomerate and ~128 Ma ignimbrites, overturned beneath the west-dipping Taylorsville fault, which places Paleozoic rocks of the northern Sierra terrane atop the early Cretaceous sequence (Moores and Day 1984; Christe 2010, 2011). Although we only have a maximum age, it is possible that the Taylorsville thrust is a 100 Ma structure and the rocks of the Evans Peak sequence might be the oldest known supracrustal rocks of the Early Cretaceous Cinco arc and trough in the Sierra Nevada. Additional studies in the area are warranted.

At the northernmost end of the White Mountains, west of White Mountain peak, (Supplementary Fig. S3[2]) is an overturned section of metasedimentary and volcaniclastic rocks, containing detrital zircons derived mostly from local 120–115 Ma volcanic sources, that sit beneath a low angle fault carrying the Jurassic Barcroft pluton (Scherer et al. 2008). If the entire section, including the Jurassic rocks in the upper plate is overturned, then the fault is likely to be a normal fault; otherwise, it is, as queried by Scherer et al. (2008), a west-vergent thrust. Whatever its kinematics, this low-angle fault is transected by a body dated by U–Pb to be 100 ± 1 Ma (Hanson et al. 1987).

Although the age of deformation is tightly constrained by metasedimentary, metavolcanic, and plutonic rocks to be about 100 Ma, another line of evidence supports both age and subduction polarity in the Sierran sector of the Peninsular Ranges orogen.

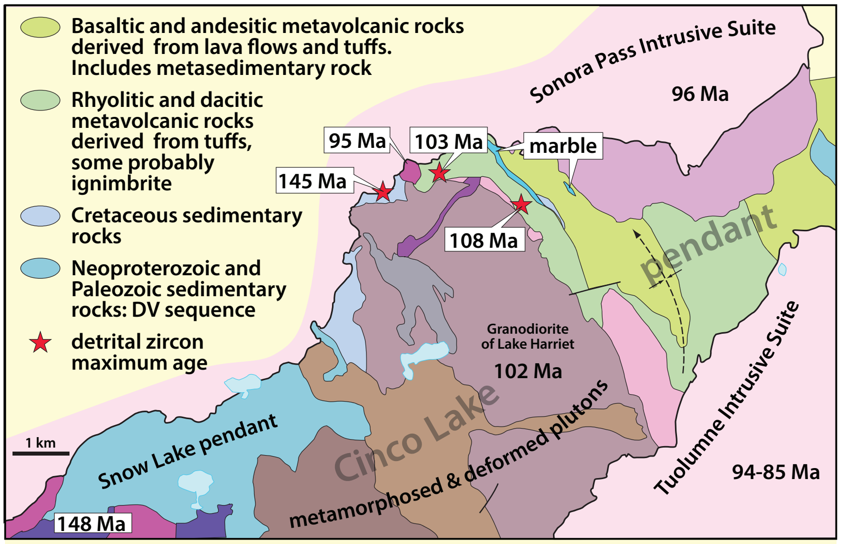
Chin et al. (2013) document granulite quartzite xenoliths (T = 700–800 °C and P = 7–10 kbar), brought to the surface in a Miocene diatreme of the central Sierra Nevada, that contain zircons with Proterozoic and Archean cores, but with rims that yield a mean metamorphic age of 103 Ma. They interpreted the Proterozoic and Archean U–Pb crystallization ages found in the cores of detrital zircon grains, and Hf isotopic ratios like those from Proterozoic basement east of the Sierra Nevada, as the vestiges of rocks deposited along the North American passive margin that were transported deep beneath the arc where they were metamorphosed at about 100 Ma. As the North American platform is unknown west of the Sierra Nevada, we infer that the rocks were underthrust beneath the Cinko Lake arc from the east.

From the above, it appears that the age of deformation in rocks of the Sierran batholith is coeval with rocks of the Peninsular Ranges batholith (Memeti et al. 2010; Chin et al. 2013), as well as easterly vergent thrust faults located in eastern California and in the Spring Mountains of Nevada discussed earlier. By analogy, we suggest that within the Sierra Nevada, subduction of the leading edge of North America beneath the Cinco Lake arc during closure of the basin led to break-off of the North American oceanic lithosphere, and its descent, along with perhaps part of the rift complex, into the mantle. Thus, even though the Cretaceous passive margin succession on the eastern side of the basin is not exposed, the overwhelming geological and temporal similarities lead us to conclude that the Cretaceous Sierra Nevada and broader Great Basin are part of the Peninsular Ranges orogen. We now briefly describe and examine the post-deformational magmatic suite within the Sierra Nevada to demonstrate that rocks of the suite are compositionally and temporally similar to the post-collisional La Posta plutonic suite, located farther south. We then utilize the geochemical and isotopic variations, as well as the timing from both suites, to constrain the origin of post-collisional magmatism by slab break-off.

The post-collisional Sierran Crest magmatic suite

Largely outcropping east of the 130–100 Ma Cinco arc assemblage, dozens of post-deformational 99–84 Ma tonalitic–granodioritic plutons (Supplementary Fig. S3[2]) are known collectively as the Sierran Crest magmatic suite (Coleman and Glazner 1998). Just as early researchers recognized that there were two intrusive suites in the Peninsular Ranges batholith, researchers in the Sierra Nevada

Fig. 11. Geological sketch map of the Snow Lake and western Cinco Lake pendant (Lahren et al. 1990; Wahrhaftig 2000; Memeti et al. 2010; Leopold 2016), showing ages of folded metavolcanic, metaplutonic, and metasedimentary rocks and their truncation by younger post-collisional plutonic complexes, which constrain the age of deformation to be between 102 and 96 Ma. DV, Death Valley. [Colour online.]



data from Lahren et al (1990), Wahrhaftig (2000), Memeti et al (2010), Leopold (2016)

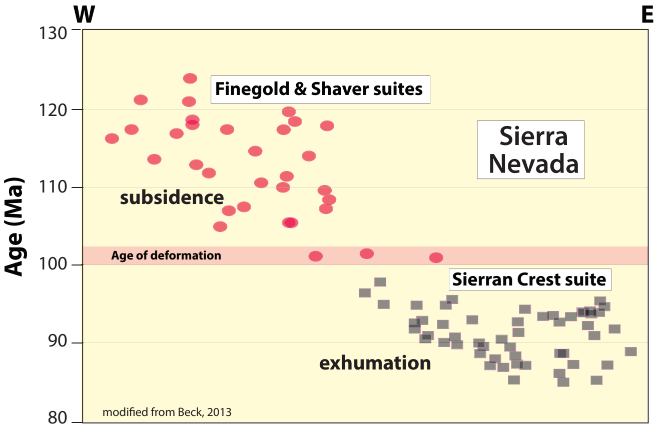
understood that the more mafic plutons within the Sierra Nevada batholith occur west of more intermediate-composition bodies (Lindgren 1915; Buddington 1927; Moore 1959; Moore et al. 1961). Many researchers have since confirmed that the intrusions of the Sierra Nevada are readily divisible into older western and younger eastern sectors (Fig. 12) on the basis of geochemistry, magnetic susceptibility, age, and both radiometric and stable isotope ratios (Chen and Tilton 1991; Bateman et al. 1991; Kistler 1990, 1993; Saleeby et al. 2008; Lackey et al. 2008, 2012*a*, 2012*b*; Chapman et al. 2012). But, like rocks of the Peninsular Ranges, the deformation that occurred between the two magmatic suites went largely unrecognized, or was considered to be related to the emplacement of the plutons (Bateman 1992).

The post-collisional plutonic rocks within the Sierran Batholith range in composition from gabbro to leucogranite, but the most common rocks are tonalite, granodiorite, and granite (Bateman and Wahrhaftig 1966; Bateman et al. 1963; Bateman 1992; Ross 1989). In general, the hundreds of mesozonal intrusions within the post-100 Ma composite batholith have sharp contacts with one other, or are separated by minor screens of older metamorphic rock (Bateman 1992; Bartley et al. 2012).

Bateman (1992) distinguished several intrusive suites of cogenetic, but not necessarily comagmatic, plutons that have distinctive petrographic, compositional, and textural characteristics, as well as spatial proximity. The best known are the <100 Ma compositionally zoned complexes of the Sierran Crest magmatic suite (Coleman and Glazner 1998), such as the Tuolumne intrusive suite, the Mount Whitney Suite, the John Muir suite, and the Sonora Pass intrusive suite (Fig. 10), all of which consist of seemingly nested units that are progressively younger and more leucocratic inward (Calkins 1930; Leopold 2016; Bateman and Chappell 1979; Huber et al. 1989; Hirt 2007). Plutons of the Sierran Crest magmatic suite, were emplaced along the eastern Sierran crest between 98 and 84 Ma, and many are characterized by an outer, older tonalite and granodiorite in sharp contact with an inner younger hornblende porphyritic granodiorite, and cored by even younger K-feldspar megacrystic granite and granodiorite (Bateman 1992; Coleman and Glazner 1998; Hirt 2007).

Besides a spatial centering, it is unclear whether or not individual plutons within any of the so-called "nested" complexes are related, other than by source. Originally, Bateman and Chappell (1979) argued that the compositional zoning within the Tuolumne intrusive complex resulted from crystal fractionation of a single voluminous influx of magma. However, subsequent isotopic work (Kistler et al. 1986) ruled out this possibility, and U–Pb zircon age determinations demonstrated that the complex was emplaced over 10 million years from 95 to 85 Ma (Coleman et al. 2004) thereby negating the two-component mixing scheme favoured by Kistler et al. (1986). Instead, Coleman et al. (2004) argued for incremental emplacement of stacked intrusive sheets.

Fig. 12. West–east section vs. age showing U–Pb zircon ages for plutons in the central Sierra Nevada (from Beck 2013) and their temporal relation to the ca. 100 Ma deformational event. Note the similar ages and relations as plutons in the Peninsular Ranges batholith in Fig. 5.



modified from Beck, 2013

Geochemistry and origin of the post-collisional plutons

Since the early days of plate tectonics, most researchers have developed models for the North American Cordillera where the older arc-related magmatism developed above an eastwardly dipping subduction zone and that shallowing subduction forced arc magmatism to prograde eastwardly into the western margin of North America, where it interacted with, and assimilated, older cratonic crust (Bateman and Clark 1974; Kistler and Peterman 1978; Kistler 1990; Gastil et al. 1981; Saleeby et al. 1990; Walawender et al. 1990; Chen and Tilton 1991; Johnson et al. 1999; Todd et al. 2003; Grove et al. 2003; Ortega-Rivera 2003; Ducea and Barton 2007; Paterson et al. 2014; Schmidt et al. 2014; Cao et al. 2015; Ducea et al. 2015).

Our analysis challenges this paradigm and proposes that the arc and post-collisional suites were derived from the mantle directly, without extensive crustal interaction (Hildebrand and Whalen 2017; Hildebrand et al. 2018). Furthermore, these data unexpectedly suggested to us that post-collisional magmatism was likely responsible for producing at least half of all continental crust and by doing so resolves the long-standing crustal composition paradox (Rudnick 1995).

On our discrimination diagrams, the Sierra plutons plot in the same fields as those of the rocks from the Peninsular Ranges (Fig. 13, Supplementary Fig. S4[2]). Although arc and post-collisional bodies are superficially similar in field characteristics, there are consistent major and minor geochemical differences between the >100 Ma arc and <100 Ma post-collisional suites (Hildebrand and Whalen 2014*b*). For example, most rocks of the La Posta and Sierran Crest magmatic suites contain 60%–70% SiO_2 whereas the arc suite displayed a continuous range from basalt to rhyolite (Fig. 14). Relative to the arc rocks, members of the La Posta – Sierran Crest suites were generally more enriched in incompatible elements, as well as Sr, Na, and Nb, have minor to negligible Eu anomalies, and are depleted in Y and heavy rare earth elements as recognized over 30 years ago by Gromet and Silver (1987). They proposed that, although the western pre-100 Ma rocks are typical arc rocks, the eastern, post-100 Ma plutons were derived from a plagioclase-free, garnet-bearing source — most likely eclogite or metabasalt. They suggested that altered basaltic magma ponded at the base of the crust and thickened it, only to be remelted later to create the post-100 Ma suite; although the process by which basalts might have been emplaced at the base of the arc crust prior to arc magmatism in the east remained unanswered. While certainly attractive, models that involve melting of basalt accumulated at the base of the arc are unsatisfactory because the post-100 Ma rocks are post-tectonic, and at the time of that magmatism, the leading edge of the continental margin had already been subducted beneath the arc, effectively isolating the arc from the mantle. And the switchover to post-collisional magmatism happened far too rapidly for accumulations of basalt to build up, as even the youngest arc rocks are intercalated with marine sedimentary rocks in both the Peninsular Ranges (Allison 1974; Phillips 1993; Busby et al. 2006) and Sierra Nevada (Nokleberg 1981; Saleeby et al. 2008; Memeti et al. 2010).

Putirka (1999) modeled aggregate melts using polybaric partial melting of mantle rocks transported from their source to the base of the lithosphere and found that Sm/Yb ratios increases with depth of melting in peridotite, eclogite, and garnet pyroxenite, as well as with greater lithospheric thickness. On a La/Sm vs. Sm/Yb diagram (Fig. 15), slab failure suites consistently have higher Sm/Yb than arc suites, indicative of initial melting at greater depths, which led us to test and utilize this diagram as another discriminator between the two suites, with a Sm/Yb boundary of 2.5.

Isotopic constraints

Lackey et al. (2008) showed that intrusions of the post-100 Ma Sierran Crest magmatic suite had $\delta^{18}O_{zircon}$ within, and close to, the range of mantle $\delta^{18}O_{zircon}$ values. For example, Tuolumne plutons have $\delta^{18}O_{zircon}$ ratios of 6.0‰–6.6‰, Mount Whitney zircons are 5.67‰–5.90‰, and other intrusive bodies emplaced at 96 Ma range as low as 4.21‰. The sub-mantle values probably represent melting of hydrothermally altered rocks that had previously interacted with low $\delta^{18}O$ meteoric water at high temperature (see Bindeman 2008). Overall, these data suggest that the

Fig. 13. Nb vs. Y discrimination diagram from Hildebrand and Whalen (2017) for various Sierra Nevada and northwestern Nevada plutonic suites: pre-collisional 120 Ma Sierran Stokes Mountain complex arc rocks (Clemens-Knott 1992), 94–84 Ma postcollisional Tuolumne intrusive suite (Memeti 2009), Sahwave intrusive suite of northwestern Nevada (Van Buer and Miller 2010), and Onion Valley hornblende gabbro (Sisson et al. 1996) plus northern Nevada plutonic rocks (du Bray 2007). WPG, within-plate granite; ORG, ocean-ridge granite. [Colour online.]

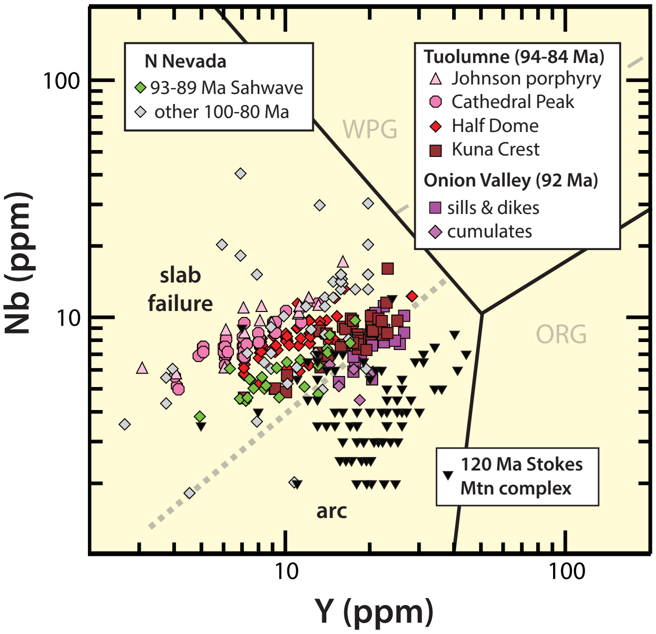


Fig. 14. Representative samples from the arc and post-collisional plutonic suites from the Peninsular Ranges and Sierra Nevada plotted on the normative Q′ vs. ANOR classification diagram (Streckeisen and LeMaitre 1979). We use the Whalen and Frost (2013) compositional trends. Note that the plutons of the Peninsular Ranges arc define the calcic trend, as do the Sierran arc samples, and both extend from granite to gabbro, whereas the post-collisional plutonic suites have more limited ranges of silica and tend to be more alkalic. [Colour online.]

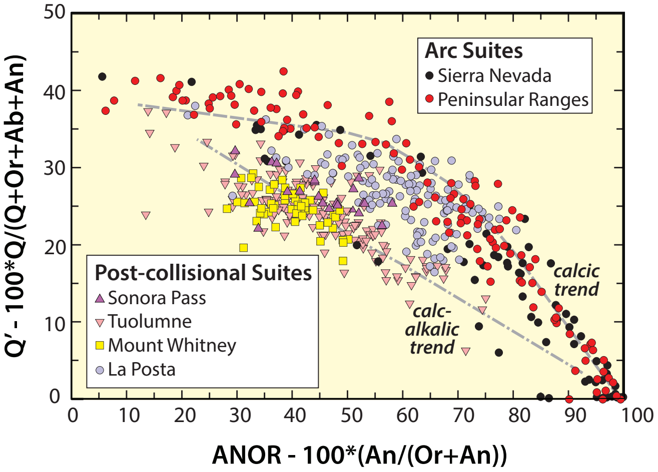
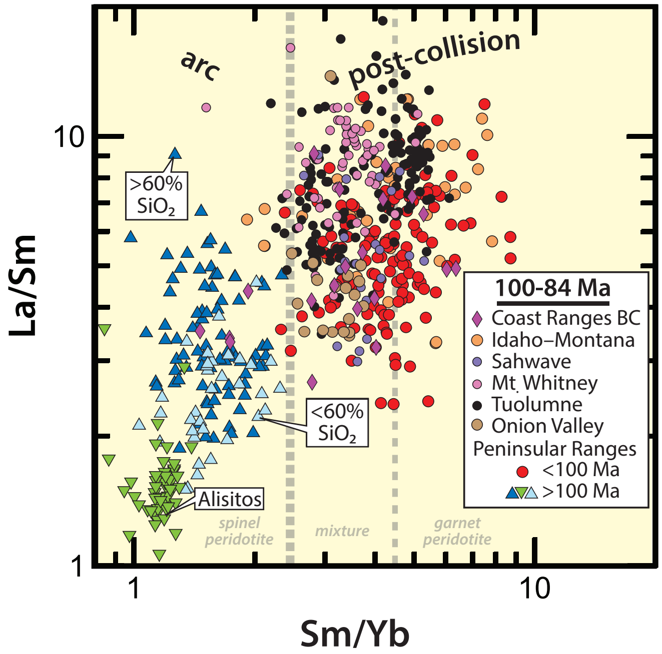


Fig. 15. Rocks from both pre- and post-100 Ma suites from the Peninsular Ranges batholith plotted in La/Sm vs. Sm/Yb space. Sm/Yb ratios are one measure of partial melting depth in the mantle (Putirka 1999). Rocks older than 100 Ma have Sm/Yb values <2.5, whereas younger rocks have Sm/Yb >2.5. The differences presumably reflect depth of melting of the original source magmas and thus whether garnet was stable in the source. According to Putirka (personal communication, 2016), partial melts of spinel peridotite should produce more melt due to larger degrees of partial melting than the deeper garnet peridotites, most partial melts of spinel peridotite will have Sm/Yb less than ~2.5. Based on values from hundreds of younger arc rocks from the GEOROC database, Hildebrand and Whalen (2017) found Sm/Yb = 2.5 to be an effective dividing line between arc and post-collisional rocks. [Colour online.]



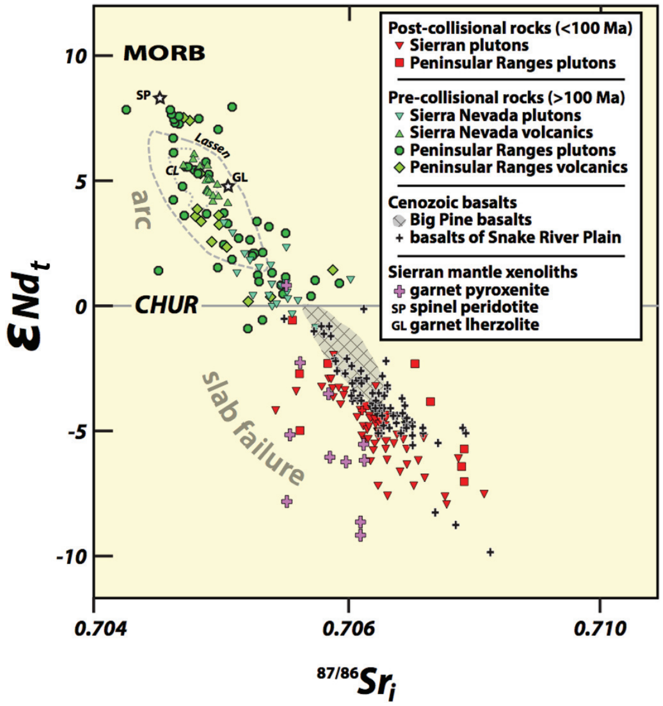
magmas were dominantly mantle derived but with some contamination by source rocks that had previously interacted with hot meteoric water.

Plutonic rocks of the post-100 Ma La Posta suite in the Peninsular Ranges batholith have heavier whole rock $\delta^{18}O$ with values between 8‰ and 11‰ (Taylor and Silver 1978). These values led Lackey et al. (2008) to argue that relatively young, hydrothermally altered oceanic crust was the most plausible source of the magmatism as hydrothermally altered, oceanic basalt has whole rock $\delta^{18}O$ ~10‰ (Eiler 2001; Bindeman et al. 2005).

Some of the most obvious differences between the arc and post-collisional magmas are their different initial Nd and Sr isotopic ratios in that the post-collisional rocks typically have negative εNd_T and $^{87}Sr/^{86}Sr_i > 0.706$, whereas the arc rocks have positive εNd_T and less evolved $^{87}Sr/^{86}Sr_i$ (Fig. 16). As mentioned earlier, the more evolved ratios are classically interpreted to represent assimilation of continental crust as the subducted slab shallowed (Kistler and Peterman 1978; DePaolo 1980, 1981; Bateman 1992; Ducea and Barton 2007; DeCelles et al. 2009), but additional data suggest another plausible source.

Mid-Cretaceous mantle-derived ~100 Ma pyroxenite xenoliths carried to the surface by Cenozoic basaltic magmas in the Sierra Nevada have dominantly mantle $\delta^{18}O$ values (Lackey et al. 2008; Ducea and Saleeby 1998), but many also have negative $\varepsilon Nd_{(0)}$ and $^{87}Sr/^{86}Sr_i > 0.706$ (Fig. 16). Both the plutons and the pyroxenite xenoliths also have Nd and Sr isotopic values similar to much younger basalts widely erupted in western North America (Fig. 16), including those of the <17 Ma Snake River Plain (Hanan et al. 2008) and the 44–7 ka Big Pine volcanic field, erupted along the eastern Sierran fault scarps (Blondes et al. 2008; Ormerod et al. 1991). Three-component isotopic mixing models, utilizing (1) the oceanic island basalt–like Steens–Imnaha lava, erupted west of the inferred continental edge, to represent the asthenospheric (Yellowstone plume) component, (2) old lithosphere like that of the Wyoming craton, and (3) younger Paleoproterozoic-like lithosphere, show that >97% of the variability can be accounted for by progressive incorporation of older subcontinental mantle lithosphere (SCLM) eastward along the Yellowstone hot spot track (Jean et al. 2014). Thus, we infer that the Sr and Nd isotopic ratios of the post-100 Ma plutonic rocks of the Sierra Nevada and Peninsular Ranges batholiths were derived from fractional melting of old, enriched SCLM.

Fig. 16. εNd_T vs. $^{87/86}Sr_i$ plot of various arc and slab failure plutonic and volcanic suites of the Peninsular Ranges and Sierra Nevada compared with some Cenozoic basalts of western North America (modified from Hildebrand and Whalen 2017), illustrating the isotopic differences between arc suites and slab failure suites and the isotopic similarities of the Peninsular Ranges and Sierran post-collisional slab failure suites with basalts from the Snake River Plain (Jean et al. 2014; Hanan et al. 2008) and Big Pine volcanic field (Blondes et al. 2008). Fields for two Cascade arc volcanoes (CL, Crater Lake and Lassen) from Bacon et al. (1994), Sierran mantle xenoliths from Ducea and Saleeby (1998). CHUR, chondritic uniform reservoir. [Colour online.]



Other post-collisional suites, such as the 100–85 Ma plutons within the Coast Range batholith of British Columbia have positive εNd_T and $Sr_i < 0.704$ (Girardi et al. 2012; Wetmore and Ducea 2011) similar to Steens basalt (Camp and Hanan 2008), but contain typical slab failure trace element signatures (Hildebrand and Whalen 2017), so apparently do not have old, enriched SCLM beneath them.

The contrasting isotopic signatures of arc and post-collisional magmatism can be explained by a scenario in which the arc magmas rose through juvenile arc lithosphere, and so exhibit non-radiogenic values. However, after collision subcontinental mantle typically belongs to the lower plate, which, if cratonic, isolates the arc from its formerly subjacent mantle. Thus, magmas triggered by slab failure may have very different (more radiogenic) isotopic ratios because enriched mantle lithosphere was pulled beneath the arc just prior to slab failure. Likewise, where both upper and lower plates are young, they both should exhibit non-radiogenic isotope ratios (Hildebrand et al. 2018).

Geochemistry and isotopic analyses suggest that pre- and post-collisional magmas were derived from two different sources at different depths as previously envisioned for the Peninsular Ranges by Gromet and Silver (1987). They also noted, as have Girardi et al. (2012) in the Coastal batholith of British Columbia, that the post-collisional rocks have minor to negligible Eu anomalies, which is the general case for post-collisional slab-failure-derived magmas (Hildebrand and Whalen 2014*b*, 2017). The lack of a Eu anomaly suggests the absence of residual plagioclase in the source.

Hildebrand and Whalen (2017) showed that most slab window adakitic rocks have trace element concentrations and ratios similar to slab failure rocks with mantle-like Sr and Nd isotopic concentrations, except for those of western North America, which have isotopic compositions typical of the Snake River Plain, Sierran Crest magmatic suite, and the Big Pine volcanic field. These results support a slab failure model that involves melting of the oceanic slab at depths sufficient for partial melting of garnetiferous, plagioclase-free rocks to produce the observed trace element profiles in both adakites and slab failure rocks, as well as the unradiogenic Sr and radiogenic Nd ratios in regions without old, enriched SCLM.

In regions where there was enriched SCLM, we found that Nd and Sr isotopes were more evolved so we suggested that the rising magmas fractionally melted the SCLM to produce the more evolved isotopic signatures, as well as the general lack of correlation between silica and incompatible elements (see Supplementary Fig. S5[2]; Hildebrand and Whalen 2017; Hildebrand et al. 2018).

Great Valley Group

Although the Sierra Nevada is characterized by voluminous 130–100 Ma arc magmatism, no temporally equivalent arc debris occurs in the adjacent Great Valley Group located on the western side of the arc terrane, and in fact, there are no Early Cretaceous sedimentary rocks known even in drill core from the eastern Central Valley of California (Ojakangas 1968; Reid 1988; DeGraaff-Surpless et al. 2002; Orme and Graham 2018). Additionally, rocks of the Great Valley Group and their basement along the western margin of the Central Valley (Constenius et al. 2000) show no evidence of deformation related to the Nevadan orogeny (Wright and Wyld 2007), or the 100 Ma deformational event of the Sierra Nevada (Hildebrand 2013). These observations are consistent with the model of Wright and Wyld (2007) in which the western Great Valle Group, Coast Ranges ophiolite, and the Early Cretaceous part of the Franciscan complex migrated into the area at about 100 Ma.

Exhumation of the hinterland in the Sierra Nevada region and emplacement of plutons of the Sierran Crest magmatic suite appear to have been contemporaneous with deposition of thick Cenomanian–Turonian clastic successions to the west (Mansfield 1979; Surpless et al. 2006) just as in the Peninsular Ranges. This same contrasting feature occurs at a few localities to the north, such as the Coast Ranges batholith of British Columbia and Wrangellia in south-central Alaska (Hildebrand and Whalen 2021 (this issue)). Examination of the 12-4 Ma Central Range orogeny of Papua, New Guinea (Cloos et al. 2005), shows that about 25 km of denudation occurred on the northern slope of the highest mountains and plateaux (Fig. 17), which rise to nearly 5 km elevation and contain many post-collisional intrusions rich in Cu and Au (Doucette 2000; McMahon 2000, 2001; Cloos and Housh 2008). Sediment transport was into the back-arc region.

The suture zone preserved?

The southernmost part of the Sierran batholith in the Tehachapi and San Emigdio mountains, which abut the San Andreas and Garlock faults to the south (Supplementary Fig. S3[2]), is dominated by amphibolite- and granulite-grade metamorphic rocks with paleopressures as high as 10–11 kbar (Pickett and Saleeby 1993; Chapman et al. 2012). Structurally beneath the high-grade rocks (Fig. 18), which have ages ranging from 136 to 101 Ma, and separated from them by the Rand fault, is the San Emigdio schist (Chapman and Saleeby 2012), which contains detrital zircons ranging mostly from 120 to 100 Ma (Jacobson et al. 2011). The few zircons younger than 100 Ma appear to be metamorphic (A. Chapman and C. Jacobson, personal communication, 2020), which indicates that, at an age of 100 Ma, the San Emigdio schist is older than, and unrelated to, the Pelona–Orocopia–Swakane schists elsewhere. Precambrian detrital zircons are plentiful within the schist, comprising ~25% of the zircons in one sample (Fig. 18), which suggests that these rocks were deposited within the seaway and do not represent material deposited on the open seafloor to the west, where there was no likely source for Precambrian zircons.

According to Chapman et al. (2011), the San Emigdio schist comprises over 75% interbedded metapsammite and metasandstone with much lesser amounts of metabasalt and talc–actinolite schist. They documented peak metamorphic assemblages as garnet + plagioclase + biotite + quartz ± muscovite ± kyanite with limited melt pods near the top. Paleopressures range from 11 to 9 kbar and paleotemperatures were inverted, ranging from 600 °C near the exposed base to 700 °C at the top.

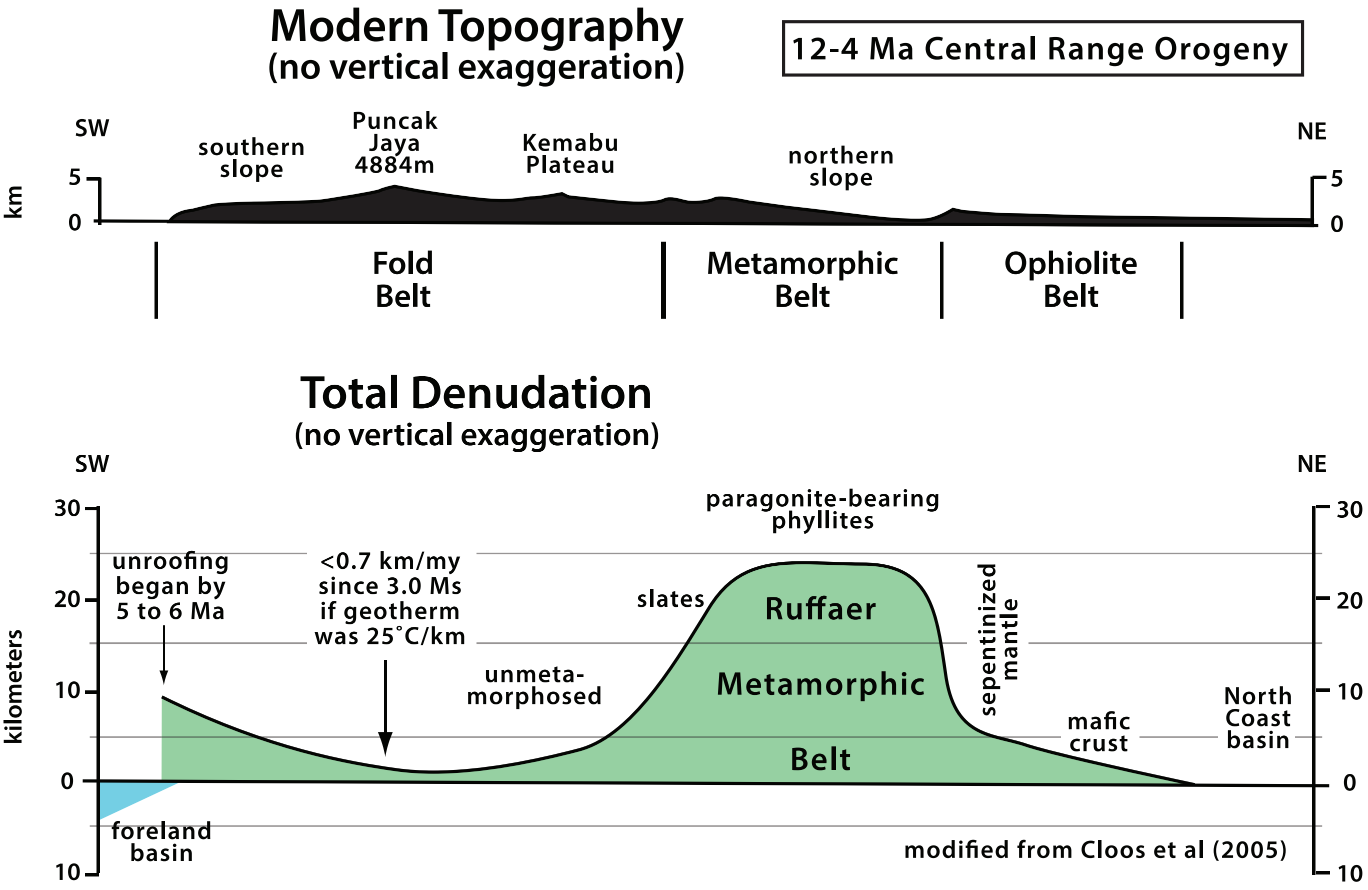
The Antimony Peak tonalite sits above the Rand thrust with paleopressures of 10 kbar and magmatic epidote (Chapman et al. 2011). U–Pb analyses of zircons revealed 136–135 Ma cores surrounded by 103–99 Ma rims (Chapman et al. (2012), which along with the results of Chin et al. (2013) from granulite xenoliths, described earlier, constrain peak metamorphism at about 101–100 Ma.

The schist structurally overlies a terrane comprising 5–10 km long slabs of marble, quartzite, and metasandstone, as well as a variety of schists (Chapman and Saleeby 2012). Their geologic map (Fig. 18) lists the large 92–88 Ma Lebec Granodiorite as having paleopressures of 3 kbar, which implies a high rate of exhumation, one similar to that seen elsewhere along the orogen (Hildebrand and Whalen 2021, this issue). Chapman et al. (2011) argued that deposition, deep subduction, and exhumation to mid-crustal depths took <3 million years, whereas Chapman et al. (2012) suggested exhumation of rocks from 9–11 kbar at 98 Ma to mid-crustal levels by about 95 Ma. These exhumation rates are typical of slab break-off at the end of collision when the cratonic lower plate is freed of its oceanic anchor and rises rapidly to exhume the collision zone (Hildebrand and Whalen 2017).

Considering the above, we suggest that the San Emigdio Mountains exposes an oblique north–south section through the 100 Ma suture consisting of (1) lower plate North American Paleozoic basement slabs, some as long as 10 km, of quartzite, metasandstone, schist, and marble, upward through (2) the San Emigdio schists, likely remnants of material eroded from the arc and deposited within the seaway, and finally up into (3) the lowermost part of the upper-plate arc, which expose abundant Early Cretaceous plutons and gneisses, with some as young as 101 Ma, at ~11 kbar paleopressures. By at least 92 Ma, rocks of the suture were exhumed to 3 kbar.

In either our collisional model or in the eastward subduction and underplate model presented by Chapman et al. (2012), the ~10 kbar paleopressures for the schist correspond to the base of the Sierran crust at 100 Ma. Thus, at that time the crust

Fig. 17. Modern topography and differences in depth of denudation in the Central Range orogen of Papua, New Guinea, modified from Cloos et al. (2005), and illustrating ∼25 km exhumation on the opposite side of the orogen from the foreland. Large rivers have transported most debris northward to the North Coast basin because the nearly 5 km high Central Range blocks drainage to the south. We see this as a more modern example of the post-collisional sedimentation in the back-arc region, such as the <100 Ma Valle and Great Valley rocks, caused by slab break-off and consequent exhumation of the hinterland belt. [Colour online.]



beneath the Sierra Nevadan arc was about equal to, or slightly less than, the average thickness of continental crust (Hacker et al. 2015). This negates models that require a thickened arc crust to remove fractionated cumulates formed during arc magmatism (Ducea and Saleeby 1998; DeCelles et al. 2009) and supports the Hildebrand et al. (2018) model that most continental and oceanic arcs are built on normal to thinned crust.

The San Emigdio collisional suture and surrounding rocks were rotated clockwise from a more northerly orientation after 80 Ma (Kanter and McWilliams 1982) and the entire southerly Sierran Nevada batholith and basal suture were uplifted during the east–west-trending Late Cretaceous Laramide orogeny (Wood and Saleeby 1998; Chapman et al. 2012), which we have argued was also collisional (Hildebrand and Whalen 2017; Hildebrand 2015). When displacements on the faults of southern California are restored (Powell 1993; Nourse 2002), the similar Pelona–Orocopia schists form an east–west band extending across much of southern California and western Arizona, and so they might in some cases represent suture zone rocks rather than the product of east-directed flat subduction as commonly hypothesized (Grove et al. 2003; DeCelles et al. 2009; Jacobson et al. 2011; Chapman et al. 2011, 2012).

Sevier fold-thrust belt

If the complex zone described above represents the basal suture of the Sierran arc system, then where to the east does it surface? In other words, where is the easternmost exposure of the contact zone?

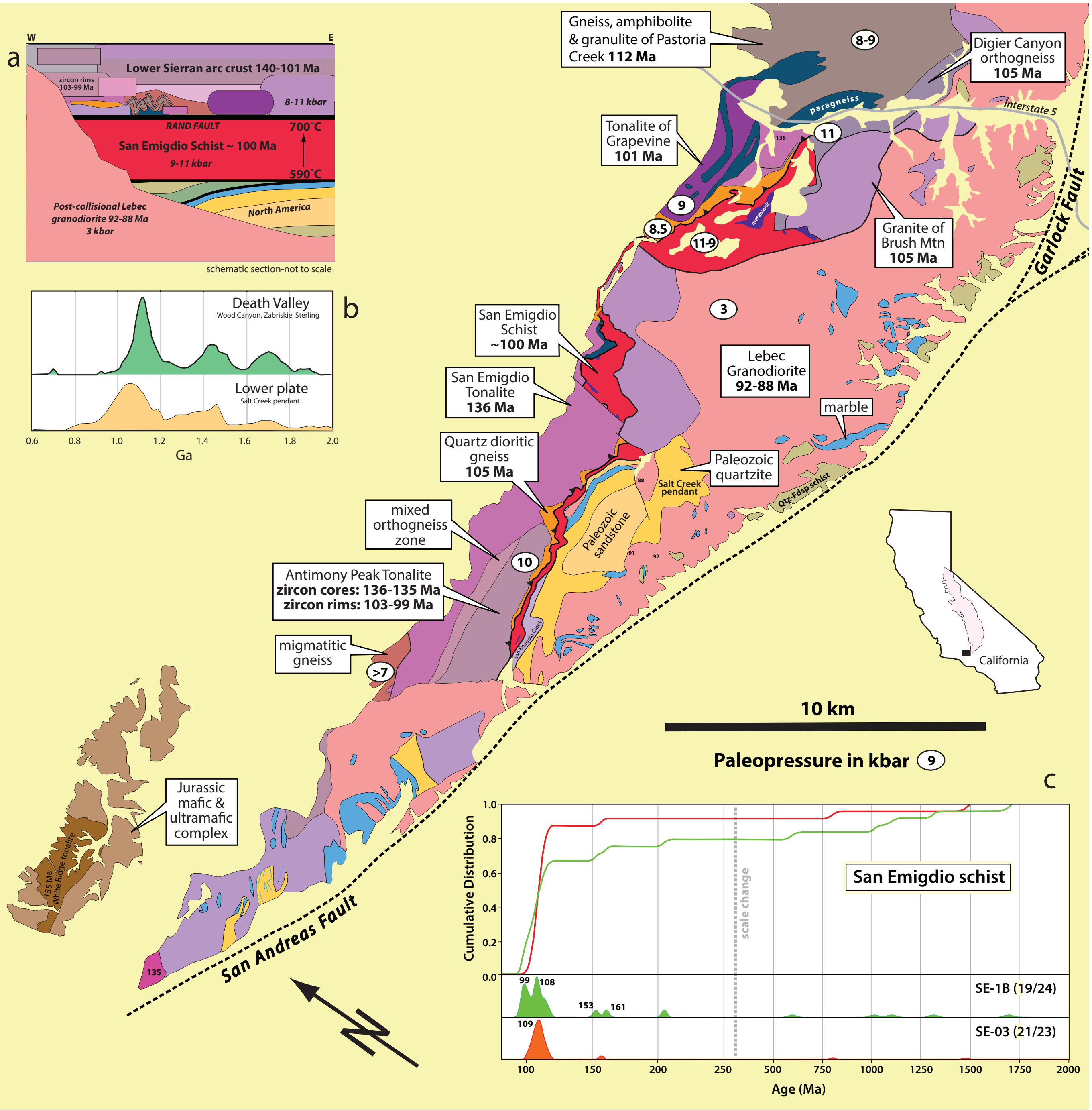
Although there are many thrust faults known in the Great Basin region east of the Sierras, temporal data suggest that the zone could lie well to the east in eastern California, the Spring Mountains just west of Las Vegas, and northward into Utah and Idaho, where the thrusts are collectively known as the Sevier fold-thrust belt (Armstrong 1968). Hildebrand (2014) pointed out that the oldest thrusts of the Sevier belt were synchronous with the first deformational thickening to affect the North American platform terrace.

In southeastern California and southern Nevada, and as described in the Mojave Desert section of the paper, a sequence of 100.5 ± 2 Ma basaltic lavas and epiclastic rocks overlain by plagioclase porphyritic ignimbrites and lavas known as the Delfonte volcanics (Fig. 9), was detached, folded, and transported eastward on thrust faults (Fleck et al. 1994; Walker et al. 1995) prior to the emplacement of the 98–90 Ma Teutonia batholith. Other allochthons in the area carry deformed plutons dated between 150 and 140 Ma (Walker et al. 1995).

The earliest of the Utah thrusts, the Canyon Range thrust, was emplaced at about 125 Ma (DeCelles 2004; DeCelles and Coogan 2006) and the resultant synorogenic foredeep was filled during the Aptian–Albian mainly by the Cedar Mountain and San Pitch formations (Lawton et al. 2010) and so predates the 100 Ma collision. The thrust was unconformably overlain and sealed by upper Albian? – Cenomanian conglomerate (DeCelles and Coogan 2006; Lawton et al. 2007).

The next youngest thrust system of south-central Utah, known as the Pavant–Nebo thrust system, transported Neoproterozoic

Fig. 18. Simplified geological map of the San Emigdio Mountains (modified from Chapman and Saleeby 2012), where we infer 11–9 kbar San Emigdio schist to represent deformed metasedimentary rocks of the Lower Cretaceous Cinco Lake arc trough caught between the pre-100 Ma high-grade base of the Cinco Lake arc and lower plate North America comprising megaslabs of Paleozoic metasedimentary rocks. Cenozoic faults, mainly related to compression adjacent to the San Andreas fault, are not shown as they appear to have little separation (Chapman and Saleeby 2012) and only limited effect on the regional tectonostratigraphy. Schematic section in upper left (*a*) illustrates the inferred geological relations. (*b*) Detrital zircon profiles illustrating the similarities of zircons in the Salt Creek pendant compared with a composite of sandstones in the Death Valley region to the east from Chapman et al (2012). (*c*) Subfigure in lower right shows cumulative distribution of detrital zircons from two samples of the San Emigdio schist replotted from Jacobson et al. (2011) and interpreted to represent metasedimentary fill of the Cinko Lake arc trough. Note the presence of sparse Precambrian zircons, which were probably derived from North America as opposed to open seafloor to the west of the arc. These relations all support our model for westward subduction of the leading edge of the North American craton and its Lower Cretaceous sedimentary cover beneath the 140–100 Ma Cinko arc. [Colour online.]



metasedimentary rocks, Paleoproterozoic crystalline basement of the Santequin complex (Nelson et al. 2002), and a Phanerozoic sedimentary succession, eastward, and led to the development of a large overturned, nearly recumbent anticline. The Pavant sector of the system deformed and elevated the Canyon Range thrust into an antiformal culmination during its emplacement (DeCelles and Coogan 2006). Zircon (U/Th)/He ages from the Pavant–Nebo thrust sheets document emplacement and exhumation of the thrust sheets between 102 and 96 Ma (Pujols et al. 2020). Using detrital zircon He, they also found that active thrust belt deformation was concurrent with sediment dispersal eastward into the Cenomanian Dakota Formation, the temporally equivalent foredeep stratigraphic unit. Thus, the Pavant–Nebo thrust system was active at about 100 Ma. To the south in southwestern Utah, the Iron Springs thrust was recently dated to be about 100 Ma on the basis of 100.18 ± 0.04 Ma zircons extracted from a dacitic tuff intercalated with coarse syn- to post-orogenic debris of the Iron Springs Formation (Quick et al. 2020).

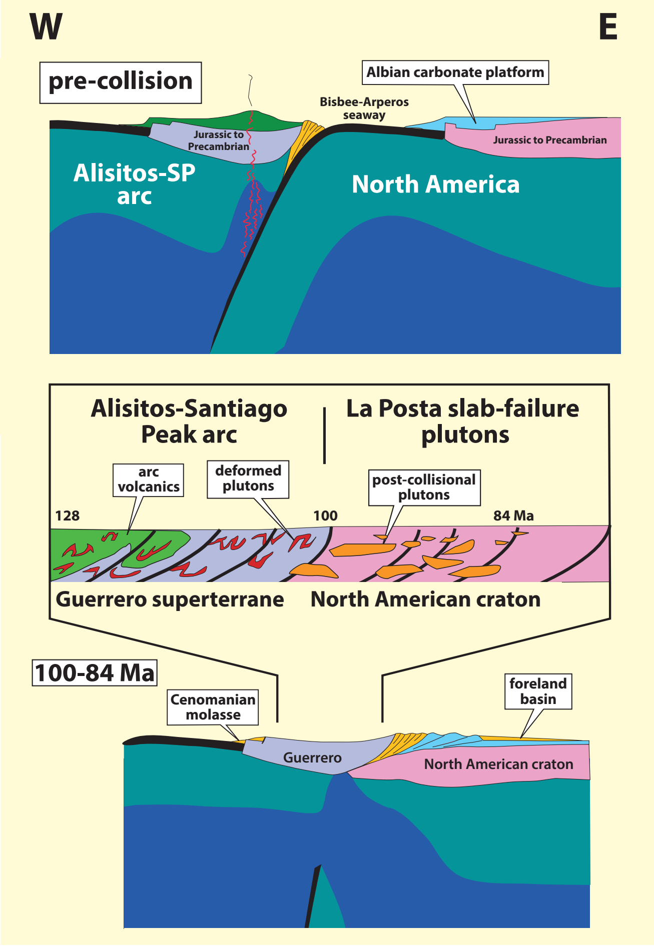
In northern Utah, major thrust activity and cooling of the ~125 Ma Willard thrust also occurred at 105–95 Ma, which led to increased subsidence to the east and deposition of the 100–96 Ma Aspen and Frontier formations in the foreland basin (Yonkee et al. 2019; Pujols et al. 2020). A thrust duplex of Paleoproterozoic crystalline rocks known as the Farmington complex seemingly sits on Archean basement of the Wyoming – Grouse Creek block (Mueller et al. 2011; Yonkee et al. 2003). The band of Paleoproterozoic crystalline rocks likely continues northward into Idaho, where Paleoproterozoic crystalline basement occurs within the Cabin – Medicine Lake thrust system just east of the Idaho batholith (Skipp 1987) and the Tendoy thrust of southwestern Montana (Skipp and Hait 1977; DuBois 1982).

Hi-flux magmatic events

Our data suggest that the so-called hi-flux magmatic events of arcs (Gehrels et al. 2009) are not arc-related, but instead occur from slab failure during collision. Some researchers recognized that flare-ups coincide with episodes of crustal thickening (Ducea and Barton 2007; Ducea et al. 2015) but interpreted the thickening to reflect retro-arc thrusting (DeCelles et al. 2009). Other researchers (Ducea and Saleeby 1998; Jagoutz and Behn 2013; Lee and Anderson 2015) suggest crustal thickening in the arc by magmatic underplating, commonly accompanied by foundering of dense cumulates, but these models fail because the arc is underplated by the lower plate lithosphere prior to the hi-flux event so there is insufficient time for magmatic underplating. In our model (Hildebrand and Whalen 2017), arc-continent collision shuts down arc magmatism, and due to the buoyancy contrast between the continental and oceanic lithosphere, the subducting plate fails and the oceanic sector, possibly plus some thin lithosphere of the rifted margin, sinks into the mantle, where the upper basaltic–gabbroic part of the oceanic slab melts to produce post-collisional magmatism. The change from arc magmatism to slab failure magmatism happens rapidly, typically within a couple of million years, so there is no time, given the low thermal diffusivity of rocks, for underthrust material to heat up and melt sufficiently to produce the quantity of observed magmatism.

The key difference between our model and those of others is that we recognize the post-collisional nature of the hi-flux magmatism and relate it to melting of the subducting slab. We utilized the timing and composition of the magmatism to resolve the crustal composition paradox because we maintain that most magmas are not arc derived (as commonly hypothesized), but instead formed during the waning stages of collision and consequent slab failure (Hildebrand et al. 2018). Because the batholiths typically have silica contents >60% and are derived directly from the mantle, we argue that they create large amounts of continental crust. In fact, on the basis of detrital zircon peaks that largely coincide with periods of continental amalgamation (Condie et al. 2009, 2017; Hawkesworth et al. 2010, 2016), we suggest that post-collisional magmatism might have created more than half of all continental crust.

Fig. 19. Our tectonic plate scale model for the Peninsular Ranges orogeny involves closure of a Lower Cretaceous seaway by west-directed subduction and arc magmatism from ~140 Ma until the collision of the arc with North America at 100 Ma. The competing buoyancies of the oceanic and cratonic lithosphere led to rapid tearing and break-off of the subducted plate and an influx of 99–84 Ma post-collisional magmatism during exhumation of the orogenic hinterland. During exhumation and plutonism, between 99–90 Ma molasse was shed westward into the old back-arc region. [Colour online.]



Conclusions

1. The Peninsular Ranges orogen is a ~100 Ma orogenic belt that extends from Mexico to Alaska, but here we discussed only the Peninsular Ranges, Mojave, and Sierran sectors of the orogen. The orogen formed when a marine trough, open for about 40 million years along the western margin of North America, closed by westerly subduction, which pulled a passive continental margin, capped by a west-facing Albian carbonate platform built on the eastern North American side of the trough, beneath an Early Cretaceous arc complex, built on the western side of the trough (Fig. 19).
2. About a million years or so following the collision, the collisional hinterland was exhumed and intruded by a swarm of

tonalite–granodiorite–granite plutons. The timing suggests that the plutons and exhumation formed in tandem when the oceanic lithosphere broke off from the partially subducted North American plate (Fig. 19).

3. The large mid-Cretaceous batholiths of the Peninsular Ranges and Sierra Nevada are composed of two contrasting magmatic suites derived from distinct mantle sources and emplaced at different times. The older arc suite represents a generally low-standing marine arc built on thinned lithosphere over a westward-dipping subduction zone, whereas the younger suite was post-collisional and invaded the orogenic hinterland during exhumation due to break-off and melting of the subducting slab.
4. Models that utilize Andino-type or cyclic hi-magmatic flux models for the development of Cordilleran batholiths, fail to recognize that the transition from arc magmatism to post-collisional hi-flux magmatism occurred rapidly, perhaps in about a million years, so that there is insufficient time to thicken the crust by underplating or for heat transfer by conduction to melt underthrust cratonic material.
5. The post-collisional magmas appear to have been derived from melting of the basaltic–gabbroic upper part of the subducted oceanic lithosphere augmented by assimilation due to fractional melting of the SCLM as they rose toward the crust. Thus, slab break-off magmas have trace element concentrations and ratios similar to slab window rocks, but where they rise through old and enriched cratonic lithosphere they acquire an enriched radiogenic signature.
6. There is no compelling evidence along the western edge of the Peninsular Ranges and Sierra Nevada for a fore-arc basin or accretionary prism during Early Cretaceous arc magmatism. Instead, voluminous quantities of material were shed westward into the back-arc region after the 100 Ma collision and termination of arc magmatism, when abundant detrital zircons from the 100–90 Ma post-collisional plutons document rapid exhumation of the orogenic hinterland.
7. An implication of our model is that retro-arc models for the Sevier thrust-fold belt should be reconsidered, as there was no eastward subduction beneath North America at about 120 Ma when the Sevier thrusting initiated. We claim there is compelling evidence that the 130–100 Ma arc magmatism in the Peninsular Ranges and Sierra Nevada were built above westward, not eastward, subduction zones (Fig. 19).
8. In the San Emigdio mountains, the ~100 Ma San Emigdio schist, with an inverse temperature gradient and paleopressures of 11–9 kbar, lies between a basal terrane comprising slabs, up to 10 km long, of marble, quartzite, schist and metasandstone, and the base of the Sierran arc, consisting of 136–101 Ma plutons and gneisses originally at pressures of 10–11 kbar. We interpret these relations to represent an oblique cross section through the uplifted 100 Ma collisional suture zone, which was exhumed to mid crustal depths by ~95 Ma. Their paleopressures suggest Sierran crust of normal, or lesser, thickness.
9. The so-called "flare-up" events in Cordilleran arcs are the result of collision followed by slab break-off magmatism.
10. In Part II, we explore the more northerly continuation of the Peninsular Ranges orogen and demonstrate that overall it extends from southern Mexico to Alaska, with geological relations and timing in the northern sector similar to the Peninsular Ranges and Sierra Nevada.

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References

Allen, C., Wooden, J.L., Howard, K.A., Foster, D.A., and Tosdal, R.M. 1995. Sources of the early Cretaceous plutons in the Turtle and West Riverside mountains, California: Anomalous Cordilleran interior intrusions. Journal of Petrology, **36**: 1675–1700. doi:10.1093/oxfordjournals.petrology.a037270.

Allison, F.C. 1974. The type Alisitos formation (Cretaceous, Aptian–Albian) of Baja California and its bivalve fauna, *In* Geology of Peninsular California. *Edited by* G. Gastil and J. Lillegraven. AAPG-SEPM-SEG Pacific Section 49th Annual Meeting Field Trip Guidebook. pp. 20–59.

Almazán-Vásquez, E. 1988*a*. Marco paleosedimentario y geodinámico de la Formación Alisitos en la península de Baja California. Universidad Nacional Autónoma de México, Instituto de Geología, Revista, **7**: 41–51.

Almazán-Vásquez, E. 1988*b*. Geoquímica de las rocas volcánicas de la Formación Alisitos del Arroyo La Bocana en el Estado de Baja California Norte. Universidad Nacional Autónoma de México, Instituto de Geología, Revista, **7**: 78–88.

Alsleben, H., Wetmore, P.H., Schmidt, K.L., Paterson, S.R., and Melis, E.A. 2008. Complex deformation during arc–continent collision: Quantifying finite strain in the accreted Alisitos arc, Peninsular Ranges batholith, Baja California. Journal of Structural Geology, **30**: 220–236. doi:10.1016/j.jsg.2007.11.001.

Anderson, T.H., Rodríguez-Castañeda, J.L., and Silver, L.T. 2005. Jurassic rocks in Sonora, Mexico: Relations to the Mojave-Sonora megashear and its inferred northwestward extension. *In* The Mojave-Sonora Megashear Hypothesis: Development, Assessment, and Alternatives. *Edited by* T.H. Anderson, J.A. Nourse, J.W. McKee, and M.B. Steiner. Geological Society of America Special Papers, 393. pp. 51–95. doi:10.1130/0- 8137-2393-0.51.

Armstrong, R.L. 1968. Sevier orogenic belt in Nevada and Utah. Geological Society of America Bulletin, **79**: 429–458. doi:10.1130/0016-7606(1968)79[429:SOBINA]2.0.CO;2.

Armstrong, R.L., and Dick, H.J.B. 1974. A model for the development of thin overthrust sheets of crystalline rock. Geology, **2**: 35–40. doi:10.1130/0091-7613(1974)2<35:AMFTDO>2.0.CO;2.

Axen, G.J. 1987. The Keystone and Red Spring thrust faults in the La Madre Mountain area, eastern Spring Mountains, Nevada. *In* Centennial field guide. *Edited by* M.L. Hill. Geological Society of America, North American Geology, 1: pp. 57–60.

Bacon, C.R., Gunn, S.H., Lanphere, M.A., and Wooden, J.L. 1994. Multiple isotopic components in Quaternary volcanic rocks of the Cascade arc near Crater Lake, Oregon. Journal of Petrology, **35**: 1521–1556. doi:10.1093/petrology/35.6.1521.

Bartley, J.M., and Gleason, G.C. 1990. Tertiary normal faults superimposed on Mesozoic thrusts, Quinn Canyon and Grant Ranges, Nye County, Nevada. *In* Basin and Range Extensional Tectonics near the Latitude of Las Vegas. *Edited by* B.P. Wernicke. Geological Society of America Memoir, **176**: 195–212. doi:10.1130/MEM176-p195.

Bartley, J.M., Glazner, A.F., and Mahan, K.H. 2012. Formation of pluton roofs, floors, and walls by crack opening at Split Mountain, Sierra Nevada, California. Geosphere, **8**(5): 1086–1103. doi:10.1130/GES00722.1.

Bateman, P.C. 1992. Plutonism in the Central Part of the Sierra Nevada Batholith. U.S. Geological Survey Professional Paper 1483. 186pp.

Bateman, P.C., and Chappell, B.W. 1979. Crystallization, fractionation, and solidification of the Tuolumne intrusive series, Yosemite National Park, California. Geological Society of America Bulletin, **90**: 465–482. doi:10.1130/0016-7606(1979)90<465:CFASOT>2.0.CO;2.

Bateman, P.C., and Clark, L.D. 1974. Stratigraphic and structural setting of the Sierra Nevada batholith, California. Pacific Geology, **8**: 79–89.

Bateman, P.C., and Wahrhaftig, C. 1966. Geology of the Sierra Nevada. *In* Geology of Northern California. *Edited by* E.H. Baily. California Division of Mines and Geology Bulletin 190. pp. 107–172.

Bateman, P.C., Clark, L.D., Huber, N.K., Moore, J.G., and Rinehart, C.D. 1963. The Sierra Nevada Batholith—A Synthesis of Recent Work across the Central Part. U.S. Geological Survey Professional Paper 414-D, 46 p.

Bateman, P.C., Dodge, F.C.W., and Kistler, R.W. 1991. Magnetic susceptibility and relation to initial $^{87}Sr/^{86}Sr$ for granitoids of the central Sierra Nevada, California. Journal of Geophysical Research, **96**: 19,555–19,568. doi:10.1029/91JB02171.

Beck, C.L. 2013. New insights into migration of the cretaceous Sierran Arc using high-precision U-Pb geochronology. M.S. thesis, University of North Carolina, Chapel Hill, North Carolina. 49pp.

Beckerman, G.M., Robinson, J.P., and Anderson, J.L. 1982. The Teutonia batholith: A large intrusive complex of Jurassic and Cretaceous age in the eastern Mojave Desert, California, *In* Mesozoic–Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada. *Edited by* E.G. Frost and D.L. Martin. Cordilleran Publishers, San Diego, California, pp. 205–220.

Bilodeau, W.L., Kluth, C.F., and Vedder, L.K. 1987. Regional stratigraphic, sedimentologic, and tectonic relationships of the Glance Conglomerate in south-eastern Arizona. *In* Mesozoic rocks of southern Arizona adjacent areas. *Edited by* W.R. Dickinson and M.F. Klute. Arizona Geological Society, Digest 18. pp. 229–256.

Bindeman, I. 2008. Oxygen isotopes in mantle and crustal magmas as revealed by single crystal analysis. Reviews in Mineralogy and Geochemistry, **69**: 445–478. doi:10.2138/rmg.2008.69.12.

Bindeman, I.N., Eiler, J.M., Yogodzinski, G.M., Tatsumi, Y., Stern, C.R., Grove, T.L., et al. 2005. Oxygen isotope evidence for slab melting in modern and ancient subduction zones. Earth Planetary Science Letters, **235**: 480–496. doi:10.1016/j.epsl.2005.04.014.

Blondes, M.S., Reiners, P.W., Ducea, M.N., Singer, B.S., and Chesley, J. 2008. Temporal–compositional trends over short and long time-scales in basalts of the Big Pine volcanic field, California. Earth and Planetary Science Letters, **269**: 140–154. doi:10.1016/j.epsl.2008.02.012.

Bohannon, R.G. 1983. Mesozoic and Cenozoic tectonic development of the Muddy, North Muddy, and northern Black Mountains, Clark County, Nevada, *In* Tectonic and stratigraphic studies in the Eastern Great Basin. *Edited by* D.M. Miller, V.R. Todd, and K.A. Howard. Geological Society of America Memoir 157. pp. 125–148. doi:10.1130/MEM157-p125.

Bonde, J.W. 2008. Paleoecology and Taphonomy of the Willow Tank Formation (Albian), Southern Nevada. M.Sc. thesis, Montana State University, Bozeman, Montana. 96pp.

Bonde, J.W., Varricchio, D.J., Bryant, G., and Jackson, F.D. 2012. Mesozoic vertebrate paleontology of Valley of Fire State Park, Clark County, Nevada. *In* Field Guide for the 71st Annual Meeting of the Society of Vertebrate Paleontology. *Edited by* J.W. Bonde, and A.R.C. Milner. Nevada State Museum Paleontological Paper Number 1. pp. 108–126.

Brown, D., Ryan, P.D., Afonso, J.C., Boutelier, D., Burg, J.P., Calvert, A., et al. 2011. Arc–continent collision: the making of an orogen. *In* Arc-continent collision. *Edited by* D. Brown and P.D. Ryan. Springer-Verlag, Berlin. pp. 477–493.

Buddington, A.F. 1927. Coast Range intrusives of southeastern Alaska. Journal of Geology, **35**: 224–246. doi:10.1086/623404.

Burchfiel, B.C., and Davis, G.A. 1972. Structural framework and evolution of the southern part of the Cordilleran orogeny, western United States. American Journal of Science, **272**: 97–118. doi:10.2475/ajs.272.2.97.

Burchfiel, B.C., and Davis, G.A. 1977. Geology of the Sagamore Canyon-Slaughterhouse Spring area. New York Mountains. California. Geological Society of America Bulletin, **88**: 1623–1640. doi:10.1130/0016-7606(1977)88<1623:GOTSCS>2.0.CO;2.

Burchfiel, B.C., Fleck, R.J., Secor, D.T., Vincelette, R.R., and Davis, G.A. 1974. Geology of the Spring Mountains, Nevada. Geological Society of America Bulletin, **85**: 1013–1022. doi:10.1130/0016-7606(1974)85<1013:GOTSMN>2.0.CO;2.

Burchfiel, B.C., Cameron, C.S., and Royden, L.H. 1998. Geology of the Wilson Cliffs–Potosi Mountain area, southern Nevada. *In* Integrated Earth and environmental evolution of the southwestern United States: The Clarence A. Hall Jr., volume. *Edited by* W.G. Ernst and C.A. Nelson. Columbia, Maryland, Bellwether Publishing for the Geological Society of America. pp. 203–227.

Busby, C., Smith, D., Morris, W., and Fackler-Adams, B. 1998. Evolutionary model for convergent margins facing large ocean basins: Mesozoic Baja California, Mexico. Geology, **26**: 227–230. doi:10.1130/0091-7613(1998)026<0227:EMFCMF>2.3.CO;2.

Busby, C.J., Adams, B.F., Mattinson, J., and Deoreo, S. 2006. View of an intact oceanic arc, from surficial to mesozonal levels: Cretaceous Alisitos arc, Baja California. Journal of Volcanology and Geothermal Research, **149**: 1–46. doi:10.1016/j.jvolgeores.2005.06.009.

Cabral-Cano, E., Lang, H.R., and Harrison, C.G.A. 2000. Stratigraphic assessment of the Arcelia±Teloloapan area, southern Mexico: implications for southern Mexico's post-Neocomian tectonic evolution. Journal of South American Earth Sciences, **13**: 443–457. doi:10.1016/S0895-9811(00)00035-3.

Calkins, F.C. 1930. The granitic rocks of the Yosemite region. *In* Geologic history of the Yosemite Valley. *Edited by* F.E. Matthes. United States Geological Survey Paper 160. pp. 120–129.

Camp, V.E., and Hanan, B.B. 2008. A plume-triggered delamination origin for the Columbia River Basalt Group. Geosphere, **4**: 480–495. doi:10.1130/GES00175.1.

Campa, M.F., and Coney, P.J. 1983. Tectono-stratigraphic terranes and mineral resource distributions in Mexico. Canadian Journal of Earth Sciences, **20**(6): 1040–1051. doi:10.1139/e83-094.

Campa-Uranga, M.F., Torres de León, R., Iriondo, A., and Premo, W.R. 2012. Caracterización geológica de los ensambles metamórficos de Taxco y Taxco el Viejo, Guerrero, México. Boletín de la Sociedad Geológica Mexicana, **64**: 369–385.

Cao, W., Paterson, S., Memeti, V., Mundil, R., Anderson, J.L., and Schmidt, K. 2015. Tracking paleodeformation fields in the Mesozoic central Sierra Nevada arc: Implications for intra-arc cyclic deformation and arc tempos. Lithosphere, **7**: 296–320. doi:10.1130/L389.1.

Carr, M.D. 1980. Upper Jurassic to Lower Cretaceous (?) synorogenic sedimentary rocks in the southern Spring Mountains. Geology, **8**: 385–389. doi:10.1130/0091-7613(1980)8<385:UJTLCS>2.0.CO;2.

Centeno-García, E. 2005. Review of Upper Paleozoic and Lower Mesozoic stratigraphy and depositional environments of central and west Mexico: Constraints on terrane analysis and paleogeography. *In* The Mojave-Sonora Megashear Hypothesis: development, assessment, and alternatives. *Edited by* T.H. Anderson. Geological Society of America Special Paper 393. pp. 233–258.

Centeno-García, E., Guerrero-Suastegui, M., and Talavera-Mendoza, O. 2008. The Guerrero composite terrane of western Mexico: Collision and subsequent rifting in a supra-subduction zone. *In* Formation and applications of the sedimentary record in arc collision zones. *Edited by* A.E. Draut, P.D. Clift, and D.W. Scholl. Geological Society of America Special Paper 436. pp. 279–308. doi:10.1130/2008.2436(13).

Centeno-García, E., Busby, C., Busby, M., and Gehrels, G. 2011. Evolution of the Guerrero composite terrane along the Mexican margin, from extensional fringing arc to contractional continental arc. Geological Society of America Bulletin, **123**: 1776–1797. doi:10.1130/B30057.1.

Chamberlain, V.E., and Lambert, R.S.J. 1985. Cordilleria, a newly defined Canadian microcontinent. Nature, **314**: 707–713. doi:10.1038/314707a0.

Chapman, A.D., and Saleeby, J. 2012. Geologic map of the San Emigdio Mountains, southern California. Geological Society of America Map and Chart 101. doi:10.1130/2012.MCH101.

Chapman, A.D., Luffi, P., Saleeby, J., and Petersen, S. 2011. Metamorphic evolution, partial melting, and rapid exhumation above an ancient flat slab: Insights from the San Emigdio Schist, southern California. Journal of Metamorphic Geology, **29**: 601–626. doi:10.1111/j.1525-1314.2011.00932.x.

Chapman, A.D., Saleeby, J.B., Wood, D.J., Piasecki, A., Kidder, S., Ducea, M.N., and Farley, K.A. 2012. Late Cretaceous gravitational collapse of the southern Sierra Nevada batholith, California. Geosphere, **8**: 314–341. doi:10.1130/GES00740.1.

Chen, J.H., and Moore, J.G. 1982. Uranium-lead ages from the Sierra Nevada batholith, California. Journal of Geophysical Research, **87**: 4761–4784. doi:10.1029/JB087iB06p04761.

Chen, J.H., and Tilton, G.R. 1991. Applications of lead and strontium isotopic relationships to the petrogenesis of granitoid rocks, central Sierra Nevada batholith, California. Geological Society of America Bulletin, **103**: 439–447. doi:10.1130/0016-7606(1991)103<0439:AOLASI>2.3.CO;2.

Chin, E.J., Lee, C.-T.A., Tollstrup, D.L., Xie, L., Wimpenny, J.B., and Yin, Q.-Z. 2013. On the origin of hot metasedimentary quartzites in the lower crust of continental arcs. Earth and Planetary Science Letters, **361**: 120–133. doi:10.1016/j.epsl.2012.11.031.

Christe, G. 2010. U/Pb ages of Kettle Rock and Mount Jura sequence volcanic rock, eastern Mesozoic belt, northern Sierra Nevada, California: A revised understanding of the age relationship of volcanism, plutonism, and tectonism within successive Jurassic arc sequences. Geological Society of America Abstracts with Programs, **42**(4): 110.

Christe, G. 2011. New U-Pb ages for the Eastern Mesozoic Belt of northeastern California: Implications for stratigraphy, tectonic evolution, terrane assignment and possible correlation with Mesozoic units in the western Great Basin of Nevada. *In* Great Basin Evolution and Metallogeny. *Edited by* R. Steininger. Geological Society of Nevada Symposium, Vol. 1. pp. 257–288.

Christe, G., and Hannah, J.L. 1990. High-K, continental-arc volcanism in the Kettle Rock Sequence of the Eastern Mesozoic Belt, northern Sierra Nevada, California: Implications for lower Mesozoic Cordilleran Tectonics. *In* The nature and origin of Cordilleran magmatism. *Edited by* J.L. Anderson. Geological Society of America, Memoir 174, Boulder, Colorado. pp. 315–329.

Clausen, B.L., Morton, D.M., Kistler, R.W., and Lee, C.T.A. 2014. Low-initial-Sr felsic plutons of the northwestern Peninsular Ranges batholith, southern California, and the role of mafic-felsic magma mixing in continental crust formation. *In* Peninsular Ranges Batholith, Baja California and Southern California. *Edited by* D.M. Morton and F.K. Miller, Geological Society of America Memoir 211. pp. 317–344.

Clemens-Knott, D. 1992. Geologic and isotopic investigations of the Early Cretaceous Sierra Nevada Batholith, Tulare County, California, and the Ivrea Zone, northwest Italian Alps: examples of interaction between mantle-derived magma and continental crust. Ph.D. thesis, California Institute of Technology, Pasadena, California. 389pp.

Clemens-Knott, D., and Saleeby, J.B. 1999. Impinging ring dike complexes in the Sierra Nevada batholith, California: Roots of the Early Cretaceous volcanic arc. Geological Society of America Bulletin, **111**: 0484–0496.

Cloos, M., and Housh, T.B. 2008. Collisional delamination: Implications for porphyry-type Cu-Au ore formation in New Guinea. *In* Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits. *Edited by* J.E. Spencer and S.R. Titley. Arizona Geological Society Digest. Vol. 22. pp. 235–244.

Cloos, M., Sapiie, B., van Ufford, A.Q., Weiland, R.J., Warren, P.Q., and McMahon, T.P. 2005. Collisional delamination in New Guinea: the geotectonics of subducting slab breakoff. Geological Society of America Special Paper 400. 51pp.

Cohen, K.M., Finney, S.C., Gibbard, P.L., and Fan, J.-X. 2013. The ICS International Chronostratigraphic Chart. Episodes, **36**: 199–204. doi:10.18814/epiiugs/2013/v36i3/002.

Coleman, D.S., and Glazner, A.F. 1998. The Sierra Crest magmatic event: rapid formation of juvenile crust during the Late Cretaceous in California. *In* Integrated earth and environmental evolution of the southwestern United States: the Clarence A. Hall Jr., Volume. *Edited by* W.G. Ernst and C.A. Nelson. Bellwether Publishing for the Geological Society of America, Columbia, Maryland. pp. 253–272.

Coleman, D.S., Gray, W., and Glazner, A.F. 2004. Rethinking the emplacement and evolution of zoned plutons: Geochronologic evidence for incremental assembly of the Tuolumne intrusive suite, California. Geology, **32**: 433–436. doi:10.1130/G20220.1.

Condie, K.C., Belousova, E., Griffin, W.L., and Sircombe, K.N. 2009. Granitoid events in space and time: constraints from igneous and detrital zircon age spectra. Gondwana Research, **15**: 228–242. doi:10.1016/j.gr.2008.06.001.

Condie, K.C., Arndt, N., Davaille, A., and Puetz, S.J. 2017. Zircon age peaks: production or preservation of continental crust? Geosphere, **13**: 227–234. doi:10.1130/GES01361.1.

Constenius, K.N., Johnson, R.A., Dickinson, W.R., and Williams, T.A. 2000. Tectonic evolution of the Jurassic–Cretaceous Great Valley forearc, California: Implications for the Franciscan thrust-wedge hypothesis. Geological Society of America Bulletin, **112**: 1703–1723. doi:10.1130/0016-7606(2000)112<1703:TEOTJC>2.0.CO;2.

Davies, J.H., and von Blanckenburg, F. 1995. Slab break-off: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. Earth and Planetary Science Letters, **129**: 85–102. doi:10.1016/0012-821X(94)00237-S.

Davis, G.A. 1973. Relations between the Keystone and Red Spring faults, eastern Spring Mountains, Nevada. Geological Society of America Bulletin, **84**: 3709–3716. doi:10.1130/0016-7606(1973)84<3709:RBTKAR>2.0.CO;2.

Davis, J.W., Coleman, D.S., Gracely, J.T., Gaschnig, R., and Stearns, M. 2012. Magma accumulation rates and thermal histories of plutons of the Sierra Nevada batholith, CA. Contributions to Mineralogy and Petrology, **163**: 449–465. doi:10.1007/s00410-011-0683-7.

DeCelles, P.G. 2004. Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA. American Journal of Science, **304**: 105–168. doi:10.2475/ajs.304.2.105.

DeCelles, P.G., Ducea, M.N., Kapp, P., and Zandt, G. 2009. Cyclicity in Cordilleran orogenic systems. Nature Geoscience, **2**: 251–257. doi:10.1038/ngeo469.

DeCelles, P.G., and Coogan, J.C. 2006. Regional structure and kinematic history of the Sevier fold-and-thrust belt, central Utah. Geological Society of America Bulletin, **118**: 841–864. doi:10.1130/B25759.1.

DeGraaff-Surpless, K., Graham, S.A., Wooden, J.L., and McWilliams, M.O. 2002. Detrital zircon provenance analysis of the Great Valley Group, California: Evolution of an arc-forearc system. Geological Society of America Bulletin, **114**: 1564–1580. doi:10.1130/0016-7606(2002)114<1564:DZPAOT>2.0.CO;2.

DePaolo, D.J. 1980. Crustal growth and mantle evolution: inferences from models of element transport and Nd and Sr isotopes. Geochimica et Cosmochimica Acta, **44**: 1185–1196. doi:10.1016/0016-7037(80)90072-1.

DePaolo, D.J. 1981. A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California. Journal of Geophysical Research, **86**(10): 10470–10410. doi:10.1029/JB086iB11p10470.

Dickinson, W.R. 1970. Relations of andesites, granites, and derivative sandstones to arc-trench tectonics. Reviews of Geophysics, **8**: 813–860. doi:10.1029/RG008i004p00813.

Dickinson, W.R. 1976. Sedimentary basins developed during evolution of Mesozoic–Cenozoic arc-trench system in western North America. Canadian Journal of Earth Sciences, **13**(9): 1268–1287. doi:10.1139/e76-129.

Dickinson, W.R., and Lawton, T.F. 2001*a*. Carboniferous to Cretaceous assembly and fragmentation of Mexico. Geological Society of America Bulletin, **113**: 1142–1160. doi:10.1130/0016-7606(2001)113<1142:CTCAAF>2.0.CO;2.

Dickinson, W.R., and Lawton, T.F. 2001*b*. Tectonic setting and sandstone petro-facies of the Bisbee basin (USA–Mexico). Journal of South American Earth Sciences, **14**: 475–504. doi:10.1016/S0895-9811(01)00046-3.

Di Fiori, R.V., Long, S.P., Fetrow, A.C., Snell, K.E., Bonde, J.W., and Vervoort, J. 2020. Syn-contractional deposition of the Cretaceous Newark Canyon Formation, Diamond Mountains, Nevada: Implications for strain partitioning within the U.S. Cordillera. Geosphere, **16**: 546–566. doi:10.1130/GES02168.1.

Doucette, J. 2000. A petrochemical study of the Mount Fubilan intrusion and associated ore bodies, Papua New Guinea. Unpublished Ph.D. thesis, Oregon State University. 400pp.

DuBois, D.P. 1982. Tectonic framework of basement thrust terrane, northern Tendoy Range, southwest Montana. *In* Geologic studies of the Cordilleran Thrust Belt. *Edited by* R.B. Powers. Rocky Mountain Association of Geologists. pp. 145–158.

du Bray, E.A. 2007. Time, space, and composition relations among northern Nevada intrusive rocks and their metallogenic implications. Geosphere, **3**: 381–405. doi:10.1130/GES00109.1.

Ducea, M.N., and Barton, M.D. 2007. Igniting flare-up events in Cordilleran arcs. Geology, **35**: 1047–1050. doi:10.1130/G23898A.1.

Ducea, M.N., and Saleeby, J.B. 1998. The age and origin of a thick mafic-ultramafic keel from beneath the Sierra Nevada batholith. Contributions to Mineralogy and Petrology, **133**: 169–185. doi:10.1007/s004100050445.

Ducea, M.N., Paterson, S.R., and DeCelles, P.G. 2015. High-volume magmatic events in subduction systems. Elements, **11**: 99–104. doi:10.2113/gselements.11.2.99.

Duque-Trujillo, J., Ferrari, L., Orozco-Esquivel, T., López-Martínez, M., Lons-Dale, P., Bryan, S.E., et al. 2015. Timing of rifting in the southern Gulf of California and its conjugate margins: Insights from the plutonic record. Geological Society of America Bulletin, **127**: 702–736. doi:10.1130/B31008.1.

Duretz, T., and Gerya, T.V. 2013. Slab detachment during continental collision: Influence of crustal rheology and interaction with lithospheric delamination. Tectonophysics, **602**: 124–140. doi:10.1016/j.tecto.2012.12.024.

Duretz, T., Gerya, T.V., and May, D.A. 2011. Numerical modelling of spontaneous slab breakoff and subsequent topographic response. Tectonophysics, **502**: 244–256. doi:10.1016/j.tecto.2010.05.024.

Duretz, T., Schmalholz, S.M., and Gerya, T.V. 2012. Dynamics of slab detachment. Geochemistry, Geophysics, Geosystems, **13**. doi:10.1029/2011GC004024.

Eiler, J.M. 2001. Oxygen isotope variations of basaltic lavas and upper mantle rocks. *In* Stable isotope geochemistry. *In* Mineralogical Society of America Reviews in Mineralogy and Geochemistry. *Edited by* J.W. Valley and D.R. Cole. Vol. 43. pp. 319–364. doi:10.2138/gsrmg.43.1.319.

Fleck, R.J. 1970. Tectonic style, magnitude, and age of deformation in the Sevier orogenic belt in southern Nevada and eastern California. Geological Society of America Bulletin, **81**: 1705–1720. doi:10.1130/0016-7606(1970)81[1705:TSMAAO]2.0.CO;2.

Fleck, R.J., and Carr, M.D. 1990. The age of the Keystone thrust: Laser-fusion ^{40}Ar/^{39}Ar dating of foreland basin deposits, southern Spring Mountains, Nevada. Tectonics, **9**: 467–476. doi:10.1029/TC009i003p00467.

Fleck, R.J., Mattinson, J.M., Busby, C.J., Carr, M.D., Davis, G.A., and Burchfiel, B.C. 1994. Isotopic complexities and the age of the Delfonte volcanic rocks, eastern Mescal Range, southeastern California: Stratigraphic and tectonics implications. Geological Society of America Bulletin, **106**: 1242–1253. doi:10.1130/0016-7606(1994)106<1242:ICATAO>2.3.CO;2.

Fletcher, J.M., and Karlstrom, K.E. 1990. Late Cretaceous ductile deformation, metamorphism and plutonism in the Piute Mountains, eastern Mojave Desert. Journal of Geophysical Research, **95**: 487–500. doi:10.1029/JB095iB01p00487.

Fries, C., Jr. 1960. Geología del Estado de Morelos y de Partes Adyacentes de México y Guerrero, Región Central Meridional de México. Boletín del Instituto de Geología, Universidad Nacional Autónoma de México. Vol. 60. 236pp.

Gastil, R.G. 1993. Prebatholithic history of peninsular California. *In* The prebatholithic stratigraphy of peninsular California. *Edited by* R.G. Gastil and R.H. Miller. Geological Society of America Special Paper 279. pp. 145–156. doi:10.1130/SPE279-p145.

Gastil, R.G., and Miller, R.H. 1981. Lower Paleozoic strata on the Pacific Plate of North America. Nature, **292**: 828–830. doi:10.1038/292828a0.

Gastil, R.G., Phillips, R.P., and Allison, E.C. 1975. Reconnaissance geology of the state of Baja California. Geological Society of America Memoir, **140**: 201. doi:10.1130/MEM140-p1.

Gastil, R.G., Morgan, G., and Krummenacher, D. 1981. The tectonic history of Peninsular California and adjacent Mexico. *In* The Geotectonic Development of California, Rubey Volume 1. *Edited by* W.G Ernst. Prentice-Hall, Englewood Cliffs, New Jersey. pp. 284–306.

Gastil, R.G., Diamond, J., Knaack, C., Walawender, M., Marshall, M., Boyles, C., et al. 1990. The problem of the magnetite/ilmenite boundary in southern and Baja California. *In* The nature and origin of Cordilleran magmatism. *Edited by* J.L. Anderson. Geological Society of America Memoir 174. pp. 19–32. doi:10.1130/MEM174-p19.

Gastil, R.G., Miller, R., Anderson, P., Crocker, J., Campbell, M., Buch, P., et al. 1991. The relation between the Paleozoic strata on opposite sides of the Gulf of California. *In* Studies of Sonoran Geology. *Edited by* E. Pérez-Segura and C. Jacques-Ayala. Geological Society of America Special Paper 254. pp. 7–18. doi:10.1130/SPE254-p7.

Gastil, R.G., Kimbrough, D.L., Kimbrough, J.M., Grove, M., and Shimizu, M. 2014. The Sierra San Pedro Mártir zoned pluton, Baja California, Mexico. *In* Peninsular Ranges Batholith, Baja California and southern California. *Edited by* D.M. Morton and F.K. Miller. Geological Society of America Memoir 211. pp. 739–758. doi:10.1130/2014.1211(24).

Gehrels, G., Rusmore, M., Woodsworth, G., Crawford, M., Andronicos, C., Hollister, L., et al. 2009. U–Th–Pb geochronology of the Coast Mountains batholith in north-coastal British Columbia: constraints on age and tectonic evolution. Geological Society of America Bulletin, **121**: 1341–1361. doi:10.1130/B26404.1.

Girardi, J.D., Patchett, P.J., Ducea, M.N., Gehrels, G.E., Cecil, M.R., Rusmore, M.E., et al. 2012. Elemental and isotopic evidence for granitoid genesis from deep-seated sources in the Coast Mountains batholith, British Columbia. Journal of Petrology, **53**: 1505–1536. doi:10.1093/petrology/egs024.

Giallorenzo, M. 2013. Application of (U-Th)/He and 40Ar/39Ar Thermochronology to the age of thrust faulting in the Sevier orogenic belt. Ph.D. dissertation, University of Nevada, Las Vegas, Nevada. 281pp.

González-Léon, C., and Jacques-Ayala, C. 1988. Estratigrafía de las rocas cretácicas del área de Cerro de Oro, Sonora Central. Boletín de Departmento de Universidad Sonora, **5**: 1–23.

González-Léon, C.M., Scott, R.W., Löser, H., Lawton, T.F., Robert, E., and Valencia, V.A. 2008. Upper Aptian- Lower Albian Mural Formation: stratigraphy, biostratigraphy and depositional cycles on the Sonoran shelf, northern México. Cretaceous Research, **29**: 249–266. doi:10.1016/j.cretres.2007.06.001.

González-León, C.M., Solari, L., Solé, J., Ducea, M.N., Lawton, T.F., Bernal, J.P., et al. 2011. Stratigraphy, geochronology, and geochemistry of the Laramide magmatic arc in north-central Sonora, Mexico. Geosphere, **7**: 1392–1418. doi:10.1130/GES00679.1.

González-León, C.M., Madhavaraju, J., Ramírez Montoya, E., Solari, L.A., Villanueva-Amadoz, U., Monreal, R., and Sánchez Medrano, P.A. 2020. Stratigraphy, detrital zircon geochronology and provenance of the Morita formation (Bisbee Group) in northeastern Sonora, Mexico. Journal of South American Earth Sciences, **103**: 102761. doi:10.1016/j.jsames.2020.102761.

Gromet, L.P., and Silver, L.T. 1987. REE variations across the Peninsular Ranges Batholith: Implications for batholithic petrogenesis and crustal growth in magmatic arcs. Journal of Petrology, **28**: 75–125. doi:10.1093/petrology/28.1.75.

Grove, M., Lovera, O., and Harrison, M. 2003. Late Cretaceous cooling of the east-central Peninsular Ranges Batholith (33 degrees N): Relationship to La Posta pluton emplacement, Laramide shallow subduction, and forearc sedimentation. *In* Tectonic Evolution of Northwestern Mexico and the Southwestern USA. *Edited by* S.E. Johnson, S.R. Patterson, J.M. Fletcher, G.H. Girty, D.L. Kimbrough, and A. Martín-Barajas. Geological Society of America Special Paper 374. pp. 355–379. doi:10.1130/0-8137-2374-4.355.

Guerrero-Suasegui, M. 2004. Depositional and tectonic history of the Guerrero terrane, Sierra Madre del Sur; with emphasis on sedimentary successions of the Teloloapan area, southwestern Mexico. Unpublished Ph.D. thesis, Memorial University of Newfoundland. 332pp.

Hacker, B.R., Kelemen, P.B., and Behn, M.D. 2015. Continental lower crust. Annual Review of Earth and Planetary Science, **43**: 167–205. doi:10.1146/annurev-earth-050212-124117.

Hamilton, W.B. 1964. Geologic map of the Big Maria Mountains NE quadrangle, California. USGS Map GQ-350, scale 1:24,000.

Hamilton, W.B. 1969*a*. Mesozoic California and the underflow of Pacific mantle. Geological Society of America Bulletin, **80**: 2409–2430. doi:10.1130/0016-7606(1969)80[2409:MCATUO]2.0.CO;2.

Hamilton, W.B. 1969*b*. The volcanic central Andes, a modern model for the Cretaceous batholiths and tectonics of western North America. Oregon Department of Geology and Mineral Industries Bulletin, **65**: 175–184.

Hanan, B.B., Shervais, J.W., and Vetter, S.K. 2008. Yellowstone plume–continental lithosphere interaction beneath the Snake River Plain. Geology, **36**: 51–54. doi:10.1130/G23935A.1.

Hanson, R.B., Saleeby, J.B., and Fates, D.G. 1987. Age and tectonic setting of Mesozoic metavolcanic and metasedimentary rocks, northern White Mountains, California. Geology, **15**: 1074–1078. doi:10.1130/0091-7613(1987)15<1074:AATSOM>2.0.CO;2.

Hawkesworth, C.J., Dhuime, B., Pietranik, A.B., Cawood, P.A., Kemp, A.I.S., and Storey, C.D. 2010. The generation and evolution of the continental crust. Journal of the Geological Society of Society, **167**: 229–248. doi:10.1144/0016-76492009-072.

Hawkesworth, C.J., Cawood, P.A., and Dhuime, B. 2016. Tectonics and crustal evolution. GSA Today, **26**: 4–11. doi:10.1130/GSATG272A.1.

Haxel, G.B., and Miller, D.M. 2007. Mesozoic rocks. *In* Geology and mineral resources of the East Mojave National Scenic Area, San Bernardino County, California. *Edited by* T.G. Theodore. United States Geological Survey Bulletin, 2160: 59-66.

Herzig, C.T., and Kimbrough, D.L. 2014. Santiago Peak volcanics: Early Cretaceous arc volcanism of the western Peninsular Ranges batholith, southern California. *In* Peninsular Ranges Batholith, Baja California and southern California. *Edited by* D.M. Morton and F.K. Miller. Geological Society of America Memoir 211. pp. 345–363. doi:10.1130/2014.1211(09).

Hildebrand, R.S. 2009. Did westward subduction cause Cretaceous–Tertiary orogeny in the North American Cordillera? Geological Society of America Special Paper, **457**: 71. doi:10.1130/2009.2457.

Hildebrand, R.S. 2013. Mesozoic assembly of the North American Cordillera. Geological Society of America Special Paper, **495**: 169. doi:10.1130/2013.2495.

Hildebrand, R.S. 2014. Geology, mantle tomography, and inclination corrected paleogeographic trajectories support westward subduction during Cretaceous orogenesis in the North American Cordillera. Geoscience Canada, **41**: 207–224. doi:10.12789/geocanj.2014.41.032.

Hildebrand, R.S. 2015. Dismemberment and northward migration of the Cordilleran orogen: Baja-BC resolved. GSA Today, **25**(11): 4–11. doi:10.1130/GSATG255A.1.

Hildebrand, R.S., and Whalen, J.B. 2014*a*. Arc and slab-failure magmatism in Cordilleran batholiths I—The Cretaceous Coastal batholith of Peru and its role in South American orogenesis and hemispheric subduction flip. Geoscience Canada, **41**: 255–282. doi:10.12789/geocanj.2014.41.047.

Hildebrand, R.S., and Whalen, J.B. 2014*b*. Arc and slab-failure magmatism in Cordilleran batholiths II—The Cretaceous Peninsular Ranges batholith of Southern and Baja California. Geoscience Canada, **41**: 399–458. doi:10.12789/geocanj.2014.41.059.

Hildebrand, R.S., and Whalen, J.B. 2017. The tectonic setting and origin of Cretaceous batholiths within the North American Cordillera: the case for slab failure magmatism and its signifcance for crustal growth. Geological Society of America Special Paper, **532**: 113.

Hildebrand, R.S., and Whalen, J.B. 2020. Arc and slab-failure magmatism of the Taconic Orogeny, western New England, USA. *In* Pannotia to Pangaea: Neoproterozoic and Paleozoic orogenic cycles in the Circum-Atlantic Region Murphy. *Edited by* J.B. Strachan, R.A. Strachan, and C.A. Quesada Mateo. Geological Society of London Special Publication 503. doi:10.1144/SP503-2019-247.

Hildebrand, R.S., and Whalen, J.B. 2021. The mid-Cretaceous Peninsular Ranges orogeny: a new slant on Cordilleran tectonics? II: northern United States and Canada. Canadian Journal of Earth Sciences. [This issue.] doi:10.1139/cjes-2021-0006.

Hildebrand, R.S., Whalen, J.B., and Bowring, S.A. 2018. Resolving the crustal composition paradox by 3.8 billion years of slab failure magmatism and collisional recycling of continental crust. Tectonophysics, **734-735**: 69–88. doi:10.1016/j.tecto.2018.04.001.

Hill, R.I. 1984. Petrology and Petrogenesis of Batholithic Rocks, San Jacinto Mountains, Southern California: Unpublished Ph.D. thesis, California Institute of Technology, Pasadena, Calif. 660pp.

Hirt, W.H. 2007. Petrology of the Mount Whitney Intrusive Suite, eastern Sierra Nevada, California: Implications for the emplacement and differentiation of composite felsic intrusions. Geological Society of America Bulletin, **119**: 1185–1200. doi:10.1130/B26054.1.

Hoffman, P.F. 2012. The Tooth of Time: How do passive margins become active? Geoscience Canada, **39**: 67–73.

Huang, C.-Y., Yuan, P.B., and Tsao, S.-J. 2006. Temporal and spatial records of active arc-continent collision in Taiwan: A synthesis. Geological Society of America Bulletin, **118**: 274–288. doi:10.1130/B25527.1.

Huber, N.K., Bateman, P.C., and Wahrhaftig, C. 1989. Geologic map of Yosemite National Park and vicinity, California. U.S. Geological Survey Miscellaneous Investigations Series Map I-1874, scale 1:125,000.

Jacobson, C.E., Grove, M., Pedrick, J.N., Barth, A.P., Marsaglia, K.M., Gehrels, G.E., and Nourse, J.A. 2011. Late Cretaceous–early Cenozoic tectonic evolution of the southern California margin inferred from provenance of trench and forearc sediments. Geological Society of America Bulletin, **123**: 485–506. doi:10.1130/B30238.1.

Jacques-Ayala, C. 1992. Stratigraphy of the Lower Cretaceous Cintura Formation, Sierra El Chanate, northwestern Sonora, Mexico. Universidad Nacional Autónoma de México, Instituto de Geologia Revista, **10**: 129–136.

Jagoutz, O., and Behn, M.D. 2013. Foundering of lower island-arc crust as an explanation for the origin of the continental Moho. Nature, **504**: 131–134. doi:10.1038/nature12758. PMID:24305163.

Jean, M.M., Hanan, B.B., and Shervais, J.W. 2014. Yellowstone hotspot– continental lithosphere interaction. Earth and Planetary Science Letters, **389**: 119–131. doi:10.1016/j.epsl.2013.12.012.

Johnson, S.E., Tate, M.C., and Fanning, C.M. 1999. New geologic mapping and SHRIMP U–Pb zircon data in the Peninsular Ranges batholith, Baja California, Mexico: Evidence for a suture? Geology, **27**: 743–746. doi:10.1130/0091-7613(1999)027<0743:NGMASU>2.3.CO;2.

Johnson, S.E., Schmidt, K.L., and Tate, M.C. 2002. Ring complexes in the Peninsular Ranges Batholith, Mexico and the USA: magma plumbing systems in the middle and upper crust. Lithos, **61**: 187–208. doi:10.1016/S0024-4937(02)00079-8.

Johnson, S.E., Fletcher, J.M., Fanning, C.M., Paterson, S.R., Vernon, R.H., and Tate, M.C. 2003. Structure and emplacement of the San Jose tonalite pluton, Peninsular Ranges batholith, Baja California, Mexico. Journal of Structural Geology, **25**: 1933–1957. doi:10.1016/S0191-8141(03)00015-4.

Johnston, S.T. 2008. The Cordilleran ribbon continent of North America. Annual Review of Earth and Planetary Sciences, **36**: 495–530. doi:10.1146/annurev.earth.36.031207.124331.

Kanter, L.R., and McWilliams, M.O. 1982. Rotation of the southernmost Sierra Nevada, California. Journal of Geophysical Research, **87**: 3819–3830. doi:10.1029/JB087iB05p03819.

Keppie, J.D., Murphy, J.B., Nance, R.D., and Dostal, J. 2012. Mesoproterozoic Oaxaquia-type basement in peri-Gondwanan terranes of Mexico, the Appalachians and Europe: T_{DM} age constraints on extent and significance. International Geology Review, **54**: 313–324. doi:10.1080/00206814.2010.543783.

Kimbrough, D.L., Smith, D.P., Mahoney, J.B., Moore, T.E., Grove, M., Gastil, R.G., et al. 2001. Forearc-basin sedimentary response to rapid Late Cretaceous batholith emplacement in the Peninsular Ranges of southern and Baja California. Geology, **29**: 491–494. doi:10.1130/0091-7613(2001)029<0491:FBSRTR>2.0.CO;2.

Kimbrough, D.L., Abbott, P.L., Balch, D.C., Bartling, S.H., Grove, M., Mahoney, J.B., and Donohue, R.F. 2014. Upper Jurassic Peñasquitos Formation—Forearc basin western wall rock of the Peninsular Ranges batholith. *In* Peninsular Ranges Batholith, Baja California and southern California. *Edited by* D.M. Morton and F.K. Miller. Geological Society of America Memoir 211. pp. 625–643. doi:10.1130/2014.1211 (19).

Kistler, R.W. 1990. Two different lithosphere types in the Sierra Nevada, California. *In* The nature and origin of Cordilleran magmatism. *Edited by* J.L. Anderson. Geological Society of America Memoir 174. pp. 271–281. doi:10.1130/MEM174-p271.

Kistler, R.W. 1993. Mesozoic intrabatholithic faulting, Sierra Nevada, California. *In* Mesozoic paleogeography of the western United States—II. *Edited by* G. Dunne,and K. McDougall. Society of Economic Paleontologists and Mineralogists, Pacific Section Book 71. pp. 247–262.

Kistler, R.W., and Peterman, Z.E. 1978. Reconstruction of crustal rocks of California on the basis of initial strontium isotopic compositions of Mesozoic granitic rocks. United States Geological Survey Professional Paper 1071. 17pp.

Kistler, R.W., Chappell, B.W., Peck, D.L., and Bateman, P.C. 1986. Isotopic variation in the Tuolumne intrusive suite, central Sierra Nevada, California. Contributions to Mineralogy and Petrology, **94**: 205–220. doi:10.1007/BF00592937.

Klute, M.A. 1991. Sedimentology, sandstone petrofacies, and tectonic setting of the late Mesozoic Bisbee Basin, southeastern Arizona. Ph.D. thesis, University of Arizona, Tucson, Ariz. 268pp.

Krebs, C.K., and Ruiz, J. 1987. Geochemistry of the Canelo Hills volcanics and implications for the Jurassic tectonic setting of southeastern Arizona. *In* Mesozoic rocks of southern Arizona and adjacent areas. *Edited by* W.R. Dickinson and M.A. Klute. Arizona Geological Society Digest 18. pp. 139–151.

Krummenacher, D., Gastil, R.G., Bushee, J., and Doupont, J. 1975. K–Ar apparent ages, Peninsular Ranges batholith, southern California and Baja California. Geological Society of America Bulletin, **86**: 760–768. doi:10.1130/0016-7606(1975)86<760:KAAPRB>2.0.CO;2.

Lackey, J.S., Valley, J.W., Chen, J.H., and Stockli, D.F. 2008. Dynamic magma systems, crustal recycling, and alteration in the central Sierra Nevada batholith: The oxygen isotope record. Journal of Petrology, **49**: 1397–1426. doi:10.1093/petrology/egn030.

Lackey, J.S., Cecil, R., Windham, C.J., Frazer, R.E., Bindeman, I.N., and Gehrels, G.E. 2012*a*. The Fine Gold intrusive suite: The roles of basement terranes and magma source development in the Early Cretaceous Sierra Nevada batholith. Geosphere, **8**: 292–313. doi:10.1130/GES00745.1.

Lackey, J.S., Eisenberg, J.I., and Sendek, C.L. 2012*b*. Day 2: The Fine Gold intrusive suite—Records of the nascent Cretaceous arc. *In* Formation of the Sierra Nevada Batholith: magmatic and tectonic processes and their tempos. *Edited by* V. Memeti, S.R. Paterson, and K.D. Putirka. Geological Society of America Field Guide 34. pp. 2-1–2-23. [Now supplanted by GSA Field Guide 34.]

Lahren, M.M., and Schweickert, R.A. 1989. Proterozoic and Lower Cambrian passive margin rocks of Snow Lake pendant, Yosemite-Emigrant Wilderness, Sierra Nevada, California: Evidence for major Early Cretaceous dextral translation. Geology, **17**: 156–160. doi:10.1130/0091-7613(1989)017<0156:PALCMR>2.3.CO;2.

Lahren, M.M., Schweickert, R.A., Mattinson, J.M., and Walker, J.D. 1990. Evidence of uppermost Proterozoic to Lower Cambrian miogeoclinal rocks and the Mojave–Snow Lake fault: Snow Lake pendant, central Sierra Nevada, California. Tectonics, **9**: 1585–1608. doi:10.1029/TC009i006p01585.

Lallemand, S., Font, Y., Bijwaard, H., and Kao, H. 2001. New insights on 3-D plates interaction near Taiwan from tomography and tectonic implications. Tectonophysics, **335**: 229–253. doi:10.1016/S0040-1951(01)00071-3.

Lambert, R.S.J., and Chamberlain, V.E. 1988. Cordilleria revisited, with a three-dimensional model for Cretaceous tectonics in British Columbia. The Journal of Geology, **96**: 47–60. doi:10.1086/629192.

Langenheim, V.E., Jachens, R.C., and Aiken, C. 2014. Geophysical framework of the Peninsular Ranges batholith— Implications for tectonic evolution and neotectonics. *In* Peninsular Ranges Batholith, Baja California and Southern California. *Edited by* D.M. Morton and F.K. Miller. Geological Society of America Memoir 211. pp. 1–20. doi:10.1130/2014.1211(01).

Lapierre, H., Tardy, M., Coulon, C., Ortiz Hernandez, E., Bourdier, J.-L., Martínez Reyes, J., and Freydier, C. 1992. Caractérisation, genèse et évolution géodynamique du terrain de Guerrero (Mexique occidental). Canadian Journal of Earth Sciences, **29**(11): 2478–2489. doi:10.1139/e92-194.

Larsen, E.S., Jr. 1948. Batholith and associated rocks of Corona, Elsinore, and San Luis Rey quadrangles, southern California. Geological Society of America Memoir 29. **29**: 185. doi:10.1130/MEM29.

Lawton, T.F., and McMillan, N.J. 1999. Arc abandonment as a cause for passive continental rifting: Comparison of the Jurassic Mexican Borderland rift and the Cenozoic Rio Grande rift. Geology, **27**: 779–782 doi:10.1130/0091-7613(1999)027<0779:AAAACF>2.3.CO;2.

Lawton, T.F., Sprinkel, D.A., and Waanders, F.L. 2007. The Cretaceous Canyon Range Conglomerate, central Utah: Stratigraphy, structure and significance. *In* Central Utah – Diverse Geology of a Dynamic Landscape. *Edited by* G.C. Willis, M.D. Hylland, D.L. Clark, and T.C. Chidsey, Jr. Utah Geological Association Publication, **36**: 101–122.

Lawton, T.F., Hunt, G.J., and Gehrels, G.E. 2010. Detrital zircon record of thrust belt unroofing in Lower Cretaceous synorogenic conglomerates, central Utah. Geology, **38**: 463–466. doi:10.1130/G30684.1.

Lawton, T.F., Amato, J.M., Machin, S.E.K., Gilbert, J.C., and Lucas, S.G. 2020. Transition from Late Jurassic rifting to middle Cretaceous dynamic foreland, southwestern U.S. and northwestern Mexico. Geological Society of America Bulletin, **132**: 2489–2516. doi:10.1130/B35433.1.

Lee, C.-T.A., and Anderson, D.L. 2015. Continental crust formation at arcs, the arclogite "delamination" cycle, and one origin for fertile melting anomalies in the mantle. Science Bulletin, **60**: 1141–1156. doi:10.1007/s11434-015-0828-6.

Leopold, M.B. 2016. Structure, construction, and emplacement of the Late Cretaceous Sonora Pass intrusive suite: Central Sierra Nevada batholith, California. M.S. thesis, San José State University, San José, California. 100pp.

Lindgren, W. 1915. The igneous geology of the Cordilleras and its problems. *In* Problems of American geology. *Edited by* W.N. Rice, F.D. Adams, A.P. Coleman, and C.D. Walcott. Yale University Press, New Haven, Connecticut. pp. 234–286.

Long, S.P. 2015. An upper-crustal fold province in the hinterland of the Sevier orogenic belt, eastern Nevada, U.S.A.: A Cordilleran Valley and Ridge in the Basin and Range. Geosphere, **11**: 404–424. doi:10.1130/GES01102.1.

Longwell, C.R. 1926. Structural studies in southern Nevada and western Arizona. Geological Society of America Bulletin, **37**: 551–584. doi:10.1130/GSAB-37-551.

Mack, G.H. 1987. Mid-Cretaceous (late Albian) change from rift to retroarc foreland basin in southwestern New Mexico. Geological Society of America Bulletin, **98**: 507–514. doi:10.1130/0016-7606(1987)98<507:MLACFR>2.0.CO;2.

Mansfield, C.F. 1979. Upper Mesozoic subsea fan deposits in the southern Diablo Range, California: Record of the Sierra Nevada magmatic arc. Geological Society of America Bulletin, **90**: 1025–1046. doi:10.1130/0016-7606(1979)90<1025:UMSFDI>2.0.CO;2.

Martini, M., Fitz, E., Solari, L., Camprubi, A., Hudleston, P.J., Lawton, T.F., et al. 2012. The Late Cretaceous fold-thrust belt in the Peña de Bernal–Tamazunchale area and its possible relationship to the accretion of the Guerrero terrane. *In* The Southern Cordillera and Beyond. *Edited by* J.J. Aranda-Gómez, G.G. Tolson, and R.S. Molina-Garza. Geological Society of America Field Guide. Vol. 25. 19–38. doi:10.1130/2012.0025(02).

Martini, M., Solari, L., and Lopez-Martínez, M. 2014. Correlating the Arperos Basin from Guanajuato, central Mexico, to Santo Tomás, southern Mexico: implications for the paleogeography and origin of the Guerrero terrane. Geosphere, **10**: 1385–1401. doi:10.1130/GES01055.1.

Mattauer, M., Collot, B., and Van den Driessche, J. 1983. Alpine model for the internal metamorphic zones of the North American Cordillera. Geology, **11**: 11–15. doi:10.1130/0091-7613(1983)11<11:AMFTIM>2.0.CO;2.

Mauel, D.J., Lawton, T.F., González-Léon, C., Iriondo, A., and Amato, J.M. 2011. Stratigraphy and age of Upper Jurassic strata in north-central Sonora, Mexico: southwestern Laurentian record of crustal extension and tectonic transition. Geosphere, **7**: 390–414. doi:10.1130/GES00600.1.

McMahon, T.P. 2000. Magmatism in an arc-continent collision zone: an example from Irian Jaya (western New Guinea), Indonesia. Buletin Geologi, **32**: 1–22.

McMahon, T.P. 2001. Origin of a collision-related ultrapotassic to calc-alkaline magmatic suite: the latest Miocene Minjuah volcanic field, Irian Jaya, Indonesia. Buletin Geologi, **33**: 47–77.

Memeti, V. 2009. Growth of the Cretaceous Tuolumne Batholith and Synchronous Regional Tectonics, Sierra Nevada, CA: A Coupled System in a Continental Margin Arc Setting. Ph.D. thesis, University of Southern California, Los Angeles, California. 282 pp.

Memeti, V., Gehrels, G.E., Paterson, S.R., Thompson, J.M., Mueller, R.M., and Pignotta, G.S. 2010. Evaluating the Mojave–Snow Lake fault hypothesis and origins of central Sierran metasedimentary pendant strata using detrital zircon provenance analyses. Lithosphere, **2**: 341–360. doi:10.1130/L58.1.

Mendoza, O.T., and Suastegui, M.G. 2000. Geochemistry and isotopic composition of the Guerrero Terrane (western Mexico): implications for the tectonomagmatic evolution of southwestern North America during the Late Mesozoic. Journal of South American Earth Sciences, **13**: 297–324. doi:10.1016/S0895-9811(00)00026-2.

Miggins, D.P., Premo, W.R., Snee, L.W., Yeoman, R., Naeser, N.D., Naeser, C.W., and Morton, D.M. 2014. Thermochronology of Cretaceous batholithic rocks in the northern Peninsular Ranges batholith, southern California: Implications for the Late Cretaceous tectonic evolution of southern California. *In* Peninsular Ranges Batholith, Baja California and Southern California. *Edited by* D.M. Morton and F.K. Miller. Geological Society of America Memoir 211. pp. 199–261. doi:10.1130/2014.1211(06).

Miller, C.F., Wooden, J.L., Bennett, V.C., Wright, J.E., Solomon, G.C., and Hurst, R.W. 1990. Petrogenesis of the composite peraluminous-metaluminous Old Woman–Piute Range batholith, southeastern California: Isotopic constraints. *In* The nature and origin of Cordilleran Magmatism. *Edited by* J.L. Anderson. Geological Society of America Memoir 174. pp. 99–109.

Miller, D.M., Miller, R.J., Nielson, J.E., Wilshire, H.G., Howard, K.A., and Stone, P. 2007. Geologic map of the East Mojave National Scenic Area, California. *In* Geology and mineral resources of the East Mojave National Scenic Area, San Bernardino County, California. *Edited by* T.G. Theodore. United States Geological Survey Bulletin 2160. Scale 1:125,000.

Monger, J.W.H., Heyden, P.V.D., Journeay, J.M., Evenchick, C.A., and Mahoney, J.B. 1994. Jurassic-Cretaceous basins along the Canadian Coast Belt: Their bearing on pre-mid-Cretaceous sinistral displacements. Geology, **22**: 175–178. doi:10.1130/0091-7613(1994)022<0175:JCBATC>2.3.CO;2.

Monod, O., Faure, M., and Salinas, J.-C. 1994. Intra-arc opening and closure of a marginal sea: The case of the Guerrero terrane (SW Mexico). The Island Arc, **3**: 25–34. doi:10.1111/j.1440-1738.1994.tb00002.x.

Monod, O., Busnardo, R., and Guerrero-Suastegui, M. 2000. Late Albian ammonites from the carbonate cover of the Teloloapan arc volcanic rocks (Guerrero State, Mexico). Journal of South American Earth Sciences, **13**: 377–388. doi:10.1016/S0895-9811(00)00030-4.

Moore, J.G. 1959. The quartz boundary line in the western United States. The Journal of Geology, **67**: 198–210. doi:10.1086/626573.

Moore, J.G., Grantz, A., and Blake, M.C., Jr. 1961. The Quartz Diorite Boundary Line in northwestern North America. United States Geological Survey Professional Paper 424-C. pp. 87–90.

Moores, E.M. 1970. Ultramafics and orogeny, with models of the U.S. Cordillera and Tethys. Nature, **228**: 837–842. doi:10.1038/228837a0. PMID:16058720.

Moores, E.M., and Day, H.W. 1984. Overthrust model for Sierra Nevada. Geology, **12**: 416–419. doi:10.1130/0091-7613(1984)12<416:OMFTSN>2.0.CO;2.

Morris, R.A., DeBari, S.M., Busby, C., Medynski, S., and Jicha, B.R. 2019. Building arc crust: plutonic to volcanic connections in an extensional oceanic arc, the southern Alisitos arc, Baja California. Journal of Petrology, **60**: 1195–1228. doi:10.1093/petrology/egz029.

Morton, D.M., Miller, F.K., Kistler, R.W., Premo, W.R., Lee, C.-T.A., Langenheim, V.E., et al. 2014. Framework and petrogenesis of the northern Peninsular Ranges batholith, southern California. *In* Peninsular Ranges Batholith, Baja California and southern California. *Edited by* D.M. Morton and F.K. Miller. Geological Society of America Memoir 211. pp. 61–143. doi:10.1130/2014.1211(03).

Mueller, P.A., Wooden, J.L., Mogk, D.W., and Foster, D.A. 2011. Paleoproterozoic evolution of the Farmington zone: Implications for terrane accretion in southwestern Laurentia. Lithosphere, **3**: 401–408. doi:10.1130/L161.1.

Müller, R.D., Sdrolias, M., Gaina, C., and Roest, W.R. 2008. Age, spreading rates, and spreading asymmetry of the world's ocean crust. Geochemistry Geophysics Geosystems, **9**: Q04006. doi:10.1029/2007GC001743.

Murray, J.D. 1979. Outlines of the structure and emplacement history of a tonalite pluton in the Peninsular Ranges batholith, northern Baja California, Mexico. *In* Mesozoic crystalline rocks. *Edited by* P.L. Abbott and V.R. Todd. California State University, Department of Geological Sciences, San Diego, Calif. pp. 163–176.

Nelson, S., Harris, R., Dorais, M., Heizler, M., Constenius, K., and Barnett, D. 2002. Basement complexes in the Wasatch fault, Utah, provide new limits on crustal accretion. Geology, **30**: 831–834. doi:10.1130/0091-7613(2002)030<0831:BCITWF>2.0.CO;2.

Nokleberg, W.J. 1981. Stratigraphy and structure of the Strawberry Mine roof pendant, central Sierra Nevada, California. United States Geological Survey Professional Paper 1154. 18pp.

Nourse, J.A. 2002. Middle Miocene reconstruction of the central and eastern San Gabriel Mountains, southern California, with implications for the evolution of the San Gabriel fault and Los Angeles basin, *In* Contributions to crustal evolution of the southwestern United States. *Edited by* A. Barth. Geological Society of America Special Paper 365. pp. 161–185.

Ojakangas, R.W. 1968. Cretaceous sedimentation, Sacramento Valley, California. Geological Society of America Bulletin, **79**: 973–1008. doi:10.1130/0016-7606(1968)79[973:CSSVC]2.0.CO;2.

Orme, D.A., and Graham, S.A. 2018. Four-dimensional model of Cretaceous depositional geometry and sediment flux in the northern Great Valley forearc, California. *In* Tectonics, sedimentary basins, and provenance: a celebration of William R. Dickinson's career. *Edited by* R.V. Ingersoll, T.F. Lawton, and S.A. Graham. Geological Society of America Special Paper 540. pp. 409–424. doi:10.1130/2018.2540(18).

Ormerod, D.S., Rogers, N.W., and Hawkesworth, C.J. 1991. Melting in the lithospheric mantle: Inverse modelling of alkali-olivine basalts from the Big Pine volcanic field, California. Contributions to Mineralogy and Petrology, **108**: 305–317. doi:10.1007/BF00285939.

Ortega-Gutiérrez, F., Ruiz, J., and Centeno-García, E. 1995. Oaxaquia, a Proterozoic microcontinent accreted to North America during the late Paleozoic. Geology, **23**: 1127–1130. doi:10.1130/0091-7613(1995)023<1127:OAPMAT>2.3.CO;2.

Ortega-Rivera, A. 2003. Geochronological constraints on the tectonic history of the Peninsular Ranges Batholith of Alta and Baja California: Tectonic implications for western México, *In* Tectonic Evolution of Northwestern Mexico and the Southwestern USA. *Edited by* S.E. Johnson, S.R. Patterson, J.M. Fletcher, G.H. Girty, D.L. Kimbrough, and A. Martín-Barajas. Geological Society of America Special Paper 374. pp. 297–335. doi:10.1130/0-8137-2374-4.297.

Ortega-Rivera, A., Farrar, E., Hanes, J.A., Archibald, D.A., Gastil, R.G., Kimbrough, D.L., et al. 1997. Chronological constraints on the thermal and tilting history of the Sierra San Pedro Mártir pluton, Baja California, Mexico, from U-Pb, ^{40}Ar/^{39}Ar and fission-track geochronology. Geological Society of America Bulletin, **109**: 728–745. doi:10.1130/0016-7606(1997)109<0728:CCOTTA>2.3.CO;2.

Page, W.R., Lundstrom, S.C., Harris, A.G., Langenheim, V.E., Wotkman, J.B., Mahan, S.A., et al. 2005. Geologic and Geophysical Maps of the Las Vegas 30′ × 60′ Quadrangle, Clark and Nye County, Nevada, and Inyo County, California. U.S. Geological Survey Scientific Investigations Map 2814, scale 1:100,000.

Pape, D.E., Spell, T.L., Bonde, J.W., Fish, B., and Rowland, S.M. 2011. ^{40}Ar/^{39}Ar isotopic dates for the fossiliferous Willow Tank Formation (Cretaceous) in Valley of Fire State Park, Nevada. Geological Society of America Abstracts with Programs, 43(5): 586.

Paterson, S.R., Memeti, V., Anderson, L., Cao, W., Lackey, J.S., Putirka, K.D., et al. 2014. Day 6: Overview of arc processes and tempos. *In* Formation of the Sierra Nevada Batholith: magmatic and tectonic processes and their tempos. *Edited by* V. Memeti, S.R. Paterson, and K.D. Putirka. Geological Society of America Field Guide 34. pp. 87–116. doi:10.1130/2014.0034(06).

Pavlis, T.L., Amato, J.M., Trop, J.M., Ridgway, K.D., Roeske, S.M., and Gehrels, G.E. 2020*a*. Subduction polarity in ancient arcs: A call to integrate geology and geophysics to decipher the Mesozoic tectonic history of the northern Cordillera of North America: Reply. GSA Today, **29**: 4–10. doi:10.1130/GSATG465Y.1.

Pavlis, T.L., Amato, J.M., Trop, J.M., Ridgway, K.D., Roeske, S.M., and Gehrels, G.E. 2020*b*. Subduction polarity in ancient arcs: A call to integrate geology and geophysics to decipher the Mesozoic tectonic history of the northern Cordillera of North America: Reply. GSA Today, **30**: e51. doi:10.1130/GSATG465Y.1.

Pearce, J.A., Harris, N.B.W., and Tindle, A.G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology, **25**: 956–983. doi:10.1093/petrology/25.4.956.

Peryam, T.C., Lawton, T.F., Amato, J.M., González-León, C.M., and Mauel, D.J. 2012. Lower Cretaceous strata of the Sonora Bisbee Basin: A record of the tectonomagmatic evolution of northwestern Mexico. Geological Society of America Bulletin, **124**: 532–548. doi:10.1130/B30456.1.

Phillips, J.R. 1993. Stratigraphy and structural setting of the mid-Cretaceous Olvidada Formation, Baja California Norte, Mexico. *In* Prebatholithic Stratigraphy of Peninsular California. *Edited by* R.G. Gastil and R.H. Miller. Geological Society of America Special Paper 279. pp. 97–106.

Pickett, D.A., and Saleeby, J.B. 1993. Thermobarometric constraints on the depth of exposure and conditions of plutonism and metamorphism at deep levels of the Sierra Nevada Batholith, Tehachapi Mountains, California. Journal of Geophysical Research: Solid Earth, **98**: 609–629. doi:10.1029/92JB01889.

Powell, R.E. 1993. Balanced palinspastic reconstruction of pre–late Cenozoic paleogeography, southern California: Geologic and kinematic constraints on evolution of the San Andreas fault system. *In* The San Andreas Fault System: displacement, palinspastic reconstruction, and geologic evolution. *Edited by* R.E. Powell, R.J.H. Weldon, and J.C. Matti. Geological Society of America Memoir 178. pp. 1–106. doi:10.1130/MEM178-p1.

Premo, W.R., and Morton, D.M. 2014. SHRIMP-RG U–Pb ages of provenance and metamorphism from detrital zircon populations and Pb–Sr–Nd signatures of prebatholithic metasedimentary rocks at Searl Ridge, northern Peninsular Ranges batholith, southern California: Implications for their age, origin, and tectonic setting. *In* Peninsular Ranges Batholith, Baja California and southern California. *Edited by* D.M. Morton and F.K. Miller. Geological Society of America Memoir 21. pp. 449–498. doi:10.1130/2014.1211(14).

Premo, W.R., Morton, D.M., Wooden, J.L., and Fanning, C.M. 2014. U–Pb zircon geochronology of plutonism in the northern Peninsular Ranges batholith, southern California. *In* Peninsular Ranges Batholith, Baja California and southern California. *Edited by* D.M. Morton and F.K. Miller. Geological Society of America Memoir 211. pp. 145–180. doi:10.1130/2014.1211(04).

Pubellier, M., Rangin, C., Rascon, B., Chorowicz, J., and Bellon, H. 1995. Cenomanian thrust tectonics in the Sahuaria region, Sonora: Implications about northwestern Mexico megashears. *In* Studies on the Mesozoic of Sonora and Adjacent Areas. *Edited by* C. Jacques-Ayala, C.M. González-León, and J. Roldán-Quintana. Geological Society of America Special Paper 301. pp. 111–120. doi:10.1130/0-8137- 2301-9.111.

Pujols, E.J., Stockli, D.F., Constenius, K.N., and Horton, B.K. 2020. Thermochronological and geochronological constraints on Late Cretaceous unroofing and proximal sedimentation in the Sevier orogenic belt, Utah. Tectonics, **39**: e2019TC005794. doi:10.1029/2019TC005794.

Putirka, K. 1999. Melting depths and mantle heterogeneity beneath Hawaii and the East Pacific Rise: constraints from Na/Ti and rare earth element ratios. Journal of Geophysical Research, **104**: 2817–2829. doi:10.1029/1998JB900048.

Quick, J.D., Hogan, J.P., Wizevich, M., Obrist-Farner, J., and Crowley, J.L. 2020. Timing of deformation along the Iron Springs thrust, southern Sevier fold-and-thrust belt, Utah: evidence for an extensive thrusting event in the mid-Cretaceous. Rocky Mountain Geology, **55**: 75–89. doi:10.24872/rmgjournal.55.2.75.

Reid, S.A. 1988. Late Cretaceous and Paleogene sedimentation along the east side of the San Joaquin basin. *In* Studies of the geology of the San Joaquin Basin. *Edited by* S.A Graham, Pacific Section S.E.P.M, 60: 157-171.

Ross, D.C. 1989. The Metamorphic and Plutonic Rocks of the Southernmost Sierra Nevada, California, and Their Tectonic Framework. United States Geological Survey Professional Paper 1381. 159pp.

Rudnick, R.L. 1995. Making continental crust. Nature, **378**: 571–578. doi:10.1038/378571a0.

Sacks, P.E., and Secor, D.T., Jr. 1990. Delamination in collisional orogens. Geology, **18**: 999–1002. doi:10.1130/0091-7613(1990)018<0999:DICO>2.3.CO;2.

Saleeby, J.B., Kistler, R.W., Longiaru, S., Moore, J.G., and Nokleberg, W.J. 1990. Middle Cretaceous silicic metavolcanic rocks in the Kings Canyon area, central Sierra Nevada, California. *In* The nature and origin of Cordilleran magmatism. *Edited by* J.L. Anderson. Geological Society of America Memoir 174. pp. 251–271. doi:10.1130/MEM174-p251.

Saleeby, J.B., Ducea, M.N., Busby, C.J., Nadin, E.S., and Wetmore, P.H. 2008. Chronology of pluton emplacement and regional deformation in the southern Sierra Nevada batholith, California. *In* Ophiolites, arcs, and batholiths: a tribute to Cliff Hopson. *Edited by* J.E. Wright and J.W. Shervais. Geological Society of America Special Paper 438. pp. 397–427. doi:10.1130/2008.2438(14).

Scherer, H.H., Ernst, W.G., and Hanson, R.B. 2008. Geologic implications of new zircon U-Pb ages from the White Mountain Peak Metavolcanic Complex, eastern California. Tectonics, **27**. doi:10.1029/2007TC002141.

Schmidt, K.L., and Paterson, S.R. 2002. A doubly vergent fan structure in the Peninsular Ranges batholith: transpression or local complex flow around a continental margin buttress? Tectonics, **21**: 14-1–14-19. doi:10.1029/2001TC001353.

Schmidt, K.L., Paterson, S.R., Blythe, A.E., and Kopf, C. 2009. Mountain building across a lithospheric boundary during arc construction: The Cretaceous Peninsular Ranges batholith in the Sierra San Pedro Mártir of Baja California, Mexico. Tectonophysics, **477**: 292–310. doi:10.1016/j.tecto.2009.04.020.

Schmidt, K.L., Wetmore, P.H., Alsleben, H., and Paterson, S.R. 2014. Mesozoic tectonic evolution of the southern Peninsular Ranges batholith, Baja California, Mexico: Long-lived history of a collisional segment in the Mesozoic Cordilleran arc. *In* Peninsular Ranges Batholith, Baja California and southern California. *Edited by* D.M. Morton, and F.K. Miller. Geological Society of America Memoir 211. pp. 645–668. doi:10.1130/2014.1211.

Shaw, S.E., Todd, V.R., and Grove, M. 2003. Jurassic peraluminous gneissic granites in the axial zone of the Peninsular Ranges, southern California. *In* Tectonic Evolution of Northwestern Mexico and the Southwestern USA. *Edited by* S.E. Johnson, S.R. Patterson, J.M. Fletcher, G.H. Girty, D.L. Kimbrough, and A. Martín-Barajas. Geological Society of America Special Paper 374. pp. 157–183. doi:10.1130/0-8137-2374-4.157.

Shaw, S.E., Todd, V.R., Kimbrough, D.L., and Pearson, N.J. 2014. A west-to-east geologic transect across the Peninsular Ranges batholith, San Diego County, California: Zircon ^{176}Hf/^{177}Hf evidence for the mixing of crustal- and mantle-derived magmas, and comparisons with the Sierra Nevada batholith. *In* Peninsular Ranges Batholith, Baja California and Southern California. *Edited by* D.M. Morton and F.K. Miller. Geological Society of America Memoir 211. pp. 499–536. doi:10.1130/2014.1211(15).

Sigloch, K., and Mihalynuk, M.G. 2020. Comment on GSA Today article by Pavlis et al., 2019: “Subduction Polarity in Ancient Arcs: A Call to Integrate Geology and Geophysics to Decipher the Mesozoic Tectonic History of the Northern Cordillera of North America”. GSA Today, **30**: e47. doi:10.1130/GSATG431C.1.

Silver, L.T., and Chappell, B. 1988. The Peninsular Ranges batholith: An insight into the Cordilleran batholiths of southwestern North America. Earth and Environmental Science Transactions of the Royal Society of Edinburgh, **79**: 105–121. doi:10.1017/S0263593300014152.

Silver, L.T., Taylor, H.P., Jr., and Chappell, B. 1979. Some petrological, geochemical and geochronological observations of the Peninsular Ranges batholith near the international border of the U.S.A. and Mexico. *In* Mesozoic Crystalline Rocks. *Edited by* P.L. Abbott, and V.R. Todd, California State University, Department of Geological Sciences, San Diego, Calif. pp. 83–110.

Sisson, T.W., and Moore, J.G. 2013. Geologic map of the southwestern Sequoia National Park. United States Geological Survey, Open-File Report 2013-1096, scale 1:24,000.

Sisson, T.W., Grove, T.L., and Coleman, D.S. 1996. Hornblende gabbro sill complex at Onion Valley, California, and a mixing origin for the Sierra Nevada batholith. Contributions to Mineralogy and Petrology, **126**: 81–108. doi:10.1007/s004100050237.

Skipp, B. 1987. Basement thrust sheets in the Clearwater orogenic zone, central Idaho and western Montana. Geology, **15**: 220–224. doi:10.1130/0091-7613(1987)15<220:BTSITC>2.0.CO;2.

Skipp, B., and Hait, M.H., Jr. 1977. Allochthons along the northeast margin of the Snake River plain, Idaho, *In* Rocky Mountain Thrust Belt Geology and Resources. *Edited by* E.L. Heisey, and D.E. Lawson, D.E. Wyoming Geological Association, Annual Field Conference, 29: 499–516.

Snow, C.A., and Ernst, W.G. 2008. Detrital zircon constraints on sediment distribution and provenance of the Mariposa Formation, central Sierra Nevada Foothills, California. *In* Ophiolites, arcs, and batholiths: a tribute to Cliff Hopson. *Edited by* J.E. Wright and J.W. Shervais. Geological Society of America Special Paper 438. pp. 311–330. doi:10.1130/2008.2438(11).

Speed, R.C., Elison, M.W., and Heck, R.R. 1988. Phanerozoic tectonic evolution of the Great Basin. *In* Metamorphism and crustal evolution of the western United States, Rubey Volume 7. *Edited by* W.G. Ernst. Prentice Hall, Englewood Cliffs, N.J. pp. 572–605.

Stewart, J.H. 2005. Evidence for Mojave-Sonora megashear — Systematic left-lateral offset of Neoproterozoic to Lower Jurassic strata and facies, western United States and northwestern Mexico. *In* The Mojave-Sonora Megashear Hypothesis: Development, Assessment, and Alternatives. *Edited by* T.H. Anderson, J.A. Nourse, J.W. McKee, and M.B. Steiner. Geological Society of America Special Paper, **393**: 209–231. doi:10.1130/0-8137-2393-0.209.

Stone, P. 2006. Geologic map of the west half of the Blyth 30’ by 60’ quadrangle, Riverside County, California and La Paz County, Arizona. United States Geological Survey Scientific Investigation Map 2922, scale 1:100,000.

Stone, P., and Kelly, M.M. 1989. Geologic map of the Palen Pass quadrangle, Riverside County, California. United States Geological Survey Miscellaneous Field Studies Map MF-2020, scale 1:24,000.

Streckeisen, A.L., and LeMaitre, R.W. 1979. Chemical approximation to modal QAPF classification of the igneous rocks. Neus Jahrbuch fur Mineralogie, **136**: 169–206.

Suppe, J. 1987. The active Taiwan mountain belt In Anatomy of Mountain Ranges. *Edited by* J.P. Schaer and J. Rodgers. Princeton University Press, Princeton, New Jersey. pp. 277–293.

Surpless, K.D., Graham, S.A., Covault, J.A., and Wooden, J.L. 2006. Does the Great Valley sequence contain Jurassic strata?: Reevaluation of the age and early evolution of a classic forearc basin. Geology, **34**: 21–24. doi:10.1130/G21940.1.

Talavera-Mendoza, O., Ruiz, J., Gehrels, G.E., Valencia, V.A., and Centeno-García, E. 2007. Detrital zircon U/Pb geochronology of southern Guerrero and western Mixteca arc successions (southern Mexico): new insights for the tectonic evolution of southwestern North America during the late Mesozoic. Geological Society of America Bulletin, **119**: 1052–1065. doi:10.1130/B26016.1.

Tardy, M., Lapierre, H., Freydier, C., Coulon, C., Gill, J.-B., Mercier de Lep- Inay, B., et al. 1994. The Guerrero suspect terrane (western Mexico) and coeval arc terranes (the Greater Antilles and the Western Cordillera of Colombia): A late Mesozoic intra-oceanic arc accreted to cratonal America during the Cretaceous. Tectonophysics, **230**: 49–73. doi:10.1016/0040-1951(94)90146-5.

Taylor, H.P., and Silver, L.T. 1978. Oxygen isotope relationships in plutonic igneous rocks of the Peninsular Ranges batholith, Southern and Baja California. *In* Short Papers of the Fourth International Conference on Geochronology, Cosmochronology, Isotope Geology, 1978. *Edited by* R.E. Zartman. United States Geological Survey Open-File Report 78-701. pp. 423–426.

Taylor, W.J., Bartley, J.M., Martin, M.W., Geissman, J.W., Walker, J.D., Armstrong, P.A., and Fryxell, J.E. 2000. Relations between hinterland and foreland shortening: Sevier orogeny, central North American Cordillera. Tectonics, **19**: 1124–1143. doi:10.1029/1999TC001141.

Teng, L.S. 1996. Extensional collapse of the northern Taiwan mountain belt. Geology, **24**: 949–952. doi:10.1130/0091-7613(1996)024<0949:ECOTNT>2.3.CO;2.

Todd, V.R. 2004. Preliminary geologic map of the El Cajon 30′ x 60′ quadrangle, southern California. United States Geological Survey Open-File Report 2004-1361.

Todd, V.R., and Shaw, S.E. 1979. Structural, metamorphic, and intrusive framework of the Peninsular Ranges batholith in southern San Diego County, California. *In* Mesozoic crystalline rocks. *Edited by* P.L. Abbott and V.R. Todd. California State University, Department of Geological Sciences, San Diego, Calif. pp. 177–231.

Todd, V.R., Erskine, B.G., and Morton, D.M. 1988. Metamorphic and tectonic evolution of the northern Peninsular Ranges batholith, southern California. *In* Metamorphism and Crustal Evolution of the Western United States, Rubey Volume VII. *Edited by* W.G. Ernst, W.G. Prentice Hall, Englewood Cliffs, New Jersey. pp. 894–937.

Todd, V.R., Shaw, S.E., and Hammarstrom, J.M. 2003. Cretaceous plutons of the Peninsular Ranges batholith, San Diego and westernmost Imperial Counties, California: Intrusion across a Late Jurassic continental margin. *In* Tectonic evolution of northwestern Mexico and the southwestern USA. *Edited by* S.E. Johnson, S.R. Patterson, J.M. Fletcher, G.H. Girty, D.L. Kimbrough, and A. Martín-Barajas. Geological Society of America Special Paper 374. pp. 185–235. doi:10.1130/0-8137-2374-4.185.

Troyer, R., Barth, A.P., Wooden, J.L., and Jacobson, C. 2006. Provenance and timing of Sevier foreland basin sediments in the Valley of Fire, southern Nevada, from U-Pb geochronology. Geological Society of America Abstracts with Programs, **38**(7): 369.

Tulloch, A.J., and Kimbrough, D.L. 2003. Paired plutonic belts in convergent margins and the development of high Sr/Y magmatism: Peninsular Ranges batholith of Baja-California and Median batholith of New Zealand. *In* Tectonic evolution of northwestern Mexico and the southwestern USA. *Edited by* S.E. Johnson, S.R. Patterson, J.M. Fletcher, G.H. Girty, D.L. Kimbrough, and A. Martín-Barajas. Geological Society of America Special Paper 374. pp. 275–295. doi:10.1130/0-8137-2374-4.275.

Van Buer, N.J., and Miller, E.L. 2010. Sahwave batholith, NW Nevada: Cretaceous arc flare-up in a basinal terrane. Lithosphere, **2**: 423–446. doi:10.1130/L105.1.

Viallon, C., Huchon, P., and Barrier, E. 1986. Opening of the Okinawa basin and collision in Taiwan: A retreating trench model with lateral anchoring. Earth and Planetary Science Letters, **80**: 145–155. doi:10.1016/0012-821X(86)90028-2.

Wahrhaftig, C. 2000. Geologic map of the Tower Peak Quadrangle, central Sierra Nevada, California. United States Geological Survey, Geologic Investigations Series Map I-2697, scale 1:62,500.

Walawender, M.J., Gastil, R.G., Clinkenbeard, J.P., McCormick, W.V., Eastman, B.G., Wernicke, R.S., et al. 1990. Origin and evolution of the zoned La Posta–type plutons, eastern Peninsular Ranges batholith, southern and Baja California. *In* The Nature and Origin of Cordilleran Magmatism. *Edited by* J.L. Anderson. Geological Society of America Memoir 174. pp. 1–18. doi:10.1130/MEM174-p1.

Walker, J.D., Burchfiel, B.C., and Davis, G.A. 1995. New age controls on initiation and timing of foreland belt thrusting in the Clark Mountains, southern California. Geological Society of America Bulletin, **107**: 742–750. doi:10.1130/0016-7606(1995)107<0742:NACOIA>2.3.CO;2.

Wells, M.L. 2016. A major mid-Cretaceous shortening event in the southern Sevier orogenic belt: Continental record of global plate reorganization. Geological Society of America Abstracts with Programs, **48**(7). doi:10.1130/abs/2016AM-287809.

Wetmore, P.H., and Ducea, M.N. 2011. Geochemical evidence of a near-surface history for source rocks of the central Coast Mountains Batholith, British Columbia. International Geology Review, **51**: 1–26. doi:10.1080/00206810903028219.

Wetmore, P.H., Alsleben, H., Paterson, S.R., Ducea, M.N., Gehrels, G.E., and Valencia, V.A. 2005. Field Trip to the Northern Alisitos Arc Segment: Ancestral Agua Blanca Fault Region. *In* Field Conference Guidebook for the VII International Meeting of the Peninsular Geological Society. Peninsular Geological Society, Ensenada, Baja California, Mexico. 39pp.

Whalen, J.B., and Frost, C.D. 2013. The Q-ANOR diagram: A tool for the petrogenetic and tectonomagmatic characterization of granitic suites. Geological Society of America Abstracts with Programs, **45**(3): 24.

Whalen, J.B., and Hildebrand, R.S. 2019. Trace element discrimination of arc, slab failure, and A-type granitic rocks. Lithos, **348-349**: 105179. doi:10.1016/j.lithos.105179.

White, J.D.L., and Busby-Spera, C.J. 1987. Deep marine arc apron deposits and syndepositional magmatism in the Alisitos Group at Punta Cono, Baja California, Mexico. Sedimentology, **34**: 911–927. doi:10.1111/j.1365-3091.1987.tb00812.x.

Wood, D.J. 1997. Geology of the eastern Tehachapi Mountains and Late Cretaceous–Early Cenozoic tectonics of the southern Sierra Nevada region, Kern County, California. Ph.D. thesis, California Institute of Technology, Pasadena, Calif. 287pp.

Wood, D.J., and Saleeby, J.B. 1998. Late Cretaceous–Paleocene extensional collapse and disaggregation of the southernmost Sierra Nevada batholith. *In* Integrated Earth and Environmental Evolution of the Southwestern United States: The Clarence A. Hall Jr. Volume. *Edited by* W.G. Ernst and C.A. Nelson. Columbia, Maryland, Bellwether Publishing for the Geological Society of America. pp. 289–325.

Wright, J.E., and Wyld, S.J. 2007. Alternative tectonic model for Late Jurassic through Early Cretaceous evolution of the Great Valley Group, California. *In* Convergent margin terranes and associated regions: a tribute to W.G. Ernst. *Edited by* M. Cloos, W.D. Carlson, Gilbert, J.G. Liou, and S.S. Sorensen. Geological Society of America Special Paper 419. pp. 81–95. doi:10.1130/2007.2419(04).

Yonkee, W.A., Parry, W.T., and Bruhn, R.L. 2003. Relations between progressive deformation and fluid-rock interaction during shear zone growth in a basement-cored thrust sheet, Sevier orogenic belt, Utah. American Journal of Science, **303**: 1–59. doi:10.2475/ajs.303.1.1.

Yonkee, W.A., Eleogram, B., Wells, M.L., Stockli, D.F., Kelley, S., and Barber, D.E. 2019. Fault slip and exhumation history of the Willard thrust sheet, Sevier fold-thrust belt, Utah: relations to wedge propagation, hinterland uplift, and foreland basin sedimentation. Tectonics, **38**: 2850–2893. doi:10.1029/2018TC005444.