Geological Society of America
Special Paper 365
2002

Controls on orogenesis along an ocean-continent margin transition in the Jura-Cretaceous Peninsular Ranges batholith

K.L. Schmidt*
Natural Sciences, Lewis-Clark State College, Lewiston, Idaho 83501, USA
P.H. Wetmore
Department of Earth Sciences, University of Southern California, Los Angeles, California 90089-0740, USA
S.E. Johnson
Department of Geological Sciences, University of Maine, Orono, Maine 04469-5790, USA
S.R. Paterson
Department of Earth Sciences, University of Southern California, Los Angeles, California 90089-0740, USA

ABSTRACT

The Jura-Cretaceous Peninsular Ranges batholith (PRb) of southern and Baja California is a remarkable example of a zoned batholith containing distinct oceanic (western) and continental (eastern) basements. The transition between these basements is marked by a crustal-scale boundary along which distinct volcano-sedimentary, structural, and metamorphic histories evolved during Mesozoic orogenesis. Our work across this boundary in the Sierra San Pedro Martir of Baja California, Mexico indicates that it controlled a number of processes in the PRb including magmatism, the location of forearc or intraarc basins, and the locus and extent of contractional deformation and denudation. However, our work farther north indicates that notable differences occur along strike in the character of the western arc and transition zone, and these differences are most pronounced across the modern Agua Blanca fault. This fault was also active in the Mesozoic, at which time it separated the western zone into northern and southern arc segments.

In the northern half of the batholith, the western arc (Santiago Peak Volcanics) lie in depositional contact with Triassic(?)-Jurassic sediments that mostly received detritus of North American origin and show a long history of contractional deformation and late extensional overprint. We concur that this part of the batholith evolved in Jura-Cretaceous time across an inherited ocean-continent crustal join. In contrast, south of the Agua Blanca fault, the boundary between the western arc (Alisitos) and transitional zones is marked by reverse mylonite shear zones that typically correspond with inverted metamorphic gradients and sharp steps in maximum pressures and cooling histories. Here the transition zone contains basins that collected mostly volcanogenic detritus during the Late Jurassic-Early Cretaceous and preserve a history of long-lived contractional deformation including shear zone development during collision. Thus, although both northern and southern segments of the transition zone share similarities in their plutonic, structural, metamorphic, and denuda-

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*E-mail: klschmidt@lcsc.edu

Schmidt, K.L., Wetmore, P.H., Johnson, S.E., and Paterson, S.R., 2002, Controls on orogenesis along an ocean-continent margin transition in the Jura-Cretaceous Peninsular Ranges batholith, *in* Barth, A., ed., Contributions to Crustal Evolution of the Southwestern United States: Boulder, Colorado, Geological Society of America Special Paper 365, p. 49–71.

tional histories only the southern segment experienced collision. These observations indicate that the crustal-scale boundary strongly controlled subsequent evolution but that collision was not the major driving process for orogenesis.

INTRODUCTION

Mesozoic batholiths emplaced along much of the Cordillera show an increasing continental basement signature from their oceanic to landward positions. In many cases it can be demonstrated that the more outboard assemblages in these batholiths evolved on oceanic to transitional crust. A classic example of one of these oceanic to continental basement transitions occurs in the Jura-Cretaceous Peninsular Ranges batholith (PRb) of the southern Cordillera, which extends >800 km from Riverside California to the 28th parallel in Baja California (Fig. 1). The transition in this batholith between a western zone with strong oceanic basement affinity and an eastern zone of strong continental affinity is narrow and sharply defined by across-strike changes in the petrology and geochemistry of plutons (e.g., Silver et al., 1979; DePaolo, 1981; Gastil et al., 1990; Walawender et al., 1991, Tate and Johnson, 2000). This zone is particularly striking because a number of other geological features also define it including a belt of distinctive clastic to volcaniclastic metasediments (e.g., Gastil et al., 1975; Gastil and Miller, 1984; Gastil, 1993), a discrete belt of contractional structures (e.g., Gastil et al., 1975; Todd et al., 1988; Thomson and Girty, 1994; Johnson et al., 1999a; Schmidt, 2000), and a sharp contrast between western shallow and eastern deeper crustal levels (e.g., Todd et al., 1988; Grove, 1994). These across-strike transitions are a hallmark of the PRb, perhaps better developed here than in any other batholith in the world.

Three tectonic models have been proposed for the PRb, in part to explain the characteristics of the transition zone. These include construction of the Mesozoic batholith across a pre-existing ocean-continental lithosphere transition, collision of a fringing oceanic arc by backarc basin collapse, and collision of an exotic island arc (Fig. 2). The first and most fixist model for the batholith, that of an inherited pre-Mesozoic ocean-continent

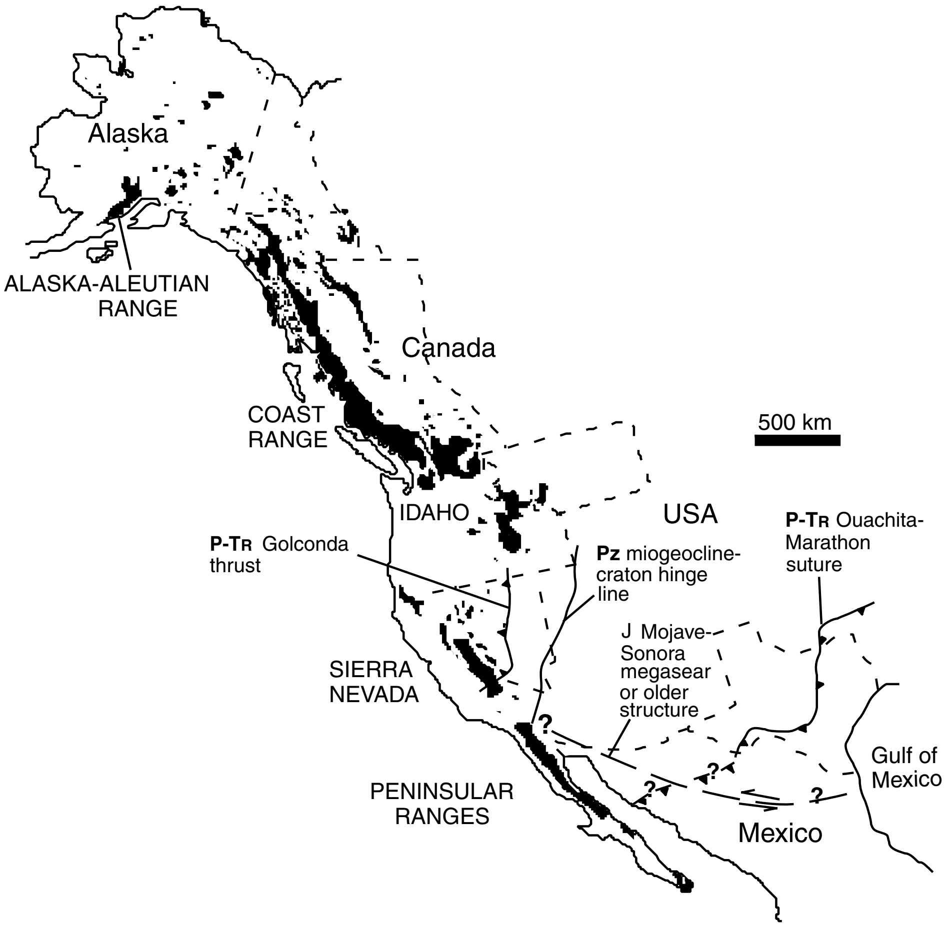

Figure 1. Map of western North America showing major Mesozoic Cordilleran batholiths and selected Paleozoic-Mesozoic tectonic features of the southwest North American margin discussed in text. Possible continuation of Ouachita-Marathon suture across Mexico from Stewart (1988).

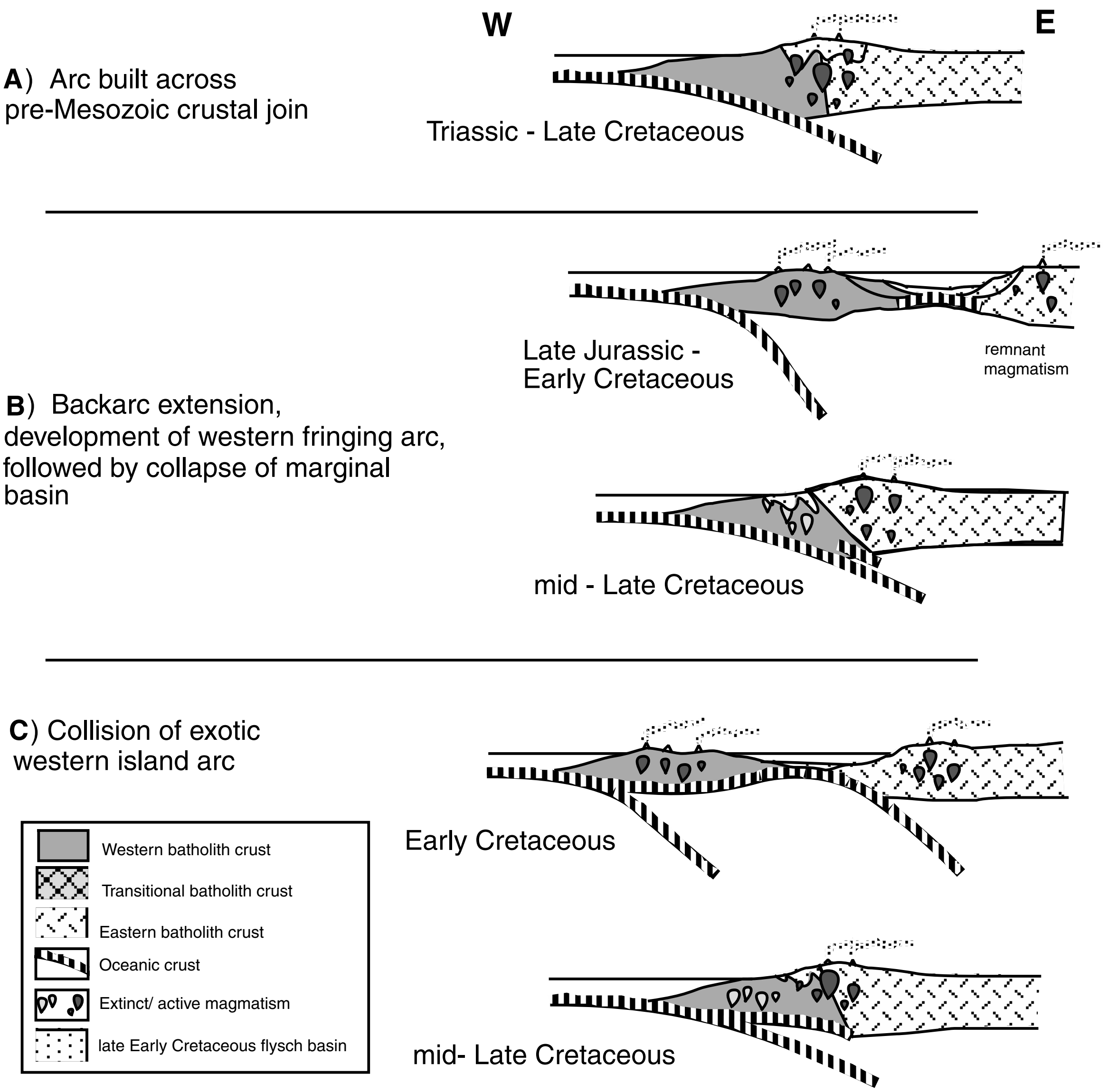

Figure 2. Tectonic models suggested for the Mesozoic evolution of the PRb. See text for historical development of models and corresponding references. (A) Western zone evolved adjacent to the rest of the batholith, separated by an inherited crustal boundary. (B) Backarc basin formation rifted western zone into a fringing arc position in Late Jurassic-Early Cretaceous time followed by collapse of intervening marginal basin and reattachment to North America. (C) Development of the western zone as an exotic island arc during Jurassic and Early Cretaceous time followed by collision and suturing of the exotic arc with North America in the latest Early Cretaceous.

transition, largely originates from work in southern California. Accordingly, Walawender et al. (1991) suggested that the PRb formed above a single subduction zone and developed its zoned character by a shallowing subduction angle and eastward arc propagation beginning at ca. 105 Ma. Thomson and Girty (1994) further suggested an early Mesozoic tie between the western and eastern zones of the batholith from a metasedimentary intra arc basin unit that overlaps both batholith zones and is intruded by a pluton that yielded a discordant Triassic age.

A second model, involving partial evolution of the western zone as a fringing oceanic arc, has been advocated by a number of researchers working in both southern and Baja California (Fig. 2B; Gastil et al., 1975, 1981; Rangin, 1978; Todd et al., 1988; Griffith and Hoobs, 1993; and Busby et al., 1998). They suggested that back-arc extension, initiated in Jurassic time, rifted the western, oceanic part of the batholith to a fringing arc position. Collapse of the marginal basin located between the two arc fragments, either by subduction within the basin (Gastil et al., 1975, 1981) or by crustal shortening (Busby et al., 1998), occurred in the mid-Cretaceous, followed by eastward arc migration. Gastil et al. (1975, 1981) further suggested that the northern half of the western zone (Santiago Peak arc segment) was sutured to the margin in Early Cretaceous time, whereas the southern half (Alisitos arc segment) collided in mid- to Late Cretaceous time. They proposed that the two segments were separated by an ancestral transform fault that has been reactivated to form the presently active Agua Blanca fault.

A third model, built on the ideas of others such as Gastil et al. (1975, 1978; 1981), Todd et al. (1988), and Griffith and Hoobs (1993), is that the western zone is an exotic island arc complex, which was sutured to the North American margin in the Early Cretaceous (Fig. 2C; Sedlock et al., 1993; Johnson et al., 1999a; Dickinson and Lawton, 2001). Intrinsic to this model is evidence that western zone rocks show little influence of continental crustal material including lack of zircon inheritance in both plutonic and volcanic rocks, paucity of quartz and K-feldspar components in volcanogenic sediments, and plutons with strong island arc geochemical and isotopic affinities (Silver and Chappell, 1988; Johnson et al., 1999a). The above authors differ on details of facing of subduction zone(s) that closed the intervening ocean basin and only one possible scenario is shown in Figure 2C.

The range of possible tectonic scenarios discussed above arises partly from researchers working in different areas separated by extensive regions that are poorly known. Most of this previous work has occurred in the northern half of the batholith. Our work has focused on the less studied section in the Sierra San Pedro Martir region of Baja California, Mexico, where relationships in the transition zone of the batholith are particularly well exposed. We have found several significant differences between relationships in this region and those described from farther north, suggesting that the northern and southern parts of the PRb do not share an identical evolution. Moreover, published data as well as our own reconnaissance work suggest that these relationships change across the presently active Agua Blanca fault, and thus, we concur with Gastil et al. (1975, 1981) that the Agua Blanca fault has a Mesozoic history and served as an important tectonic break during PRb evolution.

Below we examine the transition zone in the PRb and its relationship to the western and eastern zones. We further explore the implications of these relationships for tectonic models of the PRb acknowledging that other significant problems beyond the scope of this paper remain with regards to the relationship of the PRb to North America (e.g., paleomagnetic evidence that the batholith evolved in a more southerly location, Hagstrum et al., 1985 and suggestions for a W-northwest-striking Jurassic strike slip fault, the Mojave Sonora Megashear of Silver and Anderson, 1974, or older transform fault, Dickinson, 2000). We argue that the transition zone is a distinct entity in the PRb and has been closely tied to the eastern zone of the batholith throughout the Mesozoic. General aspects of the transition zone appear to remain consistent along-strike between northern and southern parts of the batholith including comparable degrees of Mesozoic basin formation, contractional deformation, and metamorphic and denudation histories. However, specific aspects appear to change across the Agua Blanca fault, including the age of basins and the type of detritus they collected as well as the location and timing of deformation in mylonite shear zones. These differences occur in concert with distinct variation between northern and southern parts of the western oceanic arcs, supporting our contention that the southern, Alisitos arc segment collided with the margin in Early Cretaceous time, whereas the northern, Santiago Peak arc segment evolved as an inherited oceanic terrane, across which the batholith was constructed during Jura-Cretaceous time (Wetmore and Paterson, 2000). Our studies suggest that collision of the Alisitos island arc was only one episode in a long history of orogenesis in the PRb. Other processes must have driven orogenesis along a much larger portion of the PRb during Jura-Cretaceous time masking the effects of local collision.

PREVIOUS WORK ESTABLISHING THE ZONED NATURE OF THE PENINSULAR RANGES BATHOLITH

The Peninsular Ranges batholith traditionally has been divided into distinct western and eastern zones with the boundary defined by a number of different criteria that include: prebatholithic assemblages; pluton lithologies; metamorphic histories; major, trace, and isotopic geochemistry of plutons; geophysically defined crustal structure; and magmatic and cooling histories. Typically, this boundary between western and eastern zones is designated by a single line based on one or more of the above criteria. This practice is problematic because the location of this boundary changes depending on which criteria are chosen to differentiate the two zones (compare for example the location of the $\delta^{18}O$ and magnetite/ilmenite lines on Figure 3). Moreover, some criteria such as the $\delta^{18}O$ step in plutons vary sharply across a distance <5 km, while others, such as initial Sr isotopic values vary across distances >40 km. Thus, in contrast to previous convention, it may be more accurate to define a transitional zone in the batholith, which occurs between western and eastern zones and that encompasses the transitions in criteria listed above. Below we argue that this transitional zone is geologically distinct from the crustal zones to either side, and variation in geochemical, geophysical, and geological parameters by which it is defined along strike are critical to understanding the tectonic evolution of the PRb.

The Peninsular Ranges batholith intrudes a series of northwest-trending, prebatholithic, lithostratigraphic assemblages (Fig. 4) that include from west to east (Gastil, 1993): (1) a Triassic-Cretaceous continental borderland assemblage (not shown in Figure 4); (2) a Jura-Cretaceous volcanic arc and forearc assemblage; (3) a Triassic(?)-mid Cretaceous clastic and volcaniclastic flysch assemblage of uncertain tectonic origin; (4) an Ordovician-Permian slope-basin clastic assemblage; and (5) an upper Proterozoic-Permian miogeoclinal carbonate-siliciclastic assemblage. These have been assigned to distinct belts that include a western zone consisting of the borderland and volcanic arc assemblages and an eastern zone composed of

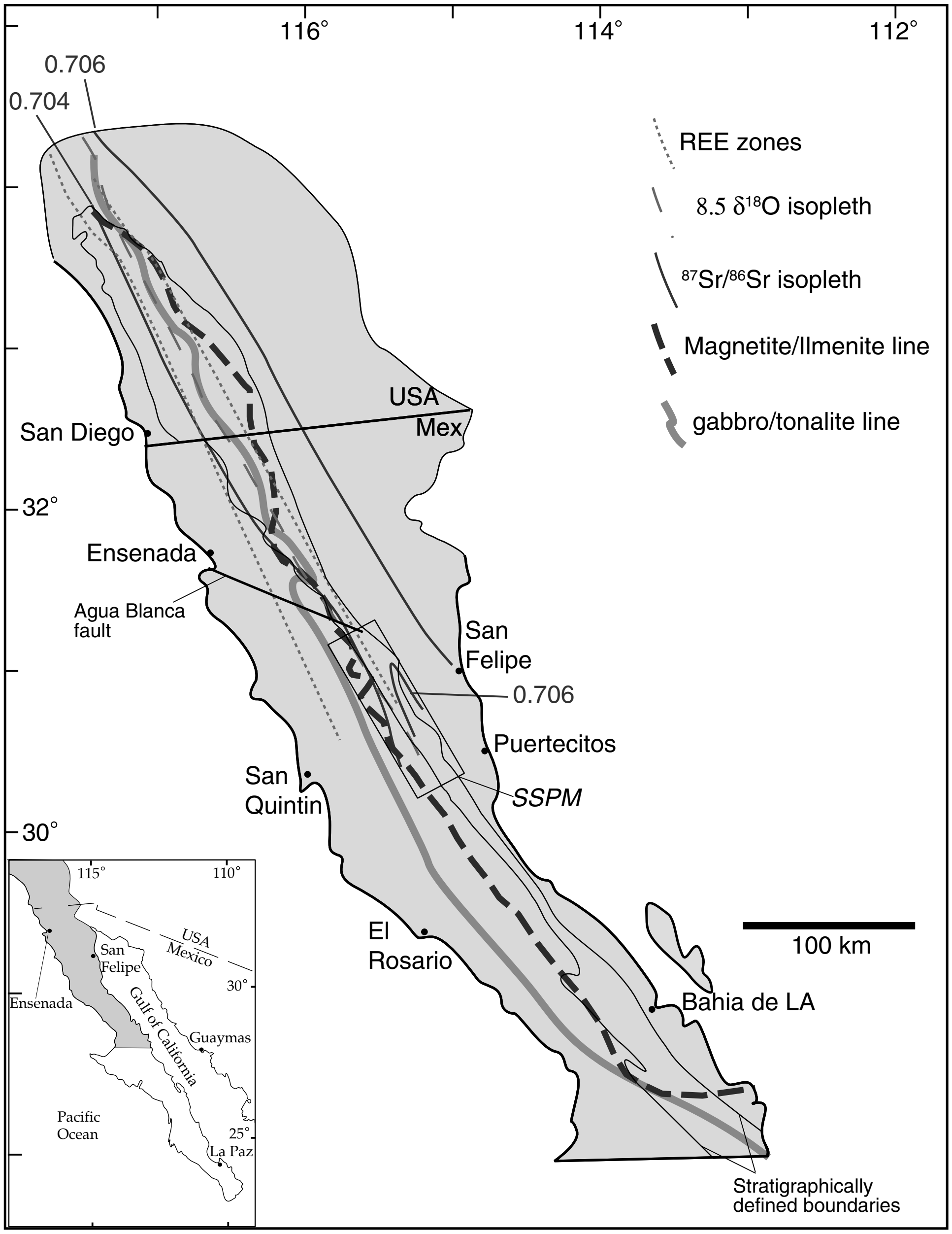

Figure 3. Map of the Peninsular Ranges batholith showing the magnetite-ilmenite line, Rare Earth Element belts, selected isopleths for initial $^{87}Sr/^{86}Sr$ and δ^{18}OSMOW, and the gabbro/tonalite line. From Gastil et al. (1990), Gromet and Silver (1987), Taylor and Silver (1978), Silver et al. (1979), and Silver and Chappell (1988). Also shown are contacts between flysch strata of the transition zone and strata in the western and eastern zones to either side.

both Paleozoic clastic and carbonate-siliciclastic assemblages. In this paper we argue that the intervening Mesozoic flysch assemblage represents the transitional zone because its extent encompasses the transitions in the known geochemical and isotopic parameters in the batholith (Fig. 3).

Plutons intruding the above units vary from tonalite, gabbro, quartz gabbro, and diorite in the west to mostly tonalite and granodiorite with some granite and rare gabbro in the east. Gastil (1983) delineated "gabbro" and "tonalite" belts on western and eastern sides of the peninsula respectively, and "granodiorite-granite" and "alkaline" belts further east in mainland Mexico (Fig. 4). Metamorphic grade changes from lower greenschist grade in the westernmost part of the western zone, to andalusite-sillimanite-bearing lower amphibolite grade in the transition zone, to sillimanite-bearing upper amphibolite grade in the eastern zone (Todd et al., 1988). Reconnaissance Al-in-hornblende studies on plutons in southern California by Ague and Brimhall (1988), Butler et al. (1991), and Ague and Brandon (1992) indicated pressures up to 6 kbar in the eastern zone and <2 kbar in the western zone.

Most geochemical and isotopic work in the PRb has been focused on the younger undeformed plutons in southern California, with little attention given to plutons farther south, as well as older, gneissic plutons that outcrop extensively in the PRb. Across-strike variation in pluton chemistry, including major element (Baird et al., 1974; Baird and Miesch, 1984), and

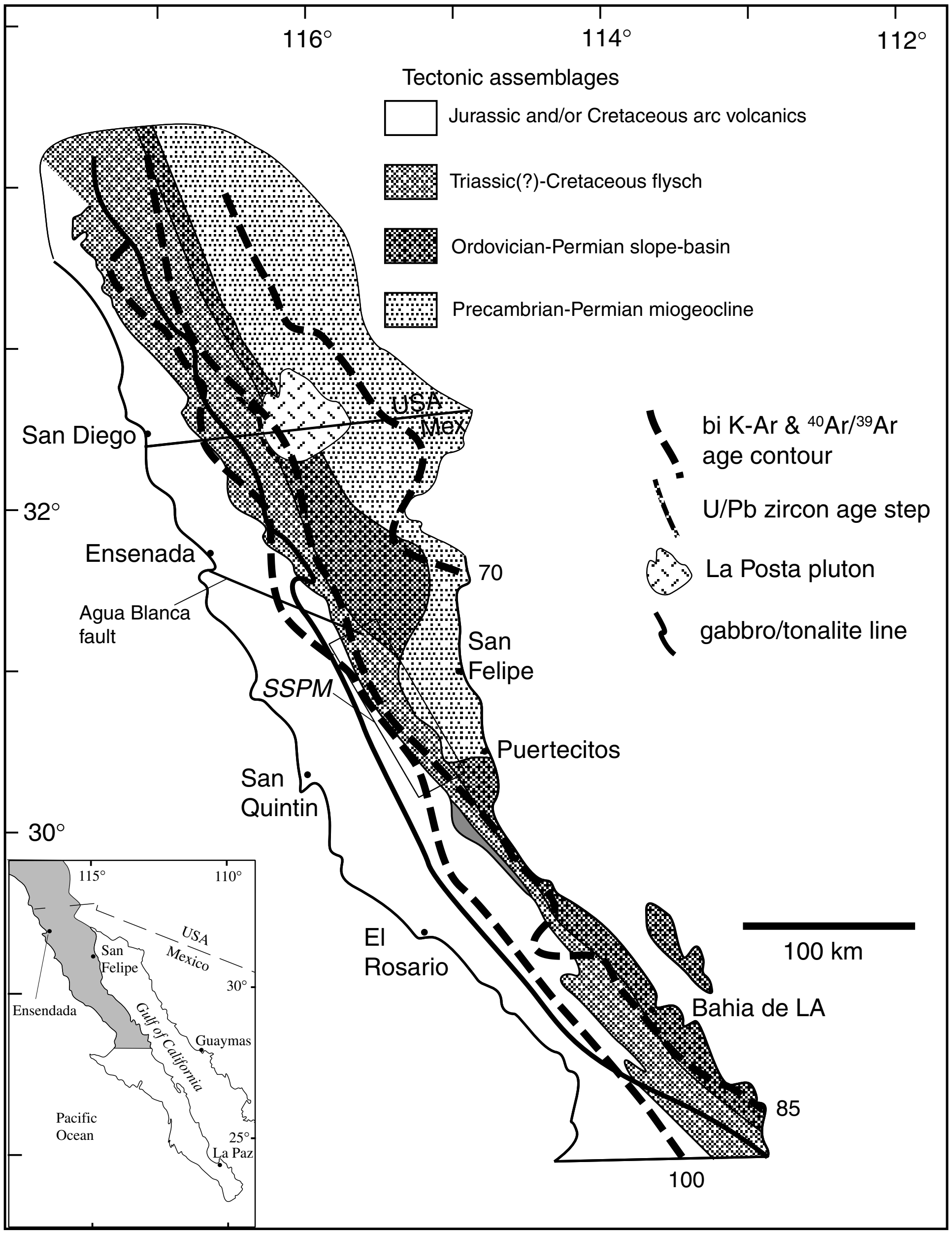

Figure 4. Map of Peninsular Ranges batholith showing tectonostratigraphic assemblages, "gabbro" and "tonalite" belts west and east of gabbro/tonalite line respectively ("granodiorite-granite" belt lies to east in Sonora), the U-Pb age step between western and eastern zones, the La Posta pluton (largest recognized pluton in the batholith), and K-Ar and ^{40}Ar/^{39}Ar biotite apparent age isopleths in the Peninsular Ranges Batholith. From Gastil et al. (1990, 1991a: 1991b), Gastil (1993), Krummenacher et al. (1975), Silver et al. (1979), Rothstein (1997), Axen et al. (2000).

rare earth element (REE, Gromet and Silver, 1987), as well as oxide mineralogy (Gastil et al., 1990), has been attributed to distinctly different primitive versus nonprimitive sources respectively in the western and eastern zones of the batholith (Fig. 3). Isotopic studies of plutons have corroborated this interpretation. Initial ^{87}Sr/^{86}Sr isotopes are generally independent of pluton composition and vary systematically across the batholith from values of $<$0.7030 in the west to 0.7080 in the east (Fig. 3, Early and Silver, 1973). Neodymium isotopes closely correspond with initial ^{87}Sr/^{86}Sr values, with ε_{Nd} ranging from $+8.0$ in the west to -6.4 in the east (DePaolo, 1980, 1981). Taylor and Silver (1978) reported distinct gradients in whole-rock oxygen isotope compositions of plutons across the northern PRb that they interpreted as magmatic in origin. Values of $\delta^{18}O_{SMOW}$ range from $+6.0$ to $+8.5‰$ across the western to central parts of the batholith, followed by an abrupt step to values of $\sim$9.0‰, then a steady eastward rise to a maximum of $+11\%$ (Fig. 3). Silver and Chappell (1988) argued that these geochemical and isotopic trends across the PRb reflect primitive island arc sources in the western PRb that are distinct from older, deeper reservoirs containing eclogitic mineral assemblages in the eastern PRb. Nonetheless, the compositionally defined boundary between these two distinct lithospheric regions occurs across an appreciable distance—compare, for example, the distance between 0.704 and 0.706 initial Sr isopleths versus REE zones or δ^{18}O isopleths in Figure 3—implying that a region of transition exists that has been influenced by magmatic processes in both oceanic as well as continental lithosphere.

Distinct basement to the western and eastern zones has been corroborated by limited geophysical studies in the northern PRb. These studies include both Bouguer gravity data (Oliver, 1980; Fuis et al., 1982; Weslow, 1985; Jachens, 1986) and three-dimensional imaging of P wave velocities from earthquakes (Magistrale and Sanders, 1995), and indicate a large density contrast (>0.035 g cm^{-1}) between western and eastern zones of the batholith to a depth of at least 22 km, and probably through the entire crust. Other studies have also noted considerable contrast in Moho depths across the compositional boundary using teleseismic receiver function techniques (Ichinose et al., 1996; Lewis et al., 2000; Richards-Dinger and Shearer, 1997) and reflection seismic studies (Zhu and Kanamori, 2000). Ichinose et al. (1996) and Lewis et al. (2000) determined a relatively deep and flat Moho (37–41 km depth) beneath the western PRb that changed across the transition zone to an eastward-shallowing Moho that decreases to ~25 km depth beneath the eastern PRb. They attributed this shallowing Moho to crustal thinning resulting from Neogene extension in the Salton Trough–Gulf of California extensional province. Their preliminary work in the Sierra San Pedro Martir indicates that similar Moho depths continue into the southern half of the batholith (Lewis et al., 2000, personal commun.).

Some of the earliest evidence for distinct western and eastern belts in the PRb comes from U-Pb zircon geochronology studies along the international border (Silver et al., 1979; Silver and Chappell, 1988). These authors defined an older, "static," western plutonic belt that ranges in age from ca. 140–105 Ma and a younger, eastward migrating, eastern belt in which largely undeformed plutons range in age from ca. 105–90 Ma, and suggested that an age boundary between the two belts corresponds with the compositional boundary in the batholith. (Fig. 4). Silver and Chappell (1988) reported U-Pb zircon ages of 80–57 Ma for the batholith farther east in Sonora, mainland Mexico. Nevertheless, the evidence for a pluton age boundary in the batholith is problematic, as apparent from subsequent geochronology studies in southern California that have yielded Jurassic, and possibly Triassic ages from orthogneiss units in both the western and eastern zones as they were originally defined in southern California (Todd et al., 1991; Walawender et al., 1991; Thomson and Girty, 1994). Furthermore, Walawender et al. (1990), in the same region, determined that magmatism in the eastern belt was not eastward migrating based on additional dates and the reinterpretation of a single pluton in the transect as a "western" rather than an "eastern" zone pluton. Additionally, a more recent geochronologic transect across the northernmost PRb (Premo et al., 1998) found an apparently smooth progression of pluton ages across the transition zone from ca. 125 Ma in the west to ca. 83 Ma in the east. We suspect that early interpretations of geochronology work in the PRb were problematic because they focused largely on undeformed plutons and were undertaken in a transect that included the largest pluton recognized in the PRb, the La Posta pluton, which has a diameter that is nearly the width of their transect (Fig. 4). This underscores the problem of representing the crustal scale boundary in the batholith as a single line. Not only do geochemical and isotopic parameters change across a perceptible distance on maps of the batholith, but individual plutons within the transition zone reach sizes of >1500 km^2 and, thus, may strongly influence geochemical, isotopic, as well as geochronologic gradients in the batholith.

In contrast to the U-Pb geochronology, the K-Ar geochronology system has consistently shown distinct differences between western and eastern zones of the PRb, in agreement with differences in crustal exposure levels between the two zones (Evernden and Kistler, 1970; Armstrong and Suppe, 1973; Silver et al., 1979). Krummenacher et al. (1975) reported K-Ar hornblende and biotite ages from plutons across an extensive region of the PRb and found that both hornblende and biotite ages systematically become younger from west to east across the batholith; hornblende ages vary from ~120 to ca. 75 Ma and biotite ages vary from ca. 115 Ma to ca. 65 Ma (Fig. 4). Differences among hornblende-biotite K-Ar cooling age pairs also vary across the batholith, a feature that they attributed to interplay among parameters such as pluton emplacement depths and timing and rates of denudation that vary between western and eastern zones. K-Ar ages are concordant with U-Pb zircon ages from plutons in the western zone, but become increasingly discordant, by as much as 25 m.y., in the eastern zone of the batholith (Silver et al., 1979).

In summary, discrete western and eastern zones can be defined in the PRb that contain distinct sedimentary assemblages, chemical and isotopic pluton compositions, geophysical parameters, and thermal and metamorphic histories. The western zone formed above dense, largely oceanic crust that presently has a thickness of ~40 km, and shows variable Mesozoic cooling histories within a supracrustal volcanic sequence, consistent with the exposure of shallow levels of the Peninsular Ranges arc. In contrast, the eastern zone evolved above less dense, largely continental crust with Paleozoic North American sedimentary assemblages that thins eastward (37–25 km thick) as a result of Neogene tectonism, and displays systematic eastward-younging cooling trends that generally correspond with deeper denudation to midcrustal levels. The transition zone between these western and eastern zones occurs across an appreciable distance and is defined by a distinct stratigraphic assemblage (flysch) and strong gradients in pluton chemistries and isotopes, metamorphism, and thermal evolution of rocks within the batholith. The origin of this transitional zone is critical to understanding the tectonic evolution of the PRb.

COMPARISON OF ZONES IN THE PRB NORTH AND SOUTH OF THE AGUA BLANCA FAULT

The three zones in the batholith in many ways are more distinct to the south, a fact that underscores important differences in the tectonic development of the PRb north and south of the Agua Blanca fault. The modern Agua Blanca fault is a Neogene-Recent, west-northwest-striking, dextral strike slip fault that forms a part of the San Andreas transform system (Fig. 3, Allen et al., 1960; Suarez-Vidal et al., 1991). However, this modern fault is located on an important Mesozoic boundary that is oriented obliquely across the western and transition zones of the batholith, dividing it into northern and southern parts (Gastil et al., 1975, 1981; Wetmore and Paterson, 2000).

In contrast to the western and transitional zones of the batholith, the Mesozoic geology in the eastern zone appears to be continuous across the eastward extension of the modern Agua Blanca fault. The eastern zone was clearly tied to North America during the Mesozoic as evidenced by North American Precambrian-Paleozoic sedimentary assemblages that underlie it as well as prevalent Pb inheritance in zircon within plutons (Gastil, 1993). These inherited components are typically ca. 1100–1300 Ma, similar to basement ages in northern mainland Mexico. The eastern zone preserves a long history of arc magmatism that stretches back much further than was originally apparent from initial studies in the northern PRb. Our recent work has yielded a ^{206}Pb/^{238}U zircon SHRIMP age of 164.3 ± 2.3 Ma (MSWD 2.5, minor older component yielded ages of ca. 900–1000 Ma) for orthogneiss that appears to underlie a substantial portion of the eastern zone near latitude 31 °N (Schmidt, 2000), suggesting that the Jurassic arc extended from present-day southern California well into Peninsular California. The ca. 99–92 Ma La Posta suite also features prominently in this zone (Kimbrough et al., 2001) and is discussed in more detail below. Nevertheless, an important along strike break is evident in the eastern zone at ~30.5°N latitude. This break occurs >100 km farther south of the Agua Blanca fault, and in contrast to the ancestral Agua Blanca fault, it appears to be an inherited, pre-Mesozoic feature in the batholith that corresponds to the transition from shelf to slope deposits in the Precambrian-Paleozoic miogeocline (Gastil et al., 1991a). This inherited boundary appears to have controlled a number of Mesozoic features in the eastern zone of the batholith including structural style and denudation history. North of this boundary, crust underlain by miogeoclinal rocks appears to have operated as a backstop to shortening in the rest of the arc to the west (Schmidt, 2000) and was deeply denuded during Cretaceous time. In contrast, south of this boundary, the eastern zone was significantly shortened and less denudation is apparent (Rothstein, 1997).

Below we examine assemblages west of the eastern zone of the PRb in more detail focusing discussion on the transition zone and its eastern and western boundaries, and compare our work in the Sierra San Pedro Martir of the southern half of the batholith (Johnson et al. 1999a, 1999b; Schmidt, 2000), with published work and our own reconnaissance work (Wetmore et al., 2002) north of the Agua Blanca fault.

Transition Zone and its boundaries with the eastern and western zones

The transition zone forms a distinct belt within the batholith that contains its own distinct stratigraphy, magmatism, and structures, and is the location of major breaks in metamorphic and rock cooling histories across the strike of the batholith. Changes in the way in which the eastern and western geological boundaries to this zone are expressed across the Agua Blanca fault is one of the critical distinctions between northern and southern parts of the batholith.

Stratigraphy

In the northern PRb, metamorphosed rocks of the flysch assemblage (Bedford Canyon Formation, French Valley Formation, and Julian Schist) and their apparent correlatives in northern Baja California (Rancho Vallecitos Formation and strata near Rancho Santa Clara, east of Ensenada) consist of pelitic and psammitic schist and gneiss with minor calc-silicate rocks interpreted as continentally derived turbidite to deltaic deposits (Fig. 5A; Germinario, 1993; Lothringer, 1993; Reed, 1993). Few volcanic protoliths have been described in these northern assemblages, with the notable exception of a poorly known and undated amphibolite-grade metavolcanic unit in San Diego County (Todd et al., 1988).

Age control for the northern flysch units is mainly from Jurassic (Bajocian–Callovian, ca. 177–159 Ma) fossils in the Bedford Canyon Formation. Fossils are either absent or provide only tentative age control for the other metasedimentary units. Thomson and Girty (1994) interpreted 234 ± 39 Ma (U-Pb TIMS zircon technique) Harper Creek orthogneiss as intrusive into Julian Schist, thus providing a pre-Triassic-earliest Jurassic age constraint on the Julian Schist. The flysch assemblage units in southern California contain zircon populations derived from Late Proterozoic, and Paleozoic-early Mesozoic sources that are consistent with ages of abundant igneous rocks in Arizona and northern Sonora (Gastil and Girty, 1993). Hence, these sedimentary basins appear to be tied to North America during their formation.

In the Sierra San Pedro Martir of the southern part of the batholith (Fig. 5A), the flysch assemblage includes a substantial volcanic component. Rock types include schistose and gneissic basalts, silicic lithic crystal tuffs, tuff breccias, and tuffaceous sandstones, as well as uncommon, relatively pure marble and quartzite layers. Age constraints are poor here. Johnson et al. (1999a) obtained a ^{206}Pb/^{238}U zircon SHRIMP age of 127.9 ± 1.2 Ma (MSWD 1.0) from a gneissic igneous layer in flysch strata on the western side of the transition zone, but are uncertain as to whether or not the layer dated is a volcanic flow in the sequence or later sill. This assemblage is faulted against Alisitos Formation strata of western zone provenance as described below. Measures (1996) obtained discordant zircon

U-Pb TIMS ages from a metavolcanic unit in the eastern side of the transition zone that he interpreted as ca. 123 Ma. This package lies in fault contact with shelf facies rocks of the eastern zone of the batholith.

In the transition zone farther south, flysch assemblage rocks occur in fault slivers that are juxtaposed with both Paleozoic assemblages and apparent Alisitos equivalents. At some locations, depositional contacts between flysch strata and both of these units have been reported. At El Marmol (Fig. 5A), a Lower Permian to Lower Triassic argillite sequence (Zamora, El Volcan, and De Indio Formations) conformably overlies Lower Permian chert and argillite strata and was interpreted by Buch and Delattre (1993) as the southern extension of a Permian-Triassic miogeocline belt that occurs in southern Nevada and east-central California. These units are overlain by an apparent Alisitos Formation equivalent unit (Olvidada Formation) that contains Aptian-Albian (ca. 121–99 Ma) fossils and includes turbiditic chert, sandstone, and shale interlayered with volcanic tuffs and breccias (Phillips, 1993). In the Calamajue region (Fig. 5A), Griffith and Hoobs (1993) mapped a metavolcanic sequence (Cañon de las Palmas unit), containing intermediate composition flow rocks and volcaniclastics with minor basalt and limestone, from which a U-Pb TIMS zircon age of ca. 156 Ma was obtained. This unit is juxtaposed with Mississippian carbonate strata (Cañon Calamajue unit) and an apparent Alisitos Formation equivalent sequence that includes intermediate volcanic flow rocks, tuffs, and breccias that yielded a U-Pb TIMS zircon age of 103 ± 4 Ma.

Magmatism

The character of plutonism in the transition zone is strongly heterogeneous and distinct in several aspects from that in the eastern and western zones. In the transition zone, pluton shapes and geometries vary from blob-like and relatively homogeneous to vertically oriented, centimeter- to meter-wide, intricately interlayered sheets. Igneous rock types range from hornblende gabbro to muscovite biotite granite, and, in many places, spectacular zones of magma mingling occur between different compositions. Textures in plutonic rocks vary from magmatic and barely discernable to strongly mylonitic and gneissic. In many cases, strong contrasts in rock rheology during deformation are apparent between adjacent rocks of different composition. For example, blob-shaped gabbro plutons in the Sierra San Pedro Martir commonly show poorly developed magmatic fabrics and locally developed spaced, high-temperature cleavage parallel to the regional structural grain, whereas adjacent tonalite and metavolcanic wall rocks typically form mylonite and ultramylonite that strongly wraps around the ends of the gabbro plutons. Extensive exposures of migmatite occur in flysch and orthogneiss wall rocks, and in some places more than one generation of migmatite are apparent.

Magmatism in the transition zone occurred during a significant portion of Mesozoic time. In the northern part of the batholith, a few important studies have identified plutonic suites that are considerably older than the ca. 120–95 Ma plutons first described by Silver et al. (1979). These assemblages include two separate units of the largely granodioritic Harper Creek orthogneiss, which yielded 234 ± 39 and 156 ± 12 Ma ages, and the Cuyamaca Creek gneiss, another arc plutonic suite, which yielded ages of 161 ± 12 and 149 ± 21 Ma (using U-Pb TIMS zircon technique, >7 fractions, reported in Thomson, 1994). All data plot along cords with inherited components of ca. 1763–1437 Ma.

In the Sierra San Pedro Martir of the southern part of the transition zone new U-Pb SHRIMP zircon geochronology has identified a number of important relationships. An areally extensive orthogneiss unit that is lithologically similar to the Cuyamaca Creek gneiss yielded an age of 164.4 ± 1.2 Ma (MSWD 0.41) and includes a minor older component that yielded ages of ca. 1100–1000 Ma (Schmidt, 2000). A long history of subsequent arc magmatism is apparent in this region. Tonalite and granite plutons have given U-Pb zircon TIMS and SHRIMP ages ranging from ca. 134–100 Ma (Johnson et al., 1999a; Schmidt, 2000). A distinctive suite of 108–102 Ma hornblende tonalite plutons occurs across the western side of the transition zone, which Johnson et al. (1999a) argued stitches the transition and western zones of the batholith following collision of the western zone. Geochemical studies show permissible evidence for mixed continental/island arc lower crustal sources for these plutons whereas previously intruded plutons in the adjacent western zone do not (Gromet and Silver, 1987; Silver and Chappell, 1988; Tate and Johnson, 2000). A major pulse of magmatism subsequently occurred in this region between 99 and 92 Ma as part of the La Posta plutonic event.

The 99–92 Ma La Posta plutonic suite occurs along the length of both the transition and eastern zones of the PRb (e.g., Gastil et al., 1991b; Kimbrough et al., 2001). La Posta-type plutons reach diameters of 40 km and are typically concentrically zoned from hornblende tonalite margins to muscovite-bearing monzogranite cores. Geochemical and isotopic data also show zoning in these plutonic complexes, ranging from values that are considered "western PRb" in their margins to "eastern PRb" in their cores, including increasing zircon Pb inheritance in pluton centers. These plutons are considered type-examples of eastern zone plutons (Walawender et al., 1990; Gastil et al., 1991b). However, a substantial region of the transitional and eastern zones of the batholith is underlain by variably deformed and metamorphosed granitoid plutons of Middle Jurassic through Early Cretaceous age. Thus, although the La Posta suite is clearly a volumetrically important igneous unit in the batholith, it is only a part of a long history of arc magmatism that is apparent in the transitional and eastern zones of the PRb.

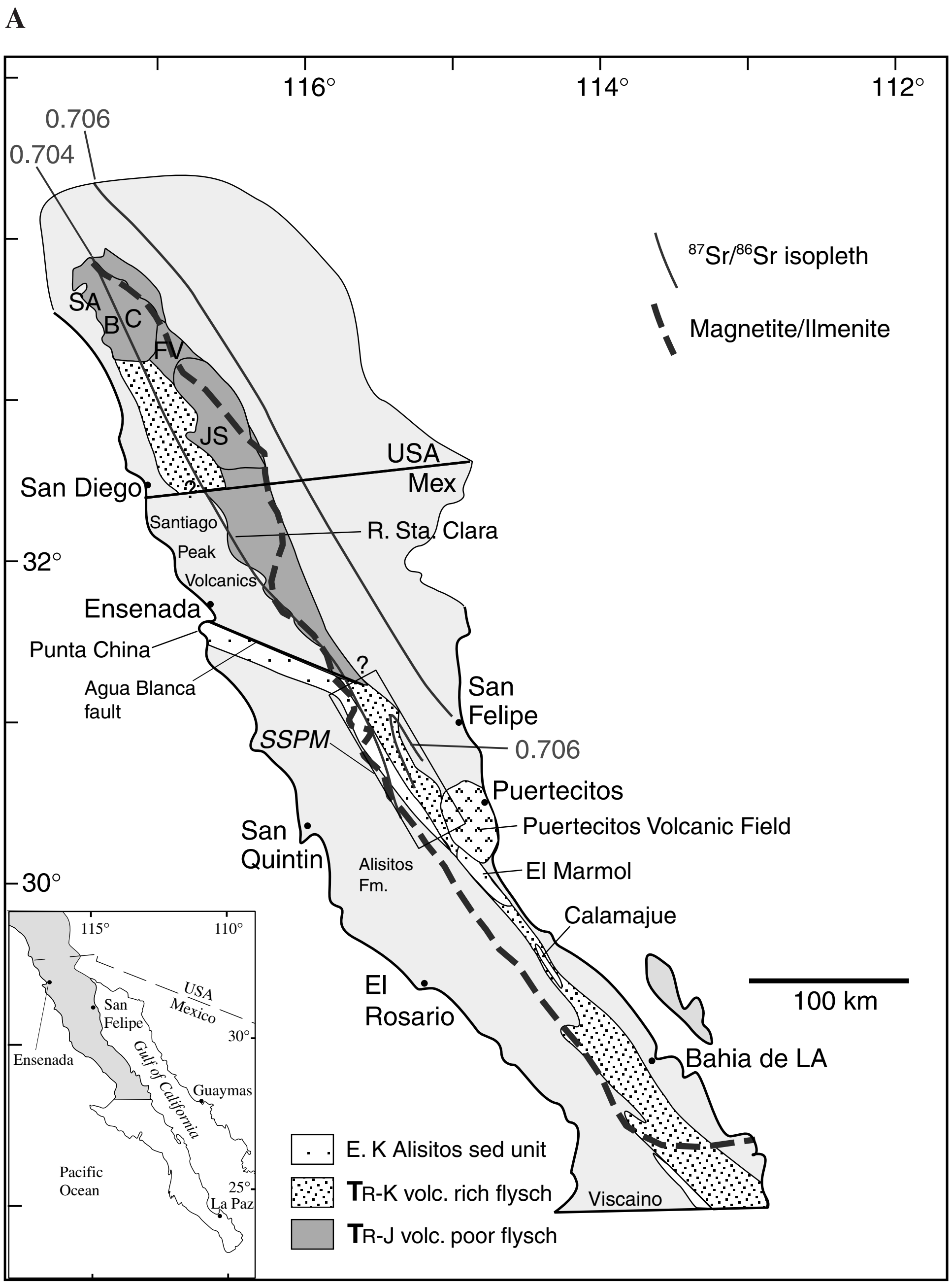

Figure 5. Series of maps of the PRb showing major stratigraphic and structural relationships within the batholith. (A) Major stratigraphic units in the transition and western zones of the PRb. Note distribution of Albian-Aptian sedimentary-rich strata of the Alisitos Formation BC—Bedford Canyon Formation; FV—French Valley Formation; JS—Julian Schist; SA—Santa Ana Mountains. From references in Gastil and Miller, eds. (1993), Todd et al. (1988), and Silver et al. (1963). (B) Major identified Mesozoic structures in the PRb including the inferred trace of the transitional PRb deformation belt: CL—Cuyamaca-Laguna Mountains Shear Zone (Todd et al., 1988), CCF—Chariot Canyon fault and CGF—Carrizo Gorge fault (Grove, 1994), AB—ancestral Agua Blanca fault (Silver et al., 1963; Gastil et al., 1975), SJ—shear zone(?) in Sierra Juarez (Gastil et al., 1975), SSPM—shear zone in the Sierra San Pedro Martir (Johnson et al., 1999a; Schmidt, 2000), C—shear zone at Calamajue (Griffith and Hoobs, 1993); A—shear zone at El Arco (Barthelmy, 1979). Also shown is estimated location of transition from sub- to lower greenschist grade rocks in the west to upper greenschist-amphibolite grade rocks in the east PRb (from references cited above) and contacts between flysch strata and strata in the western and eastern zones. Selected Cenozoic dextral strike-slip faults also shown: EF—Elsinor fault, SJ—San Jacinto fault, AB—Agua Blanca fault.

Deformation and metamorphism

Like the eastern zone of the PRb, the entire transition zone has been deeply denuded and upper greenschist to amphibolite grade metamorphism is apparent in batholithic and host rocks. Extensive regions of the transition zone are intensely deformed, and these structures appear to have been intimately related to metamorphism and denudation.

Initial studies in the PRb inferred that deformation and metamorphism largely occurred in the latest Early Cretaceous (e.g., Todd et al., 1988). However, more recent work has identified an earlier period of deformation affecting the transition zone of the batholith. In the northern part of the PRb, this older deformation is apparent in flysch assemblage rocks that were folded, penetratively cleaved, and metamorphosed between ca. 151 and 127 Ma, as constrained by Jurassic fossils in the flysch and the age of overlying undeformed volcanics (Kimbrough and Herzig, 1994). In the Sierra San Pedro Martir of the southern half of the PRb, flysch assemblage rocks were folded and cleaved prior to intrusion of a tonalite pluton that yielded a U-Pb TIMS zircon age of 132 ± 7 Ma (MSWD 2.1, Schmidt, 2000). Notwithstanding, the most prevalent episode of defor-

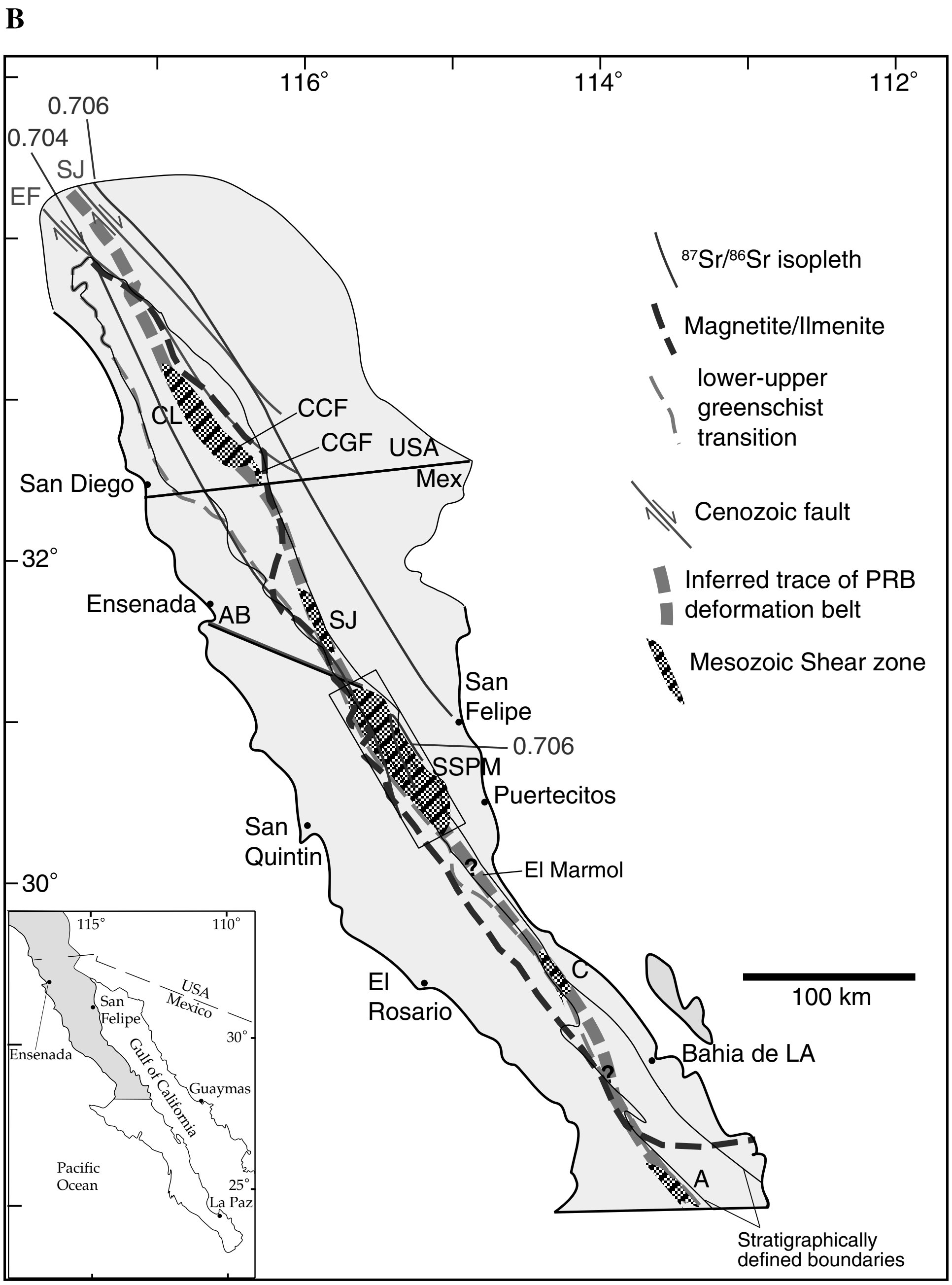

Figure 5. (*continued*)

mation and metamorphism in the PRb transition zone occurred in the Early to mid-Cretaceous. Intense folding and mylonite shear zone development associated with this episode appears to have occurred along the known extent of the PRb, and was largely restricted to the transition zone in the batholith (transitional deformation belt in Figure 5B). Recognition of the probable continuity of this deformation zone has been hampered by the extent to which it has been intruded by large, late plutonic suites such as the La Posta series and extensively covered by Tertiary volcanic strata. Moreover, the character and, to some extent, age of this deformation appears to vary along strike as described below (Fig. 5B).

In southern California, the Cuyamaca Laguna Mountains shear zone extends >100 km in two segments and represents the northernmost extent of the transitional deformation belt (Fig. 5B). It consists of penetrative northwest-striking, steeply northeast-dipping mylonitic to magmatic foliation and steeply pitching lineation with top-to-southwest shear sense indicators (Todd et al., 1988; Thomson and Girty, 1994). This episode of deformation has been constrained to the range ≥118–105 Ma and occurred under amphibolite grade metamorphic conditions. An overprinting deformation event that produced northeast-side down shear sense on nearly vertical northwest-striking mylonitic foliation and steeply pitching lineation in a ~12-km-long section of the main shear zone has been bracketed between ca. 105 and ca. 94 Ma (Thomson and Girty, 1994). Cooling below 400 °C in this portion of the batholith occurred from ca. 88–85 Ma (Grove, 1994).

In the more poorly known Sierra Juarez to the south, intensely developed, steeply-dipping, northwest-striking cleavage occurs across a broad region of the transition zone (Gastil et al., 1975). Wall rocks have been metamorphosed to amphibolite grade and extensively intruded by blob-like and sheeted plutons. Rothstein (1997) inferred rapid cooling below 400 °C in this region from ca. 85–72 Ma.

In the southern part of the batholith, south of the Agua Blanca fault, the transitional deformation belt is spectacularly exposed across the Sierra San Pedro Martir. In this region a ~20-km-wide, doubly vergent fan structure occurs, consisting of moderately inward-dipping mylonite belts on either side that steepen toward the center where both mylonitic and magmatic fabrics occur in a region syn-tectonically intruded by vertically sheeted plutons (Fig. 6, Schmidt, 2000). In this region complex deformation occurred largely at amphibolite metamorphic conditions over a protracted period of time, with much of the deformation apparent between intrusion of 118.2 ± 2.6 Ma granite (U-Pb zircon TIMS age) and ca. 85 Ma when thermal gradients determined by apatite fission track methods had equilibrated across the structure. Structural development of the fan includes extensive mylonitic shear zones, minor brittle overprinting, and multiple episodes of folding with contrasting styles and orientations. All identifiable deformation is contractional, potentially including a small amount of sinistral transpression during a restricted period of time around syn-tectonic intrusion of tonalite sheets in the center that yielded a ^{206}Pb/^{238}U zircon SHRIMP age of 100.1 ± 0.5 Ma. Rapid bedrock cooling below 400 °C in this region is inferred for the period ca. 91–85 Ma (^{40}Ar/^{39}Ar and fission track methods, Ortega-Rivera et al., 1997; Rothstein, 1997; Schmidt, 2000).

In the transitional deformation belt farther south, at El Marmol (Fig. 5A and 5B), upper greenschist to lower amphibolite metamorphic grade rocks in the transition zone have been strongly cleaved and multiply folded, with a change from production of north-northeast-plunging to west-northwest-plunging fold sets apparent during Albian-Aptian time (Buch and Delattre, 1993; Phillips, 1993). In the Calamajue region, a major northwest-striking shear zone occurs in upper greenschist to amphibolite grade rocks in the transition zone, which forms a series of southwest-vergent thrust slices consisting of 103 ± 4 Ma (U-Pb zircon TIMS methods) apparent Alisitos Formation and Jurassic flysch assemblage rocks sandwiched between Paleozoic passive margin assemblages (Fig. 5B, Griffith and Hoobs, 1993). Steeply northeast-dipping mylonitic foliation and steeply pitching lineation are well developed in the shear zone. Foliation is axial planar to steeply-plunging isoclinal folds that have progressively rotated during deformation. Flattening strains and >60%–70% shortening have been ascertained in parts of the shear zone, and deformation has been constrained to ca. 103–100 Ma as determined from deformed apparent Alisitos equivalent strata and a crosscutting undeformed granite that yielded a single fraction U-Pb zircon TIMS age of <100 Ma. In the southernmost reported exposure of the PRb transition zone, at El Arco, strongly folded and cleaved amphibolite grade flysch assemblage rocks occur in disconnected wall rock screens in a region that has been extensively intruded (Barthelmy, 1979).

Boundary with the eastern zone

The Mesozoic boundary between eastern and transitional zones in the batholith is defined by a changes in prebatholithic stratigraphy from flysch to miogeoclinal sequences, Mesozoic contractional shear zones, and sharp gradients in regional cooling histories. A spectacular escarpment with >1000 m of relief commonly coincides with this Mesozoic boundary (e.g., Grove, 1994; Rothstein et al., 1995). This feature formed in Neogene time by normal faulting associated with extension in the Gulf of California that appears to have reactivated parts of the older boundary.

In the northern batholith, the eastern side of the Cuyamaca Laguna Mountains shear zone in the Chariot Canyon and Carrizo Gorge areas corresponds with the boundary between the transition and eastern zones of the PRb and a distinct step in metamorphism and rock cooling histories (Fig. 5B, Grove, 1989, 1994). Upper amphibolite grade rocks that equilibrated at 4.5 ± 1.5 kbar and 650 ± 50 °C have been thrust westward between 76 and 72 Ma (and possibly earlier) over phyllite of the Julian Schist that attained only 2.5 ± 1.2 kbar and 550 ± 35 °C. Footwall rocks to this structure underwent rapid cooling (below 400 °C) from ca. 88–85 Ma, whereas rapid cooling is apparent in hanging wall rocks from ca. 76–72 Ma (Grove, 1994).

In the southern batholith, on the eastern side of the fan structure in the Sierra San Pedro Martir, migmatitic flysch assemblage rocks in the transition zone have been thrust eastward over miogeoclinal rocks in the eastern zone. The age of thrusting is poorly constrained to the time between ca. 164 Ma strongly deformed orthogneiss and crosscutting ca. 99–92 Ma La Posta-type plutons (Schmidt, 2000). Thrust vergence here is the opposite of that in other regions along strike in the batholith, such as in the Chariot Canyon area of southern California (Fig. 5B). Biotite ^{40}Ar/^{39}Ar apparent ages are similar across the boundary between transition and eastern zones in the fan structure, but a 14 m.y. gradient is apparent in apatite fission track ages, with younger cooling histories apparent in the footwall. Farther south in the batholith, the eastern boundary of the transition zone has not been defined.

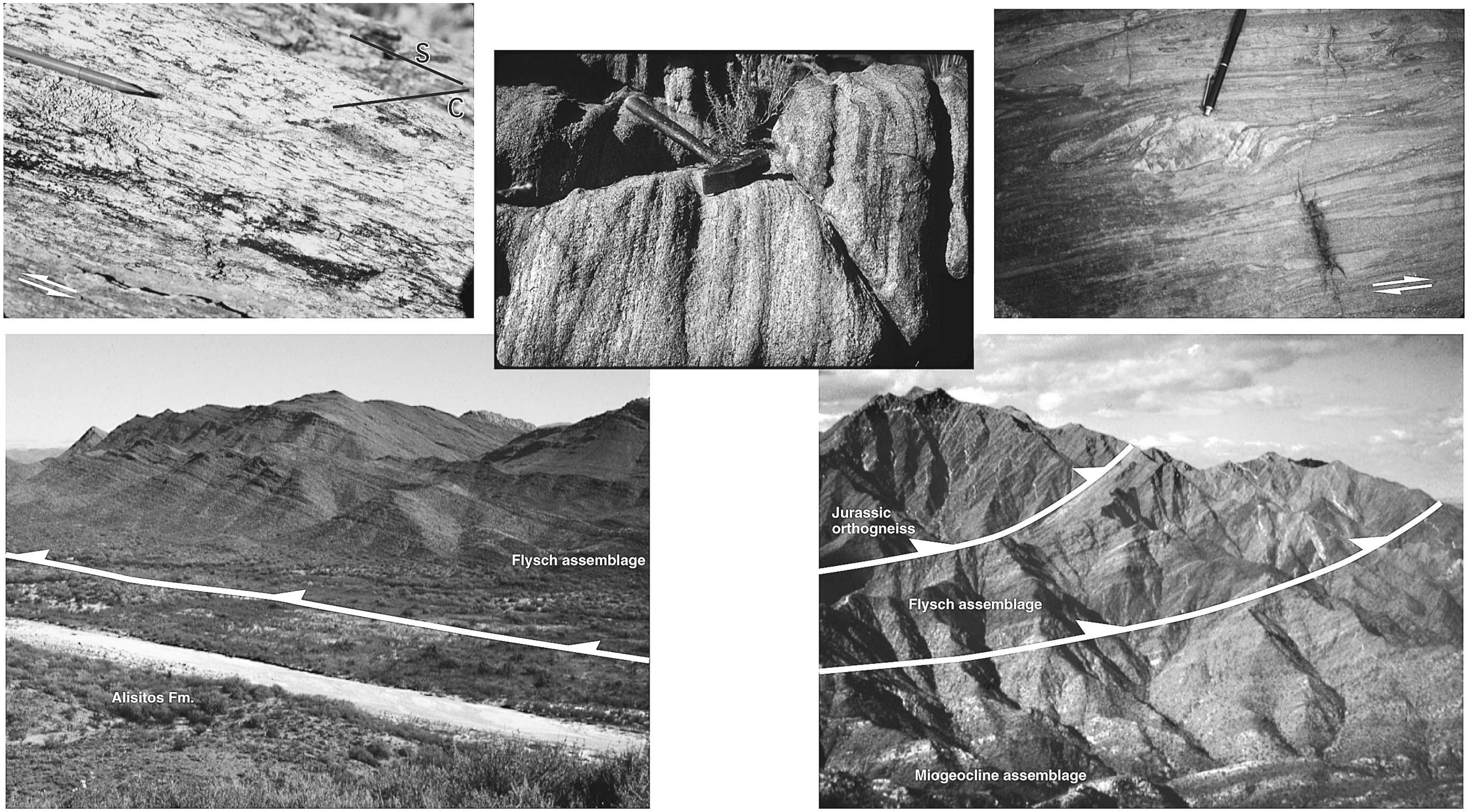

Figure 6. Field photograph composite from the southern Sierra San Pedro Martir depicting the fan structure developed across the PRb transition zone. Lower two photographs show the inward-dipping mylonite shear zones on either side of the fan structure that are nearly 20 km apart. Top three outcrop photographs show mylonite fabrics containing top-outward kinematic indicators on the sides and steeply-dipping magmatic fabrics in vertical tonalite sheets in the center of the structure. All photographs taken looking north.

Boundary with the western zone

In contrast to the eastern boundary of the transition zone, the western boundary is in places impressively exposed and defined. This boundary shows dramatic contrasts in its character across the Agua Blanca fault. North of the fault, depositional contacts between flysch assemblage and Santiago Peak Volcanic rocks occur in several places. These exposures lie well to the west of major shear zones in the transition zone deformation belt and sharp gradients in metamorphism and rock cooling histories. In the Santa Ana Mountains, deformed and metamorphosed rocks of the late Middle Jurassic Bedford Canyon Formation depositionally underlie nearly horizontal strata of the Santiago Peak Volcanics that yielded a 127 ± 2 Ma zircon U-Pb TIMS age (Herzig and Kimbrough, 1998). A similar relationship occurs near San Diego, where Santiago Peak Volcanic strata lies depositionally on the undated folded and cleaved amphibolite grade metavolcanic rocks described by Todd et al. (1988).

In the Sierra Juarez, the contact between Santiago Peak Volcanics and flysch assemblage rocks appears to remain west of the main belt of deformation in the transition zone (Fig. 5B). The contact here is gradational across a broad region displaying complex folding and strong cleavage development, and we suggest that it is a sheared unconformity.

The boundary between the transition zone and western zones of the batholith is strikingly defined in the Sierra San Pedro Martir south of the Agua Blanca fault. On the western side of the fan structure flysch assemblage rocks in the transition zone have been thrust southwestward over the Alisitos Formation in the western zone (Fig. 6, Johnson et al., 1999a). Nearly 15 km of structural throw is apparent across this shear zone as ascertained from a dramatic metamorphic pressure gradient ranging from ~2–5 kbar that corresponds with a >10 m.y. gradient in $^{40}Ar/^{39}Ar$ biotite and K-feldspar and apatite fission track cooling ages (Kopf et al., 2000; Schmidt, 2000). Wall rocks in the center of the fan structure preserve a metamorphic progression from early gedrite-sillimanite followed by overgrowth of staurolite, then late garnet-cordierite. This progression indicates decompression from peak pressures of ~5 kbar to <3 kbar that occurred between ca. 100 and 85 Ma and is confirmed by Al-in-hornblende results of 5–6 kbar from ca. 100 Ma plutons. In contrast, volcanic rocks in the footwall of the shear zone along the western side of the fan structure preserve greenschist grade pumpellyite-muscovite-chlorite assemblages and Al-in-hornblende barometry in plutons of the western zone here indicate pressures <2 kbar.

Farther south in the batholith, the western boundary of the transition zone has not been defined, and appears to be largely obscured. However, at El Arco, Barthelmy (1979) described limited exposures of a shear zone that is analogous to the one along the western side of the fan structure. Alisitos Formation rocks in the western zone are progressively more deformed and metamorphosed from chlorite to amphibolite grade toward the northeast across a <5-km-wide belt that is adjacent to exposures of strongly deformed flysch assemblage rocks. Unfortunately, the actual contact appears to be completely intruded out and/or covered.

Summary of the transition zone

In summary, the transition zone is a distinctive entity in the PRb that evolved since early Mesozoic time. Many similarities in the evolution of this zone are apparent between northern and southern parts of the batholith. Along its length, this belt preserves a long history of Mesozoic basin formation and strong ties between these basins and North America. Both northern and southern parts of the transition zone share a similar history of long-lived arc magmatism extending from Late Jurassic to Late Cretaceous time, and major plutonic suites such as the La Posta suite are continuous across the Agua Blanca fault. The entire transition zone shows more intensively developed Jura-Cretaceous deformation than the western and eastern zones to either side, and mylonite shear zones with east-side-up displacement are common. Similar metamorphic grades and peak P-T conditions are also apparent along this belt, and sharp, eastward-increasing metamorphic gradients commonly occur across the east-side-up shear zones. Sharp steps in rock cooling histories also typically correspond with the shear zones, indicating that denudation in the batholith was accommodated by these structures (Grove, 1994).

However, some important differences in the evolution of the northern and southern parts of the transition zone are apparent across the Agua Blanca fault. The northern part appears to preserve older basins (Triassic(?)-Late Jurassic) that collected mostly sedimentary detritus, largely derived from North American sources. In contrast, basins in the southern half of the batholith appear to be younger (Late Jurassic-Early Cretaceous) and contain a large proportion of locally derived volcanic detritus in addition to North American derived sediment. Moreover, from known regions to the south of the Agua Blanca fault, mylonite shear zones, and their associated metamorphic gradients and steps in cooling ages, consistently define the boundary with the western zone, while those in the north do not (Fig. 5B). Despite these changes in the locus of denudation in the batholith, it appears that both northern and southern halves of the transition zone were denuded at about the same time and to similar degrees with some local variation. Forearc basin detrital thermal studies in the northern part of the batholith indicate rapid denudation in Cenomanian–Turonian time (ca. 99–89 Ma, Lovera et al., 1999), while bedrock thermal history studies in the southern part of the batholith show rapid cooling that has been attributed to rapid denudation within the period ca. 100–85 Ma (Rothstein, 1997; Ortega-Rivera et al., 1997; Schmidt, 2000).

The boundary between the transitional and eastern zones largely corresponds with structural and lithological changes across the trend of the batholith that coincide with some variation in west-to-east cooling age gradients and minor changes in crustal exposure levels. North-south variation along the boundary appears to be minimal, and includes local changes in thrust vergence and minor variation in the relative degree of denudation and cooling histories of rocks to either side. The transitional and eastern zones of the batholith have been joined across this apparently inherited crustal boundary since pre-Mesozoic time.

In contrast, the boundary between the transitional and western zones is strikingly defined by stratigraphic, structural, and metamorphic relationships that change along-strike in the batholith. The most dramatic change occurs across the Agua Blanca fault. In general, unconformities, both depositional and sheared, define the boundary north of the Agua Blanca fault, and major gradients in metamorphic grade and bedrock cooling histories occur farther east within the transition zone. In contrast, the boundary to the south is largely defined by fault contacts between pre-Albian-Aptian assemblages, and sharply defined inverted metamorphic gradients and major eastward-younging steps in bedrock thermal histories coincide with these faults.

Western zone. The western zone of the PRb shows a number of changes in stratigraphy, pluton source characteristics, and structures across the Agua Blanca fault that are even more compelling than changes across this structure in the transition zone. Pre- to syn-batholithic stratigraphy of the western zone is subdivided into the Santiago Peak Volcanics (Larson, 1948) north of the Agua Blanca fault and the Alisitos Formation (Allison, 1955, 1974) to the south (Fig. 5A). The Santiago Peak Volcanics consist predominantly of andesite and quartz latite flow and volcaniclastic rocks (Larson, 1948; Schroeder, 1967; Adams, 1979). A largely subaerial depositional environment has been interpreted for this volcanic sequence. Age constraints for the Santiago Peak Volcanics include latest Jurassic fossils (Fife et al., 1967), and U-Pb TIMS zircon ages that range from 138 to 118 Ma for the volcanics and 120–105 Ma for plutons that intrude them (Silver and Chappell, 1988; Walawender et al., 1991; Carrasco et al., 1995). In contrast, the Alisitos Formation consists of volcanic breccia, tuff, and flows of largely andesite and dacite composition, and tuffaceous mudstone and wacke with sparse biostromal limestone. Its depositional environment appears to have been largely submarine (Santillán and Barrera, 1930; Silver et al., 1963; Allison, 1955, 1974). Near the Agua Blanca fault, in the type-section of the Alisitos Formation, the sequence is particularly rich in sedimentary strata that appears to be exclusively of volcanic and organic origin and is at least 6500 m thick, with no top or bottom exposed (Fig. 5A). Volcanic complexes identified in the Alisitos segment include large stratovolcanoes and associated caldera complexes near El Rosario that fed debris into marine basins on their flanks, which are inferred to be fault-bounded (Busby et al., 1998; Fackler-Adams and Busby, 1998). The deeper roots (5–9 km deep) to similar systems appear to be preserved as ring complexes in the western zone of the Sierra San Pedro Martir (Johnson et al., 1999b). Age constraints for the Alisitos Formation include Albian-Aptian fossils (121–99 Ma; Silver et al., 1963; Allison, 1974), U-Pb zircon ages of 116 ± 2 Ma and 115.7 ± 1.1 Ma from volcanics by, respectively, TIMS (Carrasco et al., 1995) and SHRIMP (Johnson, written commun.) methods, and ^{206}Pb/^{238}U zircon SHRIMP ages ranging from ca. 117–113 Ma from plutons that intrude the volcanics (Tate et al., 1999; Johnson et al., 1999a).

Basement to western zone volcanic sequences is not seen except in the north where eastern exposures of the Santiago Peak Volcanics lie unconformably on flysch assemblage rocks. Volcanic rocks yield zircons with some inheritance from the Santiago Peak segment (e.g., Meeth, 1993), but volcanics and plutons in the Alisitos segment have not, as yet, been shown to contain zircons with inherited Pb (e.g., Johnson et al., 1999a). Thus, at least the Alisitos segment of the western zone may not contain continental crustal basement and could have evolved in an environment that was isolated from continental influence until inferred collision at ca. 115–108 Ma (Johnson et al., 1999a). Moreover, if additional data from the Alisitos segment continue to indicate a lack of inheritance, then it is unlikely that the flysch sequences containing conspicuous inherited zircon components in the transition zone are present in the basement of the Alisitos segment of the western zone, unless magma that intruded this crust somehow avoided chemical and mechanical exchange with a portion of its host rock.

Rocks of the western zone are for the most part only weakly deformed, but along-strike and across-strike structural variation is apparent within this belt. In southern California much of the Santiago Peak Volcanics are nearly horizontal. Farther south in Baja California, near the boundary with the transition zone strata are tightly folded and contain steeply-dipping cleavage (our unpublished mapping). South of the Agua Blanca fault, in the Alisitos Fm., a deformation gradient is apparent across a west-to-east transect west of the Sierra San Pedro Martir. Alisitos strata are horizontal to gently folded near the Pacific Coast and become more folded eastward into open folds with nearly horizontal, northwest-southeast trending axes. Within a few km of the boundary between western and transition zones, Alisitos strata are tightly to isoclinally folded with moderately- to steeply-plunging axes and well-developed axial planar cleavage that are parallel (± 20°) to the strike of reverse faults along the boundary. Deformation along this transect is loosely constrained to pre- to syn-emplacement of 117–113 Ma plutons (Johnson et al., 1999a; 1999b). Farther south, inferred basin-bounding normal faults associated with the caldera complexes near El Rosario are ca. 130–120 Ma (C. Busby, 1999, personal commun.).

The contact between the Santiago Peak Volcanics and Alisitos Formation across the Agua Blanca fault appears to be an important tectonic boundary in the western zone of the batholith (Fig. 5B, Gastil et al., 1975, 1981; Wetmore and Paterson, 2000). A pre-Tertiary sinistral history has been inferred for this presently active fault based on discordances in stratigraphic and structural trends in both the Santiago Peak Volcanics and Alisitos strata (Gastil et al., 1975; Armijo and Suarez-Vidal, 1981; Wetmore and Paterson, 2000). A marked change in lithology occurs across the fault, from a sequence dominated by volcanic flows and tuffs to the north to a mixed volcanic/epiclastic and carbonate sequence to the south that continues southward along the boundary between western and transition zones of the batholith (Fig. 5A). Furthermore, the structural trend of the largely margin-parallel Santiago Peak Volcanics is highly discordant to the trend of the Agua Blanca fault, whereas Alisitos strata south of the fault bend from a margin-parallel (and highly fault-oblique) orientation at distances farther away from the fault to fault-parallel near to it. Ductilely deformed Alisitos rocks in the sedimentary-rich package near the Agua Blanca fault are intruded by undeformed western zone plutons, indicating a Mesozoic age of deformation (Wetmore and Paterson, 2000). The westward bending of stratigraphic and structural trends in the Alisitos segment near the Agua Blanca fault suggests drag-folding of the Alisitos block in a sinistral sense.

DISCUSSION

The transition zone is a long-lived entity in the PRb, extending as far back as early Mesozoic time when flysch sediments were deposited within basins located along it. Over the course of >60 m.y. during Jurassic-Cretaceous time, this boundary divided distinct lithosphere to the west and east with very different source and host rock characteristics for arc magmas that formed the batholith. Contractional deformation was focused along the transition zone during >40 m.y. as the arc developed, producing a belt of reverse shear zones, folds, and intense cleavage that was once continuous along the length of the PRb. As the batholith was exhumed in its culminating stages of formation, the transition zone served as a important boundary dividing relatively stable crust to the west that preserves high crustal levels from deeply denuded crust to the east. At least in places, east-side-up shear zones formed along this boundary that accommodated differential exhumation of the batholith. Thus, the transition zone is an inherited feature in the PRb, across which the batholith was constructed. It formed a belt of active crustal heterogeneity within the batholith that appears to have been a weak crustal zone along which orogenesis was focused.

Stratigraphic, magmatic, and structural relationships outlined above indicate that the eastern and transitional zones of the batholith evolved together during the Mesozoic. These include: (1) Triassic(?)-Early Cretaceous flysch strata in the transition zone that contain detritus of North American origin (Gastil, 1993); (2) plutons of similar lithology and identical Middle Jurassic age (164.4 ± 1.2 and 164.3 ± 2.3 Ma) intrude both the transition and eastern zones of the batholith (Schmidt, 2000); and (3) plutons in the transition zone show inherited Pb ages of ca. 1100–1300 Ma, a common basement age to the east in Sonora (Gastil and Girty, 1993; Gastil, 1993). The main question in PRb tectonics therefore concerns whether the western and transition zones evolved together during the Mesozoic, and if not then when, and by what process, were they juxtaposed? One issue that bears prominently on this problem is that the Santiago Peak and Alisitos segments of the western zone appear to have been juxtaposed during Cretaceous time by sinistral displacement on the Agua Blanca fault (Gastil et al., 1975, 1978, 1981; Wetmore and Paterson, 2000).

Implications for tectonic models of the Peninsular Ranges batholith

In the northern part of the PRb, western zone strata were deposited on flysch basement, strongly suggesting that a single, broad arc formed across an inherited continental-oceanic lithospheric boundary. This interpretation is corroborated by Pb inheritance in zircons from volcanics and plutons in the Santiago Peak segment, reflecting the presence of continentally-derived sources in its basement (possibly flysch strata). Thus, model A in Figure 7 seems to appropriately describe the Jura-Cretaceous evolution of the northern PRb.

In contrast, the Alisitos segment of the western zone does not show stratigraphic ties with the batholith transition zone until at least Albian-Aptian time (ca. 121–99 Ma), when Alisitos strata of this age were deposited and subsequently cut by reverse faults that bound the two zones. Moreover, petrological studies suggest a primitive island arc setting for plutons in the Alisitos segment, and both plutons and volcanics appear to lack inherited continental components. Finally, a major Cretaceous strike slip or transpressive shear zone is apparent along the trace of the presently active Agua Blanca fault. Thus, the Alisitos segment appears to have evolved as an island arc in isolation from continental influences, which subsequently collided with the North American margin in the period ca. 115–108 Ma (model C in Figure 7). This model is built on the ideas of many researchers for the origin of the western zone of the batholith including Gastil et al. (1981), Todd et al. (1988), Sedlock et al. (1993), and Johnson et al. (1999a), but here is restricted to the southern half of the PRb. Prior to collision of the Alisitos arc, it is likely that oceanic basement of the Santiago Peak segment continued to the south along the length of the PRb.

The tectonic setting(s) for basins that collected the diverse flysch assemblage remains open to debate. A commonly cited tectonic model for the flysch assemblage is deposition in an intraarc or backarc setting (Fig. 7B, e.g., Rangin, 1978; Gastil, 1993). Gastil et al. (1981) recognized that the flysch assemblage changes along strike; strata north of the Agua Blanca fault appear to be older than those to the south. Thus, they proposed that the marginal basin in the north collapsed prior to the one to the south and the Agua Blanca fault served as an accommodation zone between these two segments in the batholith.

However, this model has several problems. First, there is little evidence in the transitional and eastern zones of the PRb for backarc extension of the arc in latest Jurassic-Cretaceous

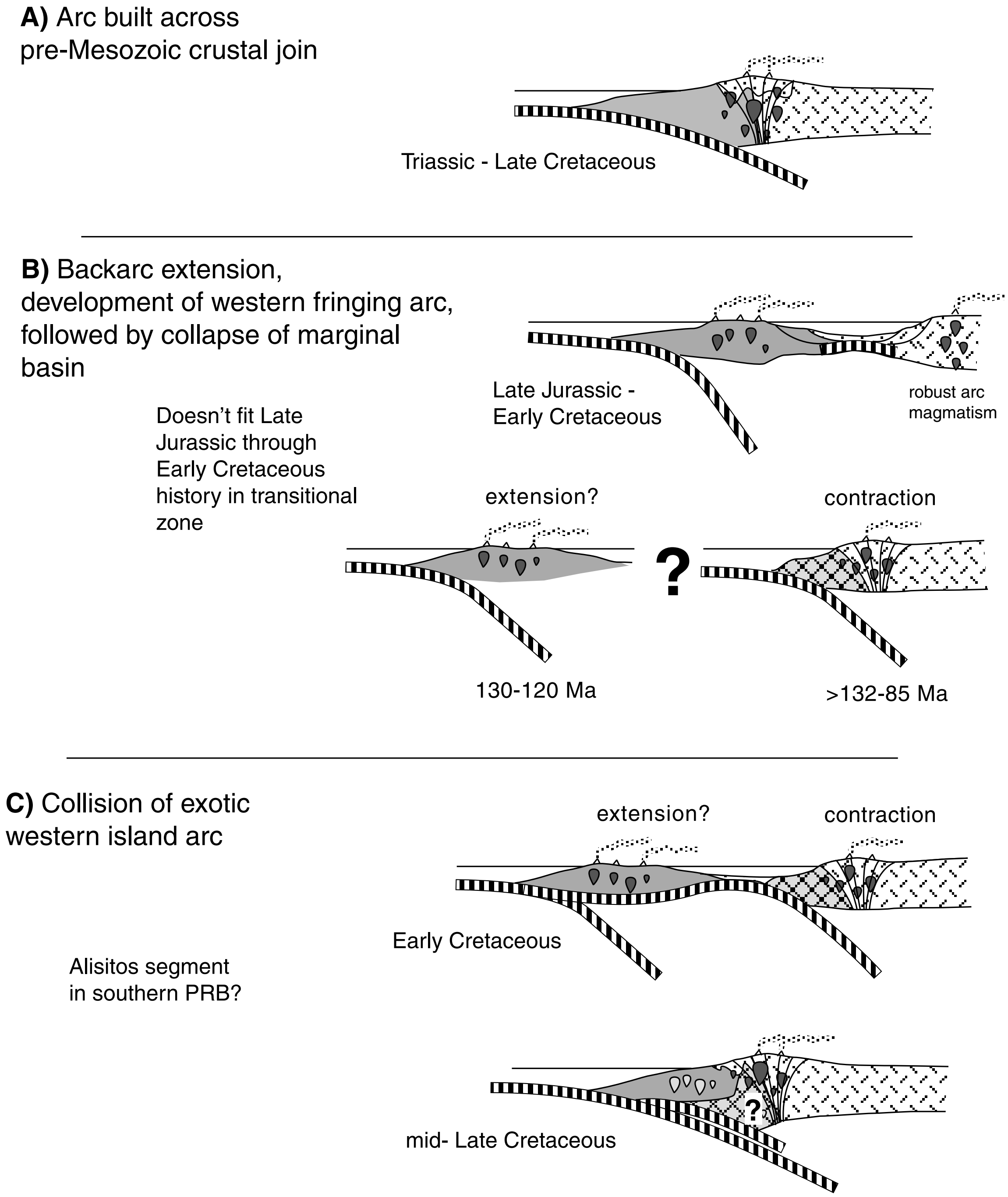

Figure 7. Tectonic models suggested for the PRb with constraints determined in this synthesis. Explanation is the same as for Figure 2.

time. Furthermore, the transitional zone of the batholith experienced voluminous arc magmatism during this time, from ca. 164 Ma to <92 Ma. This is an issue that is difficult to explain by subduction of oceanic crust produced in a backarc setting because it would require a basin large enough to sustain >50 m.y. of subduction and associated arc magmatism in the transition and eastern zones of the batholith before final suturing of the Alisitos arc segment. Thus, Early Cretaceous extension inferred in the Alisitos arc segment (Busby et al., 1998; Fackler-Adams and Busby, 1998) may be more readily reconciled with an extensional Alisitos island arc system that later collided with North America rather than backarc basin formation within the contiguous PRb (Fig. 7B).

Several observations indicate an alternative tectonic setting for the flysch assemblage that is more consistent with collision of the Alisitos island arc. First, not only are flysch strata north of the Agua Blanca fault older than their counterparts to the south, but they appear to show few recognizable volcanic components. A likely origin for these early Mesozoic basins is in a forearc setting where they received either little, or only fine-grained, volcanic detritus from a distant arc that was located well inboard of the continental margin in present-day Arizona and northern Sonora. In contrast, strata to the south appear to be Mid-Jurassic or younger in age and invariably contain coarse volcanic detritus, presumably from proximal sources. Thus, the flysch assemblage appears to be a strongly composite tectonostratigraphic unit that may consist entirely of forearc stratigraphic sequences of various Mesozoic ages that are preserved in different parts of the PRb transition zone.

A difficulty with the Alisitos arc collision model in the southern PRb is the fate of the forearc element that must have existed prior to collision. Some of this assemblage may be preserved in the flysch assemblage of the southern part of the batholith. However, the proposed suture in this area occurs within the Early Cretaceous arc, implying that part of the older forearc is missing. On Figure 7C we speculate that the western part of the old forearc was thrust beneath the transition zone of the batholith. At present there is no evidence for this event. However, this region is very poorly known and, thus, is a critical part of the PRb in which to test collisional and backarc models for the Alisitos segment.

Collision of the Alisitos arc segment in the period ca. 115–108 Ma has important implications for orogenesis in the batholith to the east. During the period ca. 100–90 Ma a major orogenic pulse is apparent along the length of the PRb. The transitional and eastern zones of the batholith adjacent to both the Santiago Peak and Alisitos segments experienced similar histories of heightened deformation, exhumation, and extensive La Posta magmatism during this time. Thus, the effects of Alisitos arc collision on the North American margin appear to have been masked by other more widespread orogenic processes, possibly including increased subduction zone coupling that affected an extensive part of the southern North American Cordillera (e.g., Tobisch et al., 1995; Miller et al., 1993).

Tectonic overview—a hypothesis for evolution of the Peninsular Ranges batholith

The eastern zone of the PRb was constructed on the remnant Precambrian-Paleozoic passive margin of southwestern North America (Fig. 8A). By Jurassic (and possibly Triassic) time, forearc basins in the presently exposed transition zone in the northern part of the batholith received detritus from North American sources, with little, or only fine grained, material from a volcanic arc(s) that was likely located well to the east (Fig. 8A). We infer the depositional substrate for the flysch to be, at least in part, oceanic crust, which subsequently served as the basement to the Santiago Peak segment. Limited arc magmatism initiated within the transitional zone in southern California in Triassic to earliest Jurassic time as indicated by the 234 ± 39 Ma Harper Creek orthogneiss (Thomson and Girty, 1994).

Sedimentation continued within the PRb transition zone through the Early Cretaceous, at least in the southern part of the batholith, and detritus was derived from both cratonal North America as well as proximal volcanic arc(s) (Fig. 8B). Middle to earliest Late Jurassic arc magmatism occurred in a belt within the transitional and eastern zones stretching from southern California through the southern Sierra San Pedro Martir, and probably farther south (Fig. 8B). We suggest that this was the southern extension of the Jurassic arc in Arizona and northern Sonora after restoring Tertiary northeast-southwest extension across the Gulf of California and western Sonora as well as ~300 km of right lateral offset across the Gulf. However, we recognize that other scenarios are possible. The earliest discernable episode of contractional deformation occurred within the period 151–127 Ma in the transition zone, and apparently affected both the northern and southern parts of the batholith. We infer an Alisitos island arc evolving well offshore during this time in Figure 8B and the presence of a transform fault that will extend into the margin to form the Agua Blanca fault in the next time step (Fig. 8C).

We infer collision of the Alisitos island arc with the margin of the Peninsular Ranges within the interval ca. 115–108 Ma (Fig. 8C, Johnson et al. 1999a). Part of the original forearc was removed, presumably by underthrusting, and the trench for the PRb arc transferred to the western side of the docked Alisitos arc. Relationships along the Agua Blanca fault suggest its role as a Cretaceous transform fault that juxtaposed Alisitos and Santiago Peak segments (Gastil et al., 1975, 1981; Wetmore and Paterson, 2000). Magmatism was widespread and robust throughout the PRb during the time leading up to collision. In the present western zone of the batholith, the Santiago Peak Volcanics erupted from 138 Ma to at least ca. 118 Ma in the north, and volcanism the Alisitos segment in the south began before ca. 116 Ma. In the transition zone, Cretaceous plutonism in the northern part of the batholith was apparently restricted to ca. 120–100 Ma, however, in the Sierra San Pedro Martir of the southern batholith, plutonism is known to have occurred within the periods ca. 135–128, and ca. 118 Ma. Contractional deformation is evident from both the northern and southern parts of the transition zone during this interval before collision.

In the time interval during and following collision (ca. 115–100 Ma), magmatism continued across all zones of the PRb and includes intrusion of abundant plutons in the western and transition zones as well as eruption of an extensive pile of volcanic strata across the eastern zone (Herzig and Kimbrough, 1998). Contractional deformation also continued to be focused within the transitional deformation belt along the length of the batholith (Fig. 8C). Much of the deformation in this belt in the southern part of the batholith occurred during inferred collision of the Alisitos arc segment, but significant deformation oc-

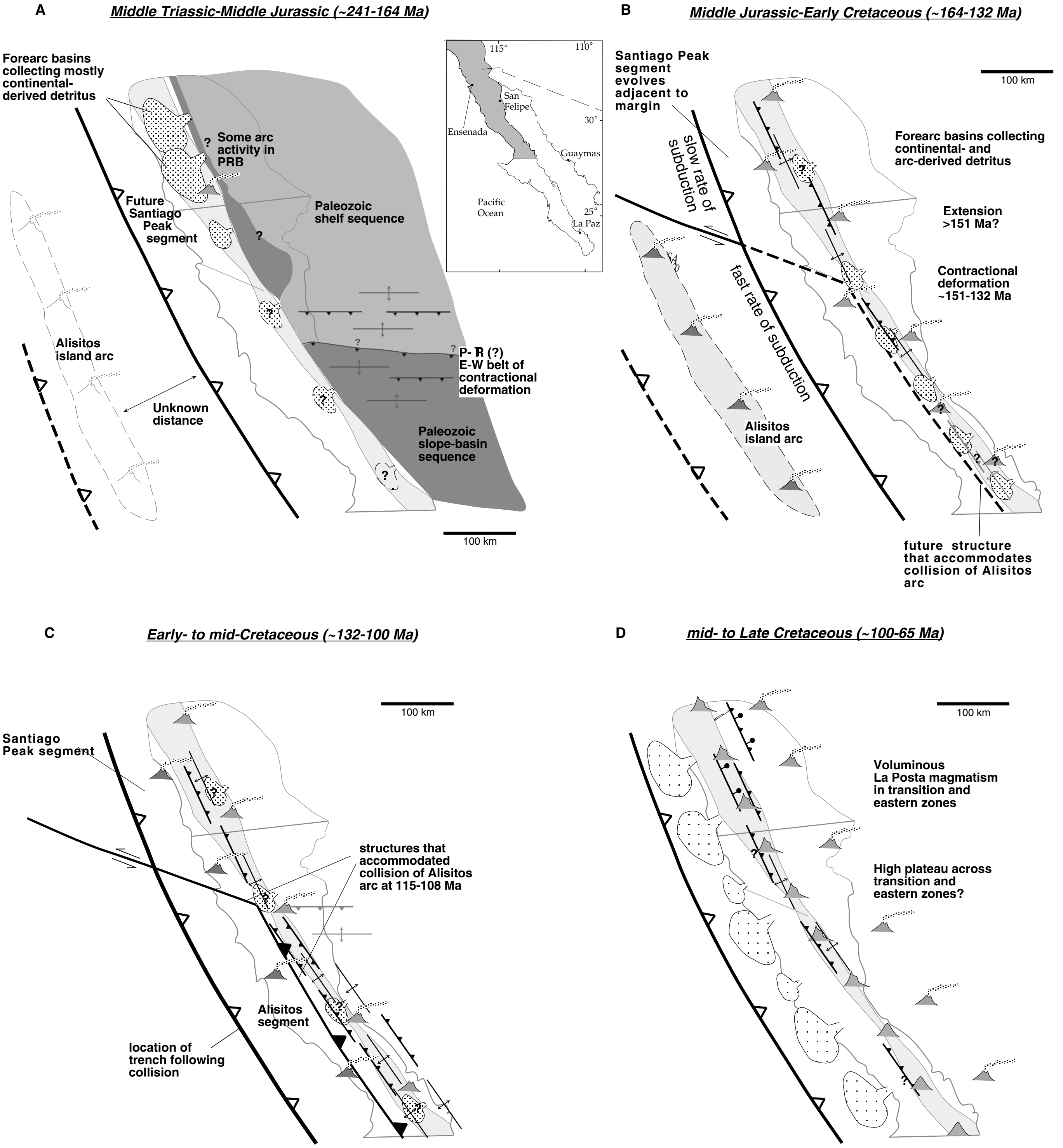

Figure 8. Series of time slices and generalized tectonic features for each time period. See text for explanation.

curred prior to and following collision adjacent to both the Alisitos and Santiago Peak segments. In comparison, little deformation is apparent in the western zone during this time, with the exception of rocks near the Agua Blanca fault. And in the eastern zone, miogeoclinal rocks north of 30.5°N were apparently only locally deformed, while significant deformation is apparent in this belt farther south.

An episode of voluminous La Posta plutonism occurred in the transitional and eastern zones along the length of the batholith from ca. 99–92 Ma (Kimbrough et al., 2001). This was followed by an apparent eastward migration of magmatism that reached present-day Sonora by latest Cretaceous-earliest Tertiary time (Fig. 8D). Dramatic exhumation of the transitional and eastern zones of the PRb occurred syn- to post La Posta time. For example, plutons in the transitional zone of the southern Sierra San Pedro Martir that were emplaced ca. 100 Ma at >15 km depth had reached near-surface conditions (<5 km) by ca. 85 Ma during uplift accommodated on reverse shear zones (Schmidt, 2000). Thick sequences of coarse detritus accumulated in forearc settings along the present western coast of Peninsular California beginning at ca. 99 Ma (Fig. 8D, e.g., Bottjer and Link, 1984; Busby et al., 1998; Kimbrough et al., 2001). Detrital ^{40}Ar/^{39}Ar K-feldspar studies of these sediments corroborate rapid denudation of the transition and eastern zones of the batholith (Lovera et al., 1999). This denudation continued until ca. 70 Ma in the transition zone of the batholith and into the Paleogene in the eastern zone, where distinct variation is apparent in the amount of denudation across the crustal boundary along ~30.5°N latitude (Rothstein, 1997).

CONCLUSIONS

Our present understanding of geologic relationships in the PRb indicate that the eastern, transitional, and western zones of the batholith are distinct basement belts across which the batholith was constructed in Jura-Cretaceous time. The eastern zone of the PRb appears to be underlain by North American basement that was variably deformed during Mesozoic orogenesis and deeply denuded in the Late Cretaceous. It contains an inherited, pre-Mesozoic boundary that crosses it at ~30.5°N latitude, which separates shelf from slope facies Paleozoic miogeoclinal rocks and appears to have influenced the Mesozoic deformation and exhumation history of the eastern zone. In contrast, the western zone was constructed on basement of oceanic character, experienced primitive arc magmatism, is generally little deformed, and preserves upper crustal levels of the Peninsular Ranges arc.

The transition zone, which evolved across the interface between western and eastern zone crust, is a long-lived feature that is tied by sedimentological and petrological criteria to the eastern zone throughout the Mesozoic. It played an important role in the evolution of the batholith in the following ways:

1. It separated distinct lithospheric belts within the batholith that generated very different magma compositions during >60 m.y. of Mesozoic arc magmatism.
2. It controlled the distribution of long-lived forearc or intraarc basins within the batholith.
3. It focused contractional deformation along a narrow belt of reverse shear zones, folds, and intense cleavage along the length of the batholith for >40 m.y.
4. It determined how exhumation progressed as the eastern belt was deeply denuded during the later stages of the batholith's history.

A significant Mesozoic across-strike boundary in the PRb occurs across the western and transition zones along the modern Agua Blanca fault. In the western zone of the batholith, the Agua Blanca fault appears to separate two distinct Mesozoic arc segments. The Santiago Peak segment is clearly tied by depositional contacts to the transition zone since ca. 127 Ma, and Pb zircon inheritance in igneous rocks within the terrane is consistent with its evolution adjacent to the transition zone. The less well understood Alisitos arc segment to the south, on the other hand, shows no ties to the transition zone until ca. 115–108 Ma. Moreover, igneous rocks from this segment, as of yet, have yielded no inherited Pb in zircons that would be consistent with the terrane's origin adjacent to North America, and petrological studies strongly suggest an island arc environment. Finally, the geometry of stratigraphy and structures in the Alisitos arc segment adjacent to the Agua Blanca fault suggests sinistral drag folding, consistent with docking of the Alisitos arc terrane south of the Santiago Peak segment.

Features that define the transition zone are continuous along-strike across the Agua Blanca fault. However, some distinct changes are also apparent including mostly clastic sediment in the flysch assemblage to the north versus volcaniclastic to the south, and the location of shear zones and gradients in metamorphic and thermal histories of rocks appears to shift from the eastern side of the transition zone in the northern batholith to its western side in the southern batholith. Consequently, an interesting problem is apparent in the PRb transition zone adjacent to the Santiago Peak and Alisitos segments. The transition zone shows some variation in evolution along-strike between regions that are adjacent to these respective noncollisional and collisional terranes. For example, the boundary between the Alisitos arc segment and the transition zone is defined by impressively developed mylonite shear zones, whereas the boundary to the north is not as well defined. However, the transition zone in both the northern and southern parts of the batholith experienced a similar degree of metamorphism, denudation, and focused deformation compared to eastern and western zones to either side. Thus, it appears that the effects of collision of the Alisitos arc segment with North America at ca. 115–108 Ma have been masked by orogenesis driven by processes such as heightened subduction zone coupling that may have affected a large part of the southern Cordilleran margin. Collision was, accordingly, not a major mechanism that drove orogeny in the PRb, and the pulse of deformation and exhumation after ca. 100 Ma resulted from other orogenic processes.

ACKNOWLEDGMENTS

This work was funded by the National Science Foundation (grant EAR9614682). We thank a number of individuals for valuable discussions on the Mesozoic tectonics of the Peninsular Ranges batholith over the past few years including Gordon Gastil, Gary Girty, Celeste Thomson-Yoshinobu, Richard Sedlock, Marty Grove, and John Fletcher. Thoughtful reviews by Greg Davis, Gary Girty, and Paul Umhoefer helped us to clarify many of our ideas and significantly improved the manuscript.

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Manuscript Accepted by the Society February 8, 2002

Printed in the U.S.A.