Medial Cretaceous Subduction Erosion of Southwestern North America: New Hypothesis for the Formation of the Catalina Schist

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Abstract The high P/T Catalina Schist underlies the inner southern California borderland outboard of southwestern North America and records amphibolite facies recrystallization and partial melting at ca. 115 Ma and 40 km depth. While inverted metamorphism down to lawsonite albite facies across low-angle faults has most commonly been regarded as a product of nascent subduction, new detrital zircon U-Pb ages (33 samples; N = 645) demonstrate that the Catalina Schist was derived from successively accreted sediment shed from the evolving northern Peninsular Ranges batholith. Zircons from high-grade metasediments represent early Aptian, craton-enriched detritus shed predominantly from the batholith's pre-Cretaceous flysch wallrocks and the Late Jurassic to Early Cretaceous volcanic cover. The lowest temperature rocks were accreted 15-20 m.y. after peak-grade recrystallization of the amphibolite facies rocks. The latter (lawsonite blueschist, actinolite albite, and lawsonite albite) were derived from Cenomanian sediments composed of Early Cretaceous plutonic and volcanic arc detritus. We note that the Catalina Schist structurally underlies the western margin of the northern PRB and that a deficit of Early Cretaceous forearc rocks exists. We propose that amphibolite facies metamorphism and anatexis within the Catalina Schist was caused by Early Cretaceous subduction erosion and collapse of the forearc. This process involved construction of a subcrustal duplex beneath the PRB beginning at 120-115 Ma. The subcrustal duplex ultimately merged with the continuously active subduction zone as the lawsonite blueschist and lower grade units were accreted at 100-95 Ma. This climax corresponded with an eastern relocation of the magmatic arc and marked a transitional stage leading into the Late Cretaceous-early Tertiary craton-ward shift of arc magmatism and contractional deformation of southwestern North America which characterized the Laramide orogeny.

Key Words: Catalina Schist, U-Pb, zircon, subduction erosion

INTRODUCTION

Subduction erosion refers to the collective processes that transfer rock mass from the overriding plate of convergent margins to positions beneath the crust, mantle lithosphere, or even into the asthenosphere (Scholl et al., 1980; Von Hueme and Scholl, 1990, 1992). There is growing appreciation that subduction erosion represents a fundamental convergent margin process, particularly in regions characterized by rapid convergence. Roughly half of all present-day convergent margins exhibit at least some geologic and/or geophysical evidence for subduction-related removal of rocks from the forearc regions of the overriding plate to positions beneath the arc and/or into the mantle (e.g., Clift and Vannucchi, 2004). Unfortunately, the consumptive nature of the process means that direct evidence that subduction erosion has affected ancient convergent margins will generally be lacking or ambiguous. Specifically, indirect evidence for subduction erosion such as "missing" or "telescoped" forearc crust is also generally explainable by alternative tectonic processes, most notably margin-parallel strike-slip faulting. A classic example illustrating the controversies that often arise is provided by the Sur-Naciemento fault in west-central California (Page, 1970). There, plutonic and metamorphic rocks of the Salinian block are juxtaposed against the high-pressure, low-temperature mélange of the Sur-Obispo terrane. This anomalous juxtaposition of lithotectonic belts has alternately been explained by underthrusting of intervening rocks (Page, 1981; Hall, 1991) or by lateral transport of hundreds of kilometers (Hill and Dibblee, 1953; Suppe, 1970; Dickinson, 1983; Dickinson et al., 2005) or even thousands of kilometers (Page, 1982; McWilliams and Howell, 1982; Vedder et al., 1983; Debiche et al., 1987).

As exemplified by the case of the Sur-Obispo terrane, exhumed high-pressure/temperature rocks offer significant potential for preserving evidence of ancient subduction erosion events. Exposure of such rocks at the Earth's surface generally involves fortuitous events related to post-subduction tectonic evolution (e.g., Ernst, 1988; Maruyama et al., 1996). A prime example involves exhumation of the medial Cretaceous high-pressure/temperature Catalina Schist during middle Miocene oblique rifting of the California continental borderland that was triggered by newly initiated Pacific-North American plate interactions (Atwater, 1970; Howell and Vedder, 1981; Wright, 1991; Crouch and Suppe, 1993; Nicholson et al., 1994; Bohannon and Geist, 1998; Ingersoll and Rumelhart, 1999).

The Catalina Schist underlies the inner southern California borderland (Fig. 1) and features inverted metamorphism from amphibolite facies anatexis to blueschist facies (Platt, 1975; see inset in Fig. 1). Amphibolite facies metamorphism took place at ca. 115 Ma (Suppe and Armstrong, 1972; Mattinson, 1986; Grove and Bebout, 1995; Anczkiewicz et al., 2004). The Catalina Schist occurs outboard of the 750-km-long Peninsular Ranges batholith and structurally underlies its northwestern margin (Crouch and Suppe, 1993). Like the Sur-Obispo terrane, the Catalina Schist also exhibits geologic relationships involving the arc and forearc that can be interpreted in terms of subduction erosion.

Miocene rifting of the forearc of northern Baja and southern California has revealed that batholithic rocks directly overlie the high-pressure/temperature rocks of the Catalina Schist across an east-dipping detachment fault (Crouch and Suppe, 1993; Fig. 1). This interpretation is well supported by the distribution of thick syn-orogenic deposits rich in Catalina Schist detritus (San Onofre Breccia; Stuart, 1979) that were shed eastward onto the batholith as the Catalina Schist basement was exhumed during early middle Miocene rifting of the southern California Continental borderland. While oblique rifting related to microplate capture (e.g., Nicholson et al., 1994) ripped forearc strata and underlying basement rocks away from the western margin of the Peninsular Ranges and transported them northwestward into the outer California borderland (Wright, 1991; Crouch and Suppe, 1993; Bohannon and Geist, 1998; Ingersoll and Rumelhart, 1999) this cannot explain how high-pressure/temperature rocks of the Catalina Schist were juxtaposed beneath the western margin of the Peninsular Ranges batholith. As is outlined in this paper, we believe that the juxtaposition originated during medial Cretaceous subduction erosion.

A long-standing and widely accepted explanation for the unusually high-temperature high-pressure/temperature inverted metamorphism of the Catalina Schist is that it formed beneath unrefrigerated mantle lithosphere during nascent subduction (e.g., Platt, 1975). This explanation has been widely applied to explain the existence of similar high-grade blocks within the Franciscan Complex and other accretionary sequences situated along the western margin of North America (e.g., Platt, 1975; Cloos, 1985; Wakabayashi, 1990, 1992, 1999, Anczkiewicz et al., 2004). Because many of these assemblages are Middle Jurassic in age, they can be explained in terms of independent evidence for regionally extensive development of a new subduction regime at this time (Platt, 1975; Cloos, 1985; Mattinson, 1988; Anczkiewicz et al., 2004). The nascent subduction hypothesis has been widely accepted largely because it makes good sense with respect to the major pulse of magmatic activity that occurred along the Middle Jurassic continental margin (Evernden and Kistler, 1970; Saleeby and Sharp, 1980; Stern et al., 1981; Chen and Moore, 1982; Wright and Fahan, 1988; Barton et al., 1988; Staude and Barton, 2001; Irwin, 2002). Formation of the Middle Jurassic Coast Range ophiolite also directly overlapped the time that the anomalously high-temperature, high-pressure/temperature rocks formed within the accretionary complex (Hopson et al., 1981; Shervais et al., 2005). While details regarding the genesis of the Coast Range ophiolite continue to be debated (Dickinson et al., 1996), it is believed by some to also represent a product of Middle Jurassic nascent subduction (e.g., Stern and Bloomer, 1992).

Although the nascent subduction model may generally explain the genesis of Middle Jurassic high-grade rocks within the Franciscan Complex, initiation of a new subduction zone off the southern California margin at ca. 115 Ma makes correspondingly little sense in terms of the intrusive history of the adjacent 750-km-long Peninsular Ranges batholith (PRB; Fig. 1). While the Cretaceous PRB was largely emplaced between 130-90 Ma (Silver and Chappell, 1988; Kistler et al., 2003), it, like the Sierra Nevada batholith to the north, also features locally significant, albeit poorly understood, Middle Jurassic intrusions (Shaw et al., 2003). In addition, Grove and Bebout (1995) have described highly overprinted, garnet-bearing blueschist blocks within lawsonite blueschist grade Catalina Schist that appear to substantially predate 115 Ma amphibolite facies recrystallization. These blocks are similar to those of the Franciscan and require a more complex history for the Catalina Schist than has been generally recognized.

In this paper, we present new detrital zircon U-Pb results from metagraywackes representing the major metamorphic units of the Catalina Schist that clarify its accretion history and confirm a genetic relationship to forearc and batholith rocks of the now adjacent Peninsular Ranges batholith. Consideration of these new results has prompted us to propose that the anomalously high-temperature rocks within the high-pressure/temperature Catalina Schist formed during subduction erosion beneath the arc rather than within the subduction zone. We interpret the Catalina Schist as a subcrustal duplex that merged with the continuously active subduction zone at about 100-95 Ma. Final assembly of the Catalina Schist corresponded with the initial stages of eastward relocation of magmatism and formation of the eastern Peninsular Ranges batholith (La Posta tonalite-trondjhemite-granodiorite belt; see Tulloch and Kimbrough,

2003) during the earliest Late Cretaceous. Hence, underplating of the Catalina Schist is logically viewed as the first event to kick off the sequence of arc extinction and regional underplating of eugeoclinal schist beneath a broad region of southwestern North America during the Late Cretaceous-early Cenozoic Laramide orogeny.

BACKGROUND

Catalina Schist High-Pressure/Temperature Complex

Scattered exposures of high-pressure/temperature rocks distributed along the western margin of southern and Baja California appear to represent the southern continuation of the better exposed Franciscan Complex of central and northern California (Fig. 1; Woodford, 1924; Suppe and Armstrong, 1972; Kilmer, 1979; Blake et al., 1984). The Catalina Schist is the most significant of these occurrences. While on-land exposures of the Catalina Schist are limited to Catalina Island (Bailey, 1941; Platt, 1976) and the Palos Verdes peninsula (Woodring et al., 1946; Dibblee, 1999), Catalina Schist has been detected throughout the inner southern California borderland and within boreholes within the southwestern Los Angeles basin (Yerkes et al., 1965; Sorensen, 1985, 1988; Wright, 1991; Crouch and Suppe, 1993; Bohannon and Geist, 1998; ten Brink et al., 2000). Further evidence for its wide distribution comes from the San Onofre Breccia, a syn-orogenic deposit (Stuart, 1979) that accumulated as the Catalina Schist was exhumed to the surface along extensional structures rooting beneath the Peninsular Ranges forearc region beginning in the middle Miocene (Wright, 1991; Crouch and Suppe, 1993; Nicholson et al., 1994; Bohannon and Geist, 1998; Ingersoll and Rumelhart, 1999).

The geologic characteristics of the Catalina Schist exposures present on Catalina Island have been described by Woodford (1924), Bailey (1941), Platt (1975, 1976), Sorensen and Barton (1987), Sorensen (1986, 1988a, 1988b), Sorensen and Grossman (1989), Bebout and

Barton (1989, 1993, 2002), and Grove and Bebout (1995) and are only briefly summarized here. In essence, the Catalina Schist consists of metasedimentary, metavolcanic, and ultramafic protoliths that were metamorphosed and sheared together under amphibolite facies to sub-blueschist facies conditions during the medial Cretaceous (Suppe and Armstrong, 1972; Platt, 1976; Mattinson, 1986; Sorensen and Barton, 1987; Sorensen, 1988; Grove and Bebout, 1995). Individual tectonic slices shown in Figure 1 contain rocks of broadly equivalent metamorphic grade. These are juxtaposed across low-angle faults to form an inverted metamorphic sequence (Platt, 1976; Fig. 1). The structurally highest rocks represent an amphibolite facies shear zone composed primarily of intercalated and metasomatically altered oceanic crust and mantle peridotite protoliths (Sorensen and Barton, 1987; Sorensen, 1988b; Bebout and Barton, 1993, 2002). The proportion of sediment, particularly immature graywacke, increases structurally downward such that the lawsonite blueschist and lower grade units tend to be sediment-dominated. Each of the major metamorphic units is characterized by meter- to kilometer-scale, compositionally heterogeneous shear zones that facilitated metasomatic fluid infiltration at near peak-grade conditions (Bebout and Barton, 1989, 1993, 2002; King et al., 2005).

Primary geologic mapping of the Catalina Schist on Catalina Island was performed by Bailey (1941) and Platt (1976). While we rely heavily upon Platt's (1976) mapping, we have distinguished somewhat different tectonometamorphic units than he recognized. These include lawsonite albite and actinolite albite rocks on the west end of Catalina Island that structurally underlie lawsonite blueschists (Altheim et al., 1997). In addition, while Platt (1976) recognized a single, high-pressure greenschist unit zoned downward from epidote amphibolite to transitional blueschist/greenschist assemblages, we separate the epidote amphibolite and epidote blueschist domains (Grove and Bebout, 1995). Results presented in Grove and Bebout (1995) and this paper confirm that the epidote amphibolite and epidote blueschist rocks had different protoliths and exhibit discernable differences in accretion and metamorphic history.

Forearc Basement and Strata

The relatively complete forearc sequence preserved on the Vizcaino Peninsula at the southern end of the Peninsular Ranges batholith forms the basis for interpreting the less well-exposed forearc within the highly disrupted southern California borderland (Fig. 2). On the Vizcaino Peninsula and on Cedros Island, both Late Triassic (221 ± 2 Ma) and Middle Jurassic (173 ± 2 Ma) ophiolite sequences have been described (Moore, 1985; Kimbrough, 1985; Kimbrough and Moore, 2003). These form the basement for Upper Jurassic, Lower Cretaceous, Upper Cretaceous, and lower Cenozoic arc volcanics and forearc strata (Boles, 1978; Kilmer, 1979, Kienast and Rangin, 1982; Boles and Landis, 1984; Patterson, 1984; Smith and Busby, 1993; Busby et al., 1998; Kimbrough et al., 2001; Critelli et al., 2002; Busby, 2004). High-pressure/temperature rocks of the Western Baja terrane represent the Cretaceous accretionary complex and found juxtaposed beneath ophiolitic rocks well outboard of the batholith margin (Suppe and Armstrong, 1972; Moore, 1986; Sedlock, 1988a, 1988b; Baldwin and Harrison, 1989; Baldwin et al., 1992).

Within the outer California continental borderland, offshore drilling and seismic exploration detect mafic basement underlying forearc strata (Bohannon and Geist, 1998; ten Brink et al., 2000). Surface exposures of these basement rocks occur on Santa Cruz Island (Weaver and Nolf, 1969; Hill, 1976; Mattinson and Hill, 1976) and have been equated with the Coast Range ophiolite (Jones et al., 1976). The petrology and geochemistry of these rocks are distinctly arc-like (Sorensen, 1985, 1988a). Equivalent, though undated, altered “saussurite” gabbro is in fault contact with the Catalina Schist on Catalina Island (Platt, 1976) and within the subsurface of the southwestern Los Angeles basin (Sorensen, 1985, 1988). Compositionally similar clasts are a major component within the San Onofre Breccia (Stuart, 1979) and confirm that low-pressure/temperature mafic basement was exhumed along with the schist during middle Miocene borderland rifting.

Cenomanian and younger forearc strata onlap the western margin of the northern Peninsular Ranges batholith (Fig. 2; Woodring and Popenoe, 1942; Yerkes et al., 1965; Flynn, 1970; Nordstrom, 1970; Peterson and Nordstrom, 1970; Kennedy and Moore, 1971; Sundberg and Cooper, 1978; Nilsen, and Abbott, 1981; Bottjer et al., 1982; Bottjer and Link, 1984; Fry et al., 1985; Girty, 1987; Bannon et al., 1989). Thick sections of Upper Cretaceous strata also occur throughout the outer borderland (Howell and Vedder, 1981; Vedder, 1987; Bohannon and Geist, 1998). Interestingly, Early Cretaceous forearc strata have not been described anywhere along the western margin of the northwestern Peninsular Ranges nor on the offshore islands. Moreover, their existence in the subsurface is mostly inferred in all areas that have been studied (Howell and Vedder, 1981; Vedder, 1987; Bohannon and Geist, 1998; ten Brink et al., 2000). As will be discussed, the apparent scarcity of these rocks within the forearc of the Peninsular Ranges batholith may be significant with respect to the origin of the Catalina Schist.

Peninsular Ranges Batholith

The Peninsular Ranges batholith of southern and Baja California is a classic Cordilleran continental margin batholith (Fig. 2; Larsen, 1948; Jahns, 1954; Gastil et al., 1975). The better-studied northern segment of the PRB has been divided longitudinally into distinct western and eastern zones based on age, petrology, prebatholithic wall rock, geophysical parameters, and depth and style of emplacement (Gastil et al., 1981; Baird and Miesch, 1984; Taylor, 1986; Gromet & Silver, 1987; Silver and Chappell, 1988; Ague & Brimhall, 1988; Todd et al., 1988;

Hill & Silver, 1988; Gastil, 1993; Johnson et al., 1999; Lovera et al., 1999; Todd et al., 2003; Kistler et al., 2003; Langenheim and Jachens, 2003). The oldest recognized intrusive rocks are gneissic S-type plutons that occupy the medial zone of the batholith and yield Middle Jurassic emplacement ages (Todd and Shaw, 1985; Thompson and Girty, 1994; Shaw et al., 2003). Earliest Cretaceous plutons occur sporadically (Silver and Chappell, 1988; Alsleben et al., 2005; D.L. Kimbrough unpublished data) and are cut by a regionally extensive dike swarm emplaced at ca. 130-120 Ma (Böhnel et al., 2002; D.L. Kimbrough, unpublished data). The well-developed western zone of the Peninsular Ranges batholith is composed mainly of 125 to 100 Ma gabbro to monzogranite plutons that have primitive island arc geochemical affinities. However, the most striking feature of the batholith is the belt of large-volume tonalite, trondjhemite, and low-K granodiorite "La Posta" plutons that defines its eastern zone (Gastil et al., 1975; Silver & Chappell, 1988; Walawender et al., 1990; Tulloch and Kimbrough, 2003). These have a deep, garnet-involved, melt source signature, expressed by high Sr, Ba, Sr/Y, Na_2O, Al_2O_3, and highly fractionated REE patterns. Field and thermobarometric data indicate emplacement at ~2-6 kbar depths (Rothstein and Manning, 2003) followed by rapid Cenomanian-Turonian uplift and denudation at rates of ~1-2 mm/yr (Krummenacher et al., 1975; Lovera et al., 1999; Johnson et al, 1999; Kimbrough et al., 2001; Ortega Rivera, 2003; Grove et al., 2003b). A delayed Late Campanian-Maastrichtian phase of uplift (e.g., Krummenacher et al., 1975) appears to be related to Laramide shallow subduction and removal of the deep crustal and lithospheric roots of the La Posta belt (Lovera et al., 1999; Grove et al., 2003a, 2003b).

SAMPLING AND METHODS

A total of 645 U-Pb zircon ages were measured from 33 samples of amphibolite through sub-blueschist facies metagraywacke of Catalina Schist collected from Catalina Island. We focused upon metagraywackes from each of the major metamorphic units in order to obtain an upper bound upon the depositional age of their sedimentary protolith and to learn whether or not the provenance of these sediments varied as the Catalina Schist was assembled. Such information is critical for constraining the accretion history of the complex and for assessing the likelihood of a genetic relationship with the presently adjacent Peninsular Ranges batholith.

In our U-Pb analysis of zircon from the Catalina Schist, we have primarily employed the UCLA Cameca ims 1270 ion microprobe. The high degree of metamorphic recrystallization affecting some of the zircons we analyzed benefited significantly from intrinsically high spatial resolution of the ion microprobe (e.g., ~1 nanogram of sputtered zircon to produce a U-Pb age). The techniques we employed are the same as those described in Grove et al. (2003b). Additional details are included within the data repository[1]. We also employed multicollector laser ablation inductively coupled mass spectrometry (MC-LA-ICPMS) using the ISOPROBE instrument at UA. Experimental methods pertaining to the laser ablation technique are outlined in Gehrels et al. (2006) with additional details provided in the data repository[1]. While the accuracy of both methods are comparable (2-3%), the MC-LA-ICPMS results were about twice as precise. This is partly due to refinement of MC-LA-ICPMS methods (Gehrels et al., 2006) and the larger overall quantity of zircon consumed (~75-150 nanograms depending upon whether a 35 μm or 50 μm spot was employed). In both styles of analysis, we analyzed conventionally sectioned and polished zircons that had been potted in epoxy mounts. The zircons were hand-selected from heavy mineral concentrates produced from standard crushing, density, and magnetic methods. Further details are provided in the data repository[1]. Because the number of zircons measured from individual samples was characteristically small due to low yields, we have elected to pool

[1]GSA Data Repository item 200XXXX, Table DR1 and references for localities, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

data from multiple samples to obtain statistically meaningful results for each of the major tectonic units of the Catalina Schist.

Metamorphic zircon growth was a significant issue for some of the grains we examined, particularly for the metasediments from the amphibolite unit. Anczkiewicz et al. (2004) also described evidence for metamorphic zircon growth in reconnaissance U-Pb zircon measurements they reported from the Catalina Schist amphibolite unit. While we have been influenced by morphologic and optical criteria (i.e., cathodolumenesce imaging), our approach for recognizing analyses that overlapped metamorphic zircon growth was quantitatively based upon magnitude of the Th/U value associated with a given analysis. Metamorphic overgrowths on igneous zircons is generally characterized by very low Th/U (Th/U ~ 0.001; Kröner et al., 1994; Rubatto, 2002). Within this context, a Th/U value of 0.1 is often described as a lower limit for igneous zircon (e.g. Williams and Claesson, 1987).

We have found a cutoff of Th/U = 0.1 to be empirically well supported by detrital zircon results from the adjacent Cretaceous forearc of the Peninsular Ranges batholith (Mahoney et al., 2005). As indicated in Fig. 3A, 1506 out of 1527 or 98.6% of the zircon U-Pb analyses obtained from these dominantly pluton-derived strata yielded Th/U values equal to or greater than 0.1. The average Th/U value measured was 0.48 ± 0.41 with 3.3% of the analyses falling between within the 0.1-0.2 range. Hence we feel confident in using Th/U = 0.1 as a cutoff for discarding detrital igneous zircon results that were adversely affected by metamorphic recrystallization. Because high spatial resolution U-Pb age depth-profiling measurements (e.g., Mojzsis and Harrison, 2002; Carson et al., 2002; Breeding et al., 2004) that are currently in progress with the Catalina Schist zircons are expected to provide a much higher resolution assessment of the age of metamorphic zircon growth, we have elected to defer most discussion related to this topic to a subsequent paper. Consequently, unless otherwise specified, this paper considers only zircon analyses with Th/U values greater than 0.1. Accordingly, we have excluded all analyses with Th/U < from the summary plots or calculations presented below.

Complete data tables of U-Pb age measurements, lithologic descriptions, and sample locations are available from the GSA data repository[1]. In this paper, quoted uncertainties are ± 1σ errors unless otherwise specified. The U-Pb ages we report are generally $^{206}Pb/^{238}U$ values for < 1 Ga zircons and $^{207}Pb/^{206}Pb$ ages for older grains. We have discarded poorly determined analyses (i.e., those with age uncertainties exceeding 10%). More importantly, we have used $^{207}Pb/^{206}Pb$ ages to represent the U-Pb age of zircon analyses that exhibited resolvable $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ discordance.

RESULTS

Amphibolite Facies

We examined 5 metagraywacke and 2 metachert samples from the amphibolite unit. Subhedral to well-rounded zircon are typically abundant within the amphibolite metagraywackes. Metacherts yielded only metamorphic zircon. As mentioned above, metamorphic zircon growth affected many detrital igneous grains. While external overgrowths up to <1 to 5 μm or more were common, grains also exhibited internal areas of patchy diffuse recrystallization. Of the 169 analyses attempted, 48 (28%) appeared to overlap metamorphic zircon based upon measured Th/U. About half of the analyses affected by metamorphic recrystallization yielded obviously mixed ages. U-Pb ages calculated for the remaining analyses with Th/U < 0.1 fell between 107-126 Ma with a peak at 116 ± 6 Ma. This result is in good agreement with independent estimates for the timing of amphibolite grade recrystallization (ca. 115 Ma; Mattinson, 1986; Grove and Bebout, 1995; Anczkiewicz et al., 2004).

Our results from zircon with Th/U > 0.1 clearly indicate that the sedimentary protolith of the amphibolite facies metagraywackes contained a large proportion of craton-derived detritus (Fig. 4A). Roughly 50% of the analyses we obtained were from Middle Proterozoic zircon (Fig. 4G). Unfortunately, many of these grains exhibited variable Pb loss and high degrees of discordance. This condition complicates our ability to precisely characterize the Middle Proterozoic age distribution. Specifically, while $^{207}Pb/^{206}Pb$ ages more accurately approximate the crystallization age than the highly discordant U-Pb ages, they are, under these conditions, insufficiently precise to reveal strong clustering of ages. Nevertheless, the subdued maxima that occur at 1.15, 1.40, and 1.65-1.80 Ga are highly compatible with a southwestern North American provenance. A significant number of Mesozoic zircons present in our samples yield resolvable peaks at 126, 145, and 162 Ma.

The five youngest zircons measured from the amphibolite unit metagraywackes yield an age of 122 ± 1 Ma. These analyses were from oscillatary zoned regions in Cl imagery that we interpret as igneous crystallization and were characterized by a mean Th/U value of 0.30 ± 0.20. Because the U-Pb ages of the youngest zircons cluster at a value that is resolvable from the time of peak-grade recrystallization deduced from other techniques (ca. 115 Ma; Mattinson, 1986; Grove and Bebout, 1995; Anczkiewicz et al., 2004), we regard 122 Ma as a geologically meaningful upper bound upon the depositional age of the sedimentary protolith.

Epidote Amphibolite Facies

Detrital zircons were less abundant within the epidote amphibolite facies metagraywackes relative to amphibolite facies samples with subhedral to euhedral grains predominating over the well-rounded grains that characterized the latter. Cathodoluminence imaging and measured Th/U indicated that metamorphic recrystallization of the detrital grains was not nearly as much of an issue as it was in the amphibolite unit. For example, only 13 of 135 or 10% of analyses had Th/U < 0.1. Our U-Pb zircon measurements revealed a diminished cratonal provenance relative to the amphibolite facies metagraywackes with only about 20% of the zircons yielding Middle Proterozoic ages (Fig. 4G). Although fewer analyses were available for comparison, the overall age distribution of Middle Proterozoic zircon in the epidote amphibolite metagraywackes was broadly similar to that measured for the amphibolite facies rocks (Fig. 4B). The deficit of Proterozoic grains is compensated for by a proportionate increase of < 200 Ma grains. Distinct peaks are present at 115 and 126 Ma with a strong peak occurring at 150 Ma (Fig. 4B). The five youngest detrital zircons from the epidote amphibolite metagraywackes yielded an age of 113 ± 3 Ma and had a mean Th/U value of of 0.42 ± 0.05 which is typical of magmatic zircon; see Fig. 3A.

Epidote Blueschist Facies

A single sample of fine-grained epidote blueschist metagraywacke yielded 30 zircon U-Pb age results. The modest quantity of zircons recovered from this sample overwhelmingly consisted of clear subhedral to euhedral grains. No evidence for metamorphic zircon growth was detected by optical means or in terms of measured Th/U. Six other samples, equally fine-grained, failed to yield more than one or two zircons despite intensive effort. The poor zircon yield is attributed to the metavolcanic nature of the protolith. The zircons we were able to measure yielded two distinct maxima at 103 and 142 Ma and comparatively few older grains (Fig. 4C). While results from the epidote blueschist are clearly transitional between those obtained from the highest and lowest grade portions of the Catalina Schist (Fig. 4G), the epidote blueschist unit is much more closely allied with the lawsonite blueschist and lower grade rocks in terms of the age of the youngest zircons detected. Specifically, the five youngest zircons measured yielded an average U-Pb age of 101±3 Ma with a mean Th/U of 0.63 ± 0.23.

Lawsonite Blueschist Facies and Lower Grade Rocks

Results obtained from the sedimentary protolith of the lawsonite blueschist and lawsonite albite, and albite actinolite facies rocks are discussed together because of the highly similar results produced (Fig. 4D-G). Overall, we obtained 164 analyses from 11 lawsonite albite facies rocks; 59 analyses from 3 albite actinolite facies rocks, and 82 analyses from 7 lawsonite albite facies metagraywackes. No metamorphic zircon growth was detected and measured Th/U values were all above the 0.1 threshold. The calcic metagraywackes prevalent through the low-grade portion of the Catalina Schist overwhelming yielded clear subhedral to euhedral grains. These grains primarily gave U-Pb ages between 95 and 130 Ma (Fig. 4D-F). Late Jurassic-Early Cretaceous zircon was greatly subordinate and only trace quantities of Proterozoic zircon were present. Because the youngest zircon U-Pb ages measured from the three lowest grade units all agreed with error (96 ± 2 Ma, 97 ± 2 Ma, and 98 ± 3 Ma for lawsonite blueschist, actinolite albite, and lawsonite albite respectively), they collectively define a 97 ± 2 Ma upper bound for the depositional age of the sedimentary protolith for all low-grade Catalina Schist.

DISCUSSION

Evaluation of the Nascent Subduction Model for the Catalina Schist

Determining why high-temperature, high-pressure/temperature assemblages formed within the Catalina Schist is of utmost importance for assessing its tectonic significance. Amphibolite facies metamorphism and anatexis are atypical features within subduction complexes and are thought to signify unusual occurrences along a convergent margin. For example, high-temperatures accompany the earliest developmental stages of subduction before the overlying hangingwall is refrigerated), ridge subduction, and or during slow underflow of very young oceanic crust (e.g., Peacock, 1987, 1992; Hacker, 1990, 1991; Peacock et al., 1994).

Our new detrital zircon results (Fig. 4) allow us to directly assess the hypothesis that high-T, high P/T rocks of the Catalina Schist formed together in an inverted metamorphic aureole in response to transient heating during nascent subduction at ca. 115 Ma. We have found that the youngest zircon U-Pb ages from the amphibolite facies metagraywackes are about 122 Ma (Fig. 5A). These data imply that the depositional age of the protolith preceded amphibolite facies metamorphism by up to 7 m.y. (or more if unrecognized metamorphic recrystallization reduced measured U-Pb ages). This age difference is resolvable since the resolution afforded by our methods is ~ 2-4 m.y. based upon measurements performed with homogeneous standards.

The available data including our newly obtained results indicate that high temperatures prevailed within the amphibolite unit for a significant period of time (Fig. 5A; see also Grove and Bebout, 1995). Hornblende ages from the coherent slab metagabbro that underlies the metagraywacke within the amphibolite unit (Fig. 1) are also as young as 107 Ma (Fig. 5A; Grove and Bebout, 1995). Muscovite $^{40}Ar/^{39}Ar$ cooling ages for the amphibolite unit metagraywackes are even younger at 105-100 Ma (Fig. 5A; Grove and Bebout, 1995). Collectively, all data from the amphibolite facies metagraywackes indicate the interval required to erode, underplate, metamorphose, and cool the materials comprising them was on the order of 15-20 m.y (i.e., from 122-115 Ma to less than 105-100 Ma). As will be described below, this interval is much longer than that required to accomplish the same cycle of events for the low-temperature, low-pressure/temperature lawsonite blueschist and lower grade rocks that almost certainly formed within the subduction zone.

Our detrital zircon results conclusively demonstrate that the Catalina Schist must have been accreted over a protracted period of time. The youngest detrital zircon ages we produced from the epidote amphibolite metagraywackes are ca. 113 Ma or about 10 m.y. younger than those present within the amphibolite unit metagraywackes (Fig. 5B). Assuming that we have identified and excluded analyses affected by metamorphic recrystallization, our results indicate that the protolith of the epidote amphibolite facies rocks was deposited after peak 115 Ma metamorphism took place within the amphibolite unit. While this relationship is ambiguous due to overlapping errors, data from still lower grade rocks clearly require that the complex was successively accreted. The youngest zircons from the lawsonite blueschists, and lower-grade rocks (collectively 97 ± 2 Ma; Fig. 5C-F) indicate that their sedimentary protolith was deposited 15-20 m.y. after the 115 Ma amphibolite facies metamorphism had occurred.

If the amphibolite and epidote amphibolite facies assemblages of the Catalina Schist are regarded to have formed within a subduction zone environment, then it must be explained why these high-grade rocks managed to escape blueschist facies overprinting (Platt, 1976; Sorensen and Barton, 1987; Bebout and Barton, 1989; Grove and Bebout, 1995). Blocks of equivalent metamorphic grade within the Franciscan and Shuksan subduction complexes characteristically are heavily overprinted by blueschist facies assemblages (e.g., Brown et al., 1982; Cloos, 1985; Wakabayashi, 1990). In contrast, the high-grade assemblages within the Catalina Schist exhibit very sparse evidence for low-temperature, high pressure/temperature overprinting. The sole evidence comes in the form of occasional cross-cutting pumpellyite veins and trace amounts of lawsonite in white mica + zoisite + albite assemblages that replace oligoclase in amphibolite facies rocks (Grove and Bebout, 1995). We believe that the uncharacteristic lack of blueschist facies overprinting of the amphibolite facies rocks is an important clue that the high grade rocks of the Catalina Schist formed and resided in a location well-removed from the subduction zone and only became associated with subduction zone rocks at a very late stage coincident with exhumation.

Provenance Ties Linking the Catalina Schist to the Peninsular Ranges Batholith

In this section we demonstrate that the dramatic variation in detrital zircon provenance signature exhibited by successively accreted rocks within the Catalina Schist (Fig. 4) accords well with the medial Cretaceous shift in the provenance of sediment supplied to the Peninsular Ranges forearc (Fig 6). Because the overall provenance signature of the Peninsular Ranges batholith is so distinctive and similar to that of the Catalina Schist, we feel confident that the two metamorphic belts evolved together. However, since lithologic trends within the batholith exhibit remarkable along-strike persistence (e.g., Silver and Chappell, 1988; Todd et al., 1988; 2003), our results do not allow us to preclude limited margin-parallel lateral displacement of the Catalina Schist relative to the 750-km-long Peninsular Ranges.

The most complete forearc section associated with the Peninsular Ranges occurs in the south on the Vizcaino Peninsula (Fig, 2). Just as in the case of the Catalina Schist, a prominent provenance shift occurs between Albian and Cenomanian strata. The Albian and older forearc rocks are dominated by Jurassic and older detrital zircon (Fig. 6A; Mahoney et al., 2005). Conversely, zircon contained within Cenomanian and younger strata strongly reflect the age distribution of the main phase plutons that comprise the batholith (i.e., 130-90 Ma; Fig. 6A; Kimbrough et al., 2001; Mahoney et al., 2005). As indicated in Figure 6A, a nearly identical zircon age distribution is exhibited by Cenomanian and younger forearc strata that onlap the west-central and northwestern Peninsular Ranges (Mahoney et al., 2005; see Fig. 2 for locations).

It is clear that the Peninsular Ranges can easily account for the 95-130 Ma zircon that is so abundant within the lawsonite blueschist and lower grade rocks of the Catalina Schist. For example, the detrital zircon age distribution measured from the Cenomanian Trabuco Formation within the Santa Ana Mountains of the northwestern Peninsular Ranges is extremely similar to the low grade Catalina Schist (Fig. 6B). Alternatively, the significance of the elevated concentrations of 140-150 Ma zircon present within the amphibolite, epidote amphibolite, and epidote blueschist units is less obvious and requires further consideration. While the best exposed volcanic rocks present along the northwestern margin of the Peninsular Ranges appear to be Late Cretaceous (Herzig and Kimbrough, 1991), they overlie older, strongly sheared volcanic rocks that contain marine fossils which include Buchia piochii, a well know Tithonian bivalve (Fife et a., 1967; Jones and Miller, 1982). These older rocks could represent an important source for the 140-150 Ma zircon within the Catalina Schist (Fig. 7). Similarly, zircon may also have been supplied by latest Jurassic-earliest Cretaceous plutonic rocks within the arc-ophiolite basement of the medial Cretaceous Peninsular Ranges batholith (Mattinson and Hill, 1976; Silver and Chappell, 1988; Alsleben et al., 2005; D.L. Kimbrough, unpublished data).

A third provenance tie between the northern Peninsular Ranges and the Catalina Schist is provided by the correspondence of the Middle Proterozoic detrital zircon age distributions from the Triassic-Jurassic flysch wallrocks of the northern Peninsular Ranges batholith and the Catalina Schist amphibolite unit (Fig. 8). The flysch wallrocks crop out within the deeply denuded axial zone of the northern batholith. We have represented them with a composite detrital zircon distribution constructed from data obtained from four different localities from southern (Bedford Canyon, French Valley, and Julian Schist) and northern Baja California (Vallecitos). The the age distributions defined by Middle to Late Proterozoic zircon in these samples (Morgan et al., 2005) is quite similar to the Catalina Schist amphibolite unit and highly evocative of the cratonal rocks of southwestern North America. In contrast, detrital zircon from flysch wallrocks of the southern Peninsular Ranges batholith (Morgan et al., 2005; Alsleben et al., 2005), tend to be more strongly enriched in either Grenville zircon and or Early Proterozic (particulary 1.8-2.0 Ga) and Archean zircon (particularly 2.6 Ga). We therefore conclude that the Catalina Schist is most akin to the presently adjacent northern Peninsular Ranges batholith.

In order to further evaluate the strength of the provenance tie between the Catalina Schist and the Peninsular Ranges, we have carried out ternary mixing calculations. We have identified three distinctive components (Fig. 9A): (1) “J-Tr flysch” wallrocks (Morgan et al., 2005); (2) “J-K volcanics” that are represented by results from Jurassic and Lower Cretaceous sandstones within the volcanic arc (Alsleben et al., 2005) and the volcanic rocks themselves (D.L. Kimbrough, unpublished data); and (3) “Late Cretaceous forearc” represented by Cenomanian-Maastrichtian strata distributed along the western margin of the Peninsular Ranges batholith (Mahoney et al., 2005).

As indicated in Figure 9B, the detrital zircon provenance signature of the earliest accreted material within the amphibolite unit of the Catalina Schist is best approximated by a 68:32 mixture of sediment derived predominantly from the J-Tr flysch and the Late J-K volcanic arc, respectively. Application of the Kolmorgorov-Smirnoff statistic (see Fletcher et al., 2006) indicates that for this example, the measured and model distributions are indistinguishable at the 95% confidence level. Such a high proportion of cratonally derived material within the amphibolite unit metasediments makes sense given the abundance of middle Proterozoic zircon, the aluminous and quartz-rich nature of the protolith, and the fact that pegmatites, metasediments, and mélange sampled from the amphibolite unit tend to yield a relatively radiogenic Sr, Nd, and Pb isotopic signature (i.e., similar to evolved arc crust; Bebout and Barton, 1993, 2002; King et al., 2005).

The provenance signature of sediment shed from the Peninsular Ranges batholith shifted dramatically between early Aptian to early Cenomanian time (Mahoney et al., 2005). A parallel shift is recorded by the Catalina Schist (Fig. 4). In the case of the epidote amphibolite unit, the relative proportions of J-Tr flysch to Late J-K volcanic arc sediment diminishes to 44:56 (Fig. 9B). Compositionally, there is still a resolvable cratonal input in that epidote amphibolite metagraywackes. This makes sense since the rocks are sufficiently aluminous that they carry abundant muscovite-rich and, in some instances, garnet + biotite. A further shift is exhibited by the epidote blueschist metagraywackes which compositionally are more similar to the calcic lawsonite blueschist metagraywackes than they are to the metasediments from the high-grade rocks. Their epidote blueschist detrital zircon age distribution is well modeled by a 20:58:22 mixture of J-Tr flysch, Late J-K volcanic arc, and Late K forearc sediment respectively (Fig. 9B). The provenance shift is completed by the lawsonite blueschist and lower grade metagraywackes. The detrital zircon age distribution of these highly calcic metasediments is well modeled by a 49:51 mixture of Late J-K volcanic arc and Late K forearc sediment respectively (Fig. 9B).

Subduction Erosion Model for the Formation of the Catalina Schist

Our new detrital zircon results and previous petrologic and thermochronologic data have motivated us to consider the possibility that the highest grade portions of the Catalina Schist formed at a setting well-removed from the subduction zone. The specific process we envision was one in which the Early Cretaceous forearc was underthrust to a stalled position beneath the western margin of the northern Peninsular Ranges batholith. The initial condition depicted in

Figure 10A is based partly upon based upon the relatively undisrupted geometry of the Vizcaino forearc basin at the southern termination of the Peninsular Ranges. We believe the northern Peninsular Ranges was also characterized by broad forearc at 125 Ma. We hypothesize that between 120-115 Ma, the northern Peninsular Ranges began to override its forearc and that lower Cretaceous forearc strata and ophiolitic basement were underthrust beneath the leading edge of the Peninsular Ranges batholith where they were heated to amphibolite facies conditions over an extended period of time (Fig. 10B).

There is significant evidence for shortening within the batholith during the late Early Cretaceous. This shortening has been linked to closure of a back arc or marginal ocean basin that separated the early Cretaceous arc from southwest North America (Gastil et al., 1981; Todd et al., 1988; Silver and Chappell, 1988; Thompson and Girty, 1994; Busby et al., 1998; Johnson et al., 1999: Schmidt et al., 2002; Wetmore et al., 2002; Schmidt and Patterson, 2002; Wetmore, 2003; Busby, 2004). The appreciable concentrations of Middle Proterozoic zircon in volcanic arc sediments that exhibit age distributions characteristic of southwestern North America (Alsleben et al., 2005) rule out the possibility that the Early Cretaceous magmatic arc was a far-traveled exotic terrane (see Busby et al., 2006).

Limited underthrusting of the forearc rocks to a stalled position at the base of the magmatic arc (Fig. 10B) explains the protracted nature of the high-temperature metamorphism within the amphibolite unit (Fig. 5A). The lack of blueschist facies overprinting is readily explained if the rocks were well-removed from the subduction zone. In our interpretation, the structurally lower, coherent portion of the Catalina amphibolite unit on Catalina Island (Fig. 1) represents metamorphosed ophiolitic or arc basement to the forearc while the overlying metagraywacke formed from pre-Late Cretaceous forearc sediments (Fig. 10B). As indicated in

Figure 10C, we regard also regard the epidote amphibolite rocks as forearc-derived lithologies that were successively underthrust to form a subcrustal duplex as the forearc was progressively shortened and brought into close proximity to the subduction zone. In contrast, the lower tempature, high-pressure/temperature epidote blueschists, lawsonite blueschist, and lower grade rocks within the Catalina Schist probably formed either in close proximity to, or within, the subduction zone (Fig 10D).

Because our model has continuous subduction since the Jurassic, it permits the simple explanation that the Middle Jurassic(?) garnet blueschist blocks reported by Grove and Bebout (1995) were reworked from the older portions of the accretionary complex in much the same fashion as has been proposed for the Franciscan complex (e.g., Cloos, 1985; Wakabayashi, 1990). Grove and Bebout's (1995) thermochronologic results strongly suggest that assembly and partial unroofing of the Catalina Schist had occurred by 95 Ma (Fig. 10D). Potentially, stacking of accreted rocks west of the PRB over thickened the wedge and triggered dendation via low-angle extensional faulting which attenuated the crust and established the presently observed contact relationships within the Catalina Schist (e.g., Platt, 1986).

Relationship to Emplacement of the La Posta Tonalite-Trondjhemite-Granodiorite Suite

During earliest Late Cretaceous time, the eastern Peninsular Ranges batholith was massively intruded by the La Posta tonalite-trondjhemite-granodiorite plutonic suite (Fig. 2; Gastil et al., 1975; Silver & Chappell, 1988; Walawender et al., 1990; Tulloch and Kimbrough, 2003; Kimbrough and Grove, 2006). Intrusion of the plutons involved a sustained (ca. 98-92 Ma) magmatic flux of ~100 km^3/m.y./km strike length over more than 1200 km (Kimbrough and Grove, 2006). The high Sr, Ba, Sr/Y, Na_2O, Al_2O_3, and highly fractionated REE patterns exhibited by these plutons indicate deep, garnet-involved melting of a fundamentally mafic source region. Oxygen and Rb-Sr isotopic measurements reported by Taylor (1986), Gromet and Silver (1987), Silver and Chappell (1988), Hill and Silver (1988), and Kistler et al. (2003) have revealed that the northern La Posta belt features highly elevated $\delta^{18}O$ (9-12 ‰ whole rock equivalent) but only intermediate initial $^{87}Sr/^{86}Sr$ values (typically 0.704-0.708). The supracrustal input implied by these combined isotopic attributes cannot be accounted for by high-level assimilation of highly radiogenic Triassic-Jurassic cratonally-derived flysch host rocks (Shaw et al., 2003). These characteristics are more readily explained by partial melting of isotopically primitive low-grade metasedimentary and metavolcanic rocks and altered oceanic crust within the deep source region (Taylor, 1986; Gromet and Silver, 1987).

Emplacement of the La Posta belt plutons involved eastern relocation of the locus of magmatism within the Peninsular Ranges over a strike length of 1200 km (Fig. 10D; Kimbrough and Grove, 2006). This event can be viewed as the initial stage of the eastern sweep of magmatism into formerly adjacent northern Mexico that occurred during the Late Cretaceous-early tertiary (e.g., Silver and Chappell, 1988; McDowell et al., 2001; Staude and Barton, 2001; Henry et al., 2003). We believe that the subduction erosion processes depicted in Figure 10D delivered Catalina Schist into close proximity to the La Posta source region between 100-95 Ma. We believe the coincidence of crustal thickening of the former back arc extensional basin, focused asthenospheric corner flow, and massive devolatilization of Catalina Schist depicted in Figure 10D were all important factors in La Posta magmatism. Recent $\delta^{18}O$ measurements (Kimbrough and Grove, 2006) indicate that La Posta plutons have high $\delta^{18}O$ only over the northern segment of the batholith that we infer was underplated by the Catalina Schist (Fig. 2). This is a good indication that Catalina Schist subduction erosion was sufficiently important to modify the underlying causes and source region characteristics that produced La Posta belt magmatism. Further details are provided in Kimbrough and Grove (manuscript in review).

Relationship to Laramide Underthrusting

Accretion of the lowest grade units of the Catalina Schist beneath the western Peninsular Ranges and eastern relocation of the La Posta plutonic belt to the eastern Peninsular Ranges at 95 Ma can be viewed as an important precursor to the Laramide craton-ward shift of arc magmatism and contractional deformation (Coney and Reynolds, 1977; Dickinson and Snyder, 1978). During the Laramide episode of Late Cretaceous-early tertiary deformation, large tracts of southern California and southwestern Arizona were underplated by high-pressure/temperature Pelona and related schists with no intervening lithospheric mantle preserved (Fig. 10E; Ehlig, 1968, 1981; Crowell, 1968, 1981; Yeats, 1968; Haxel and Dillon, 1978; Haxel et al., 2002; Burchfiel and Davis, 1981; Jacobson, 1983, 1990; Jacobson et al., 1988, 2002, 2006; Dillon et al., 1990; Malin et al., 1995; Wood and Saleeby, 1997; Saleeby, 2003; Grove, 2003a). Xenoliths of Late Cretaceous, lawsonite bearing ecolgite have been recovered from kimberlite pipes as far east as northeastern Arizona (Usui et al., 2003).

The earliest recognized accretion of the distinctive Pelona and related schists occurred at 91 ± 1 Ma along the southwesternmost tip of the Sierra Nevada batholith (Rand Schist within the San Emigdio Mountains; Saleeby, 2003; Grove et al., 2003a). Lawsonite blueschist and lower grade Catalina Schist represents nearly equivalent material that was underplated at a slightly older time (i.e., between 100-95 Ma) beneath the northern Peninsular Ranges (Fig. 6B). Thermochronology and detrital zircon results obtained from the northwest-southeast trending belt of schist exposures have revealed that schist underplating associated with the Laramide event was widespread by 80-70 Ma beneath the medial Cretaceous arc (Jacobson, 1990;

Jacobson et al., 2000; Barth et al., 2003; Grove et al., 2003a). By 70-60 Ma, cratonal rocks were being underplated by schist at positions well east of the medial Cretaceous arc (Grove et al., 2003a; Usui et al., 2003; Jacobson et al., 2006).

We believe that Laramide shallow subduction processes tectonically removed the deep lithospheric mantle roots of the La Posta belt within the northern Peninsular Ranges batholith between 80-65 Ma (Fig. 10E). Receiver function seismic studies indicate that the deep crust and lithospheric mantle roots that must have existed to account for the deep-melting signature of the earliest Late Cretaceous La Posta belt no longer exist beneath within the northeastern Peninsular Ranges (Ichinose et al., 1996; Lewis et al., 2001). While the Peninsular Ranges batholith exhibited predominately syn-to late batholithic cooling in its southern extent (>85 Ma; e.g., Ortega Rivera, 2003), the northeastern segment of the batholith was further characterized by a delayed and very significant pulse of rapid cooling between 80-65 Ma (Krummenacher et al., 1975; George and Dokka, 1994; Lovera et al., 1999; Grove et al., 2003b). Lovera et al. (1999) and Grove et al. (2003b) have attributed this cooling to denudation related to the removal of lithospheric mantle and the underplating of schist during Laramide shallow subduction. Holk et al. (2006) have reported that Laramide age deformation within the northern Peninsular Ranges was associated with infiltration of high δD and $\delta^{18}O$ fluids that are most readily explained by devolatilization of subducted oceanic crust or underplated volcanogenic sediments. The impact of the Laramide Orogeny upon the northern Peninsular Ranges appears to have contrasted significantly with its effect upon the southern Sierra Nevada batholith. There, an inflection in the Laramide subduction zone (Pickett and Saleeby, 1993; Malin et al., 1995; Saleeby, 2003) apparently allowed the deep crust and upper mantle to be preserved until much more recently (Ducea and Saleeby, 1996, 1998; Zandt et al., 2004).

CONCLUSIONS

(1) Major tectonometamorphic units of the Catalina Schist where successively accreted over a 15-20 m.y. interval beginning with the amphibolite unit at ca. 120-115 Ma and concluding with the lawsonite blueschist and lower grade lithologies by 100-95 Ma;

(2) The amphibolite unit resided at high temperatures for a protracted period of time (10-15 m.y.) while the lawsonite blueschist and lower grade units that most likely formed near or within the subduction zone were deposited, accreted, metamorphosed, and cooled over a narrow interval that was too brief to be resolved by our methods (< 3 m.y.);

(3) The Catalina Schist exhibited a remarkable shift in provenance as a function of time of accretion (and metamorphic grade). Metagraywackes from the earliest accreted amphibolite were derived from an early Aptian sediment that was apparently derived from erosion of Late Triassic-Jurassic flysch wallrocks and Early Cretaceous volcanics of the Peninsular Ranges batholith. Successively younger accreted materials became enriched with Early Cretaceous plutonic zircon from the Peninsular Ranges. The last accreted lawsonite blueschist and lower grade rocks were derived from Turonian sediment with a detrital zircon provenance virtually identical to similarly aged sediment within the Peninsular Ranges forearc.

(4) Our results rule out the possibility that the Catalina Schist represent a synchronously formed inverted metamorphic aureole formed during nascent subduction. The highest grade portions of the complex appear to have formed in a subduction erosion process in which portions of the forearc were underthrust beneath the western margin of the Peninsular Ranges batholith at ca. 120-115 Ma. Progressive shortening of the forearc resulted in a subcrustal duplex which ultimately merged with the subduction complex by 100-95 Ma. Only the epidote

blueschist, lawsonite blueschist, and lower grade rocks are believed to have originated near, and/or within the subduction zone.

(5) The accretion of the Catalina Schist marked the initial stage of shallowing subduction and inboard migration of magmatism and sediment underplating that culminated in the Late Cretaceous-early tertiary Laramide Orogeny. The sedimentary protolith of the youngest Catalina schist are nearly identical in age and provenance to that of the the oldest representative of the Pelona and related schist that was emplaced beneath the southwesternmost Sierra Nevada batholith at ca. 92 Ma.

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REFERENCES CITED

Ague, J. and Brimhall, G. H, 1988, Magmatic arc asymmetry and distribution of anomalous plutonic belts in the batholiths of California: Effects of assimilation, crustal thickness, and depth of crystallization, v. 100, p. 912-927.

Alsleben, H., Wetmore, P., Gehrels, G., Paterson, S., 2005, Using detrital zircon geochronology to track island arc collision, Geological Society of America Abstracts with programs, v. 37, p. 551. [Placeholder for ms in preparation].

Altheim, B.K., Christoffel, C.A., Bebout, G.E., Grove, M., 1997, Detection of subtle variations in low-T, high-P/T metamorphism in the Catalina Schist; tectonic and kinetic implications: Program with Abstracts - Geological Association of Canada; Mineralogical Association of Canada; Canadian Geophysical Union, Joint Annual Meeting, v. 22, p. 2.

Anczkiewicz, R., Platt, J.P., Thirlwall, M.F., & Wakabayashi, J., 2004. Franciscan subduction off to a slow start: Evidence from high-precision Lu-Hf garnet ages on high grade-blocks. Earth and Planetary Science Letters, 225, 147-161. doi: 10.1016/j.epsl.2004.06.003.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. Bull. Geol. Soc. Amer., v. 81, p. 3513-3536.

Bailey, E.H., 1941, Mineralogy, petrology, and geology of Catalina Island, California, Stanford University PhD. Thesis, 193p.

Baird, A.K., and Miesch, A.T., 1984, Batholithic rocks of southern California—A model for the petrochemical nature of their source materials: U.S. Geological Survey Professional Paper 1284. 24p.

Baldwin, SL., Harrison, TM., 1989, Geochronology of blueschists from west-central Baja California and the timing of uplift in subduction complexes. J. Geology, 97, 149-163.

Baldwin, SL., Harrison, TM., 1992, The P-T-T history of blocks in serpeninitematrix melange, west-central Baja California. Geol. Soc. America Bull., 104, 18-31.

Bannon, J.L., Bottjer, D.J., Lund S.P., and Saul, L.R., 1989, Campanian/Maastrichtian stage boundary in southern California: Resolution and implications for large-scale depositional patterns, *Geolog*y, 17, 80-83, 1989.

Barton, M.D., Battles, D.A., Debout, G.E., Capo, R.C., Christensen, J.N., Davis, S.R., Hanson, R.B., Michelsen, C.J., and Trim, H.E. 1988, Mesozoic contact metamorphism in the western United States, In Ernst, W.G., ed., Metamorphism and crustal evolution of the western United States, Rubey Volume 7: Englewood Cliffs, New Jersey, Prentice-Hall, p. 110–178.

Bebout, G. E. and Barton, M. D. 1989. Fluid flow and metasomatism in a subduction zone hydrothermal system: Catalina Schist terrane, California. Geology 17, 976-980.

Bebout, G.E., and Barton, M.D., 1993, Metasomatism during subduction: Products and possible paths in the Catalina Schist, California: Chemical Geology, v. 108, p. 61–92.

Bebout, G.E., and Barton, M.D., 2002, Tectonic and metasomatic mixing in a high-*T*, subductionzone me´lange—Insights into the geochemical evolution of the slab-mantle interface: Chemical Geology, v. 187, p. 79-106.

Blake, M C Jr, Jayko, A S, Moore, T E, Chavez, V, Saleeby, J B, and Seel, K, 1984, Tectonostratigraphic terranes of Magdalena Island, Baja California Sur, in Frizzel, V A Jr, ed., Geology of the Baja California Peninsula, Pacific Section SEPM, 39, 183-191.

Bohannon, R G, Geist, E L, 1998, Upper crustal structure and Neogene tectonic development of the California continental borderland, Geol. Soc. America Bull., 110, 779-800.

Böhnel, H., Delgado-Argote, L.A., and Kimbrough, D.L., 2002, Discordant paleomagnetic data for middle-Cretaceous intrusive rocks from northern Baja California: Latitude displacement, tilt, or vertical axis rotation? Tectonics, v. 21, doi:10.1029/2001TC001298.

Boles, J.R., 1978, Basin analysis of the Eugenia Formation (Late Jurassic), Punta Eugenia area, Baja, California, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic paleogeography of the western United States, Pacific Coast Paleogeography Symposium 2: Sacramento, California, Society of Economic Paleontologists and Mineralogists, p. 493.498.

Boles, J.R., and Landis, C.A., 1984, Jurassic sedimentary mélange and associated facies, Baja California, Mexico: Geological Society of America Bulletin, v. 95, p. 513.521.

Bonini, J.A., Baldwin, S.L., 1998, Mesozoic metamorphic and middle to late Tertiary magmatic events on Magdalena and Santa Margarita islands, Baja California Sur, Mexico: Implications for the tectonic evolution of the Baja California continental borderland. Geol. Soc. America Bull., 110, 1094-1104.

Bottjer, D.J., and Link, M.H., 1984, A synthesis of Late Cretaceous southern California and northern Baja California paleogeography, in Tectonics and sedimentation along the California margin, edited by J.K. Crouch and S.B. Bachman, pp. 171-188, Pacific Section SEPM, Fullerton, CA.

Bottjer, D.J., Colburn, I.P., and Cooper, J.D., 1982, Late Cretaceous Depositional Environments and Paleogeography, Santa Ana Mountains, Southern California, Pac. Sect., pp. 121, Soc. Econ. Paleontol. Mineral., Los Angeles, CA.

Breeding, C.M., Ague, J.J., Grove, M., and Rupke , A.L., 2004, Isotopic and chemical alteration of zircon by metamorphic fluids: U-Pb age depth-profiling of zircon crystals from Barrow's garnet zone, northeast Scotland, American Mineralogist, v. 89, p.1067-1077.

Brown et al., 1982, Petrologic, structural, and age relations of serpentinite, amphibolite, and blueschist in the Shuksan Suite of the Iron Mountain-Gee Point area, North Cascades, Washington. Geological Society of America Bulletin, v. 93, p. 1087-1098.

Burchfiel, B.C., and Davis, G.A., 1981, Mojave Desert and environs, *in* Ernst, W. G., ed., The geotectonic development of California (Rubey Vol. I): Englewood Cliffs, New Jersey, Prentice-Hall, p. 217-252.Jacobson, 1983a

Busby, C.J., 2004, Continental growth at convergent margins facing large ocean basins: a case study from Mesozoic Baja California, Mexico: Tectonophysics, v.392, p. 241-277.

Busby, C.J., Smith, D.P., Morris, W.R. and Adams, B, 1998, Evolutionary model for convergent margins facing large ocean basins: Mesozoic Baja California (Mexico): Geology, v. 26, p. 227-230.

Carson, C.J., Ague, J.J., Grove, M., Coath, C.D., and Harrison, T.M., 2002, U-Pb isotopic behaviour of zircon during upper-amphibolite facies fluid infiltration in the Napier Complex, east Antarctica: Earth and Planetary Science Letters, v. 199, p. 287-310.

Chen, J.H., and Moore, J.G., 1982, Uranium-lead isotopic ages from the Sierra Nevada batholith: Journal of Geophysical Research, v. 87, p. 4761–4784.

Clift, P., and Vannucchi, P., 2004, Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust, Review of Geophysics, 42, 2003RG000127

Cloos, M., 1985, Thermal evolution of convergent plate margins-thermal modeling and reevaluation of isotopic Ar-ages for blueschists in the Franciscan complex of California, Tectonics, v.4, p, 421-433.

Coney, P.J., and Reynolds, S.J., 1977, Cordilleran Benioff zones, Nature, v. 270, p. 403-406.

Critelli, S., Marsaglia, K.M., and Busby, C.J., 2002, Tectonic history of a Jurassic backarc-basin sequence (the Gran Cañon Formation, Cedros Island, Mexico), based on compositional modes of tuffaceous deposits: Geological Society of America Bulletin, v. 114, p. 515.527.

Crouch, J K. and Suppe, J, 1993, Late Cenozoic tectonic evolution of the Los Angeles Basin and inner California borderland; a model for core complex-like crustal extension, Geological Society of America Bulletin, v. 105, p. 1415-1434.

Crowell, J.C., 1968, Movement histories of faults in the Transverse Ranges and speculations on the tectonic history of California, *in* Dickinson, W. R., and Grantz, A. eds., Proceedings of conference on geologic problems of San Andreas fault system: Stanford University Publications in the Geological Sciences, v. 11, p. 323–341.

Crowell, J.C., 1981, An outline of the tectonic history of southeastern California, *in* Ernst, W. G., ed., The geotectonic development of California (Rubey Vol. I): Englewood Cliffs, New Jersey, Prentice-Hall, p. 583-600.

Debiche, M.G., Cox, A., and Engebretson, D., 1987, The motion of allochthonous terranes across the North Pacific basin: Geological Society of America Special Paper 207, 49 p.

DeGraaff-Surpless, K., Graham, S.A., Wooden, J.L., McWilliams, M.O., 2003, Detrital zircon provenance analysis of the Great Valley Group, California: Evolution of an arc-forearc system. Geological Society of America Bulletin, v. 115, p. 639–639.

Dibblee, T.W. Jr., 1999, Geologic map of the Palos Verdes Peninsula and vicinity, Redondo Beach, Torrance, and San Pedro Quadrangles, Los Angeles County, California, Dibblee Geological Foundation, Camarillo, CA.

Dickinson, W.R., 1983, Cretaceous sinistral strike slip along Nacimiento fault in coastal California: American Association of Petroleum Geologists Bulletin, v. 67, p. 624–645.

Dickinson, W.R., and Snyder, W.S., 1978, Plate tectonics of the Laramide orogeny, *in* Matthews, V., III, ed., Laramide Folding Associated with Basement Block Faulting in the Western United States: Boulder, Colorado, Geological Society of America Memoir 151, p. 355-366.

Dickinson, W.R., Hopson, C.A., and Saleeby, J.B., 1996, Alternate origins of the Coast Range ophiolite (California): Introduction and implications: GSA Today, v. 6, no. 2, p. 1-10.

Dickinson, W.R., Ducea, M., Rosenberg, L.I., Greene, H.G., Graham, S.A., Clark, J.C., Weber, G.E., Kidder, S., Ernst, W.G., and Brabb, E.E., 2005, Net dextral slip, Neogene San Gregorio–Hosgri fault zone, coastal California: Geologic evidence and tectonic implications: Geological Society of America Special Paper 391, 43 p.

Dillon, J.T., Haxel, G.B., and Tosdal, R.M., 1990, Structural evidence for northeastward movement on the Chocolate Mountains thrust, southeasternmost California: Journal of Geophysical Research, v. 95, p. 19953-19971.

Ducea, M.N., and Saleeby, J.B., 1996, Buoyancy sources for a large, unrooted mountain range, the Sierra Nevada, California: Evidence from xenolith thermobarometry; Journal of Geophysical Research, v. 101, p. 8229–8244.

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, v. 133, p. 169–185.

Ehlig, P.L., 1968, Causes of distribution of Pelona, Rand, and Orocopia Schists along the San Andreas and Garlock faults, *in* Dickinson, W.R., and Grantz, A. eds., Proceedings of

Conference on Geologic Problems of San Andreas Fault System: Stanford, California, Stanford University Publications in the Geological Sciences, v. 11, p. 294-306.

Ehlig, P.L., 1981, Origin and tectonic history of the basement terrane of the San Gabriel Mountains, central Transverse Ranges, *in* Ernst, W.G., ed., The geotectonic development of California (Rubey Volume I): Englewood Cliffs, New Jersey, Prentice-Hall, p. 253-283.

Engebretsen, D.C., Cox, A., and Gordon, R.G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Geological Society of America Special Paper 206, 59 p.

Ernst, W. G., 1988. Tectonic history of subduction zones inferred from retrograde blueschist P-T paths. Geology 16, 1081-1085.

Evernden, J.F., and Kistler, R.W., 1970, Chronology of emplacement of Mesozoic batholithic complexes in California and western Nevada: U.S. Geological Survey Professional Paper 623, 42 p.

Fife, D.L., Minch, J.A., and Crampton, P.J., 1967, Late Jurassic age of the Santiago Peak Volcanics, California: Geological Society of America Bulletin, v. 78, p. 299-303.

Fletcher, J.M., Grove, M., Kimbrough, D.L., Lovera , O.M., and Gehrels, G.E., 2006, Ridge-trench interactions and the Neogene tectonic evolution of the Magdalena Shelf: Insights from detrital zircon U-Pb ages from the Magdalena fan and adjacent areas, Geological Society of America Bulletin, in press.

Flynn, C. J., 1970, Post-batholithic geology of La Gloria-Presa Rodriquez area, Baja California, Mexico: Geological Society of America Bulletin, v. 81, p. 1789-1806.

Fry, J.G., Bottjer, D.J., and Lund, S.P., 1985, Magnetostratigraphy of displaced Upper Cretaceous strata in southern California, *Geolog*y, 13, 648-651.

Gastil, R.G., 1993, Prebatholithic history of Peninsular California, *in* Gastil, R.G., and Miller, R.H., eds., The prebatholithic stratigraphy of peninsular California: Geological Society of America Special Paper 279, p. 145–156.

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, 170 p.

Gastil., R.G., Morgan, G.J., Krummenacher, D., 1981, The tectonic history of Peninsular and adjacent Mexico, in W.G. Ernst, ed., The Geotectonic Development of California, Rubey Volume I, Prentice Hall, Englewood Cliffs, New Jersey, p. 284-306.

Girty, G. H., 1987, Sandstone provenance, Point Loma formation, San Diego, California: Evidence for uplift of the Peninsular Ranges during the Laramide orogeny: Journal of Sedimentary Petrology, v. 57, n. 5, p. 839-844.

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.

Grove, M. and Bebout, G.E., 1995. Cretaceous tectonic evolution of coastal southern California: Insights from the Catalina Schist. Tectonics, 14, 1290-1308.

Grove, M., C.E. Jacobson, A.P. Barth, and A. Vucic, 2003a, Temporal and spatial trends of Late Cretaceous-Early Tertiary underplating of Pelona and related schist beneath southern California and southwestern Arizona, Geological Society of America Special Paper 374: Tectonic evolution of northwestern Mexico and the Southwestern USA, 381-406.

Grove, M., Lovera, O.M., and Harrison, T.M., 2003b, 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. Geological Society of America Special Paper 374: Tectonic evolution of northwestern Mexico and the Southwestern USA, p. 355–379.

Hacker, B.R., 1990, Simulation of the metamorphic and deformational history of the metamorphic sole of the Oman Ophiolite, Journal of Geophysical Research, v. 95, p. 4895-4907.

Hacker, B.R., 1990, The role of deformation in the formation of metamorphic gradients: Ridge subduction beneath the Oman Ophiolite. Tectonics, v. 10, p. 455-473.

Hall, C.A., 1991, Geology of the Point Sur–Lopez Point region, Coast Ranges, California: A part of the Southern California allochthon: Geological Society of America Special Paper 266, 40 p.

Haxel, G.B, Jacobson, C.E., Richard, S.M., Tosdal, R.M., and Grubensky, M.J., 2002, The Orocopia Schist in southwest Arizona: Early Tertiary oceanic rocks trapped or transported far inland, in A. P. Barth, ed., Crustal evolution of the southwestern United States: Geological Society of America Special Paper 365, p. 99-128.

Haxel, G.B., and Dillon, J.T., 1978, The Pelona-Orocopia Schist and Vincent-Chocolate Mountain thrust system, southern California, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Pacific Section, Society of Economic Paleontologists and Mineralogists Pacific Coast Paleogeography Symposium 2, p. 453-469.

Henderson, L.J., Gordon, R.G., and Engebretson, D.C., 1984, Mesozoic aseismic ridges on the Farallon plate and southward migration of shallow subduction during the Laramide orogeny: Tectonics, v. 3, no. 2, p. 121–132.

Henry, C.D., McDowell, F.W., and Silver, L.T., 2003, Geology and geochronology of granitic batholith complex, Sinaloa, México: Implications for Cordilleran magmatism and tectonics. Geological Society of America Special Paper 374: Tectonic evolution of northwestern Mexico and the Southwestern USA, p. 237–273.

Herzig, C.T., Kimbrough D.L., 1991, Early Cretaceous zircon ages prove a non-accretionary origin for the Santiago Peak Volcanics, northern Santa Ana Mountains, California: Geological Society of America Abstracts w/ Programs, v. 23, p. 35.

Hill, D.J., 1976, Geology of the Jurassic basement rocks, Santa Cruz Island, California, and correlation with other Mesozoic basement terranes in California, in D.G. Howell ed., Aspects of the geologic history of the California Continental borderland, Pacific Section American Association of Petroleum Geologists Miscellaneous Publications, v. 24, p. 16-56.

Hill, M.L., and Dibblee, T.W., 1953, San Andreas, Garlock, and Big Pine faults, California—A study of the character, history, and tectonic significance of their displacements: Geological Society of America Bulletin, v. 64, p. 443–458.

Hill, R.I., and Silver, L.T., 1988, San Jacinto intrusive complex: Constraints on crustal magma chamber processes from strontium isotope heterogeneity: Journal of Geophysical Research, v. 93, p. 10373-10388.

Holk, G.J., Taylor, H.P., Gromet, P.L., 2006, Stable isotope evidence for large-scale infiltration of metamorphic fluids generated during shallow subduction into the eastern Peninsular

Ranges mylonite zone (EPRMZ), Southern California, International Geology Review, v. 48, p. 209-222.

Hopson, C.A., Mattinson, J.M., and Pessagno, E.A., Jr., 1981, Coast Range Ophiolite, western California, *in* Ernst, W.G., ed., The geotectonic development of California, Rubey Volume I: Englewood Cliffs, New Jersey, Prentice-Hall, p. 418.510.

Howell, D.G., and Vedder, J.G., 1981, Structural implications of stratigraphic discontinuities across the southern California continental borderland, in W.G. Ernst, ed., The Geotectonic Development of California, Rubey Volume I, Prentice Hall, Englewood Cliffs, New Jersey, p. 535-559.

Ichinose, G. A., Day, S.,Magistrale, H., Prush, T.,Vernon, F., and Edelman, A., 1996, Crustal thickness variations beneath the Peninsular Ranges, southern California: Geophysical Research Letters, v. 23, p. 3095–3098.

Ingersoll, R.V., Rumelhart, P.E., 1999, Three-stage evolution of the Los Angeles Basin, Southern California Geology, v.27, p 593-596.

Irwin, W.P., 2002, Correlation of the Klamath Mountains and Sierra Nevada, U.S. Geological Survey Open-File Report 02-490.

Jacobson, C.E., 1983, Structural geology of the Pelona Schist and Vincent thrust, San Gabriel Mountains, California: Geological Society of America Bulletin, v. 94, p. 753-767.

Jacobson, C.E., 1990, The $^{40}Ar/^{39}Ar$ geochronology of the Pelona Schist and related rocks, southern California: Journal of Geophysical Research, v. 95, p. 509-528.

Jacobson, C.E., Dawson, M.R., and Postlethwaite, C.E., 1988, Structure, metamorphism, and tectonic significance of the Pelona, Orocopia, and Rand Schists, southern California, *in*

Ernst, W.G., ed., Metamorphism and crustal evolution of the western United States (Rubey Volume VII): Englewood Cliffs, New Jersey, Prentice-Hall, p. 976-997.

Jacobson, C.E., Grove, M., Stamp, M.M., Vucic, A., Oyarzabal, F.R., Haxel, G.B., Tosdal, R.M., and Sherrod, D.R., 2002, Exhumation history of the Orocopia Schist and related rocks in the Gavilan Hills area of southeasternmost California, *in* A.P. Barth, ed., Crustal evolution of the southwestern United States: Geological Society of America Special Paper 365, p. 129-154.

Jacobson, C.E., Grove, M., Vucic, A., and Pedrick, J., 2006, Exhumation of the Orocopia Schist and crystalline hangingwall rocks of southeastern California: Relative roles of erosion, synsubduction tectonic denudation, and middle Cenozoic extension, Geological Society of America Special Paper xxx, in press.

Jahns, R.H., 1954, Geology of the Peninsular Ranges Province, southern California and Baja California, *in* Jahns, R.H. editor, Geology of southern California: California Div. of Mines Bull. 170, chapter 2, p. 29-52.

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, v. 27, p. 743–746.

Jones, D. L., Blake, M. C., Jr., and Rangin, C., 1976, The four Jurassic belts of northern California and their significance to the geology of the southern California Borderland, *in* Howell, D. G., ed., Aspects of the geologic history of the California Continental Borderland: Pacific Section, American Association of Petroleum Geologists, Miscellaneous Publication 24, p. 343-362.

Jones, D.A., and Miller, R.H., 1982, Jurassic fossils from the Santiago Peak Volcanics, San Diego County, California, in Abbott, P.L., ed., Geologic Studies in San Diego, San Diego Association of Geologists Field Trips April 1982, p. 93-102.

Kennedy, M. P., and Moore, G. W., 1971, Stratigraphic relations of Upper Cretaceous and Eocene Formations, San Diego coastal area, California: American Association of Petroleum Geologists Bulletin, v. 55, p. 709-722.

Kienast, J R, Rangin, C, 1982, Mesozoic blueschists and melanges of Cedros Island (Baja California, Mexico); a consequence of nappe emplacement or subduction?, Earth and Planetary Science Letters, 59, 119-138.

Kilmer, F J, 1979, A geological sketch of Cedros Island, Baja California, Mexico, in Gastil, R G, and Abbott, P L, eds., Baja California Geology, San Diego State University (field trip guidebook for the 1979, Geological Society of America Annual Meeting, San Diego, California, 1-28.

Kimbrough, D L, 1985, Tectonostratigraphic terranes of the Vizcaino Peninsula and Cedros and San Benitos islands, Baja California, Mexico, in Howell, D G, ed., Tectonostratigraphic Terranes of the Circum-Pacific Region: Circum-Pacific council for Energy and Mineral Resources Earth Science Series, 1, 285-298.

Kimbrough, D L, and Moore, T.E. (2003) Ophiolite and volcanic arc assemblages on the Vizcaino Peninsula and Cedros Island, Baja California Sur, México: Mesozoic forearc lithosphere of the Cordilleran magmatic arc. Geological Society of America Special Paper 374, pp. 43–71.

Kimbrough, D.L., Smith, D.P., Mahoney, B.J., Moore, T.E., Grove, M., Gastil, R.G., Ortega-Rivera, A., Fanning, M.C., 2001, Forearc-basin sedimentary response to rapid Late

Cretaceous batholith emplacement in the Peninsular Ranges of southern and Baja California, *Geology,* v. 29, p. 491–494.

Kimbrough, D.L., and Grove, M., 2006, The eastern Peninsular Ranges batholith magmatic flare-up: Insight from zircon U-Pb ages and oxygen isotope ratios, Geological Society of America Abstracts with programs, Backbone of the Americas—Patagonia to Alaska, (3–7 April 2006), Paper No. 14-3.

King, R.L., Bebout, G.E., Grove, M ., Moriguti, T., Nakamura, E., Crustal Inputs, Metamorphic Processing, and Fluid Flow Architecture in the Catalina Schist Subduction Complex: Constraints From Detrital Zircon U-Pb Ages and Pb-B Isotope Systematics of Melange Zones, Eos Transactions. American Geophysical Union v. 86(52), Fall Meeting Supplement, Abstract V31C-0640. [Placeholder for submitted manuscript].

Kistler, R.W., Wooden, J.L., and Morton, D.M., 2003, Isotopes and Ages in the Northern Peninsular Ranges Batholith, Southern California. United States Geological Survey Open File Report 03-489.

Kröner, A., Jaeckel, P., Williams, I.S., 1994, Pb-loss patterns in zircons from a high-grade metamorphic terrain as revealed by different dating methods: U–Pb and Pb–Pb ages for igneous and metamorphic zircons from northern Sri Lanka: Precambrian Research, v. 66, p. 151–181.

Krummenacher, D., Gastil, R.G., Bushee, J., and Dupont, J., 1975, K-Ar apparent ages, Peninsular Ranges batholith, southern California and Baja California: Geological Society of America Bulletin, 86, 760–768.

Langenheim, V.E., and Jachens, R.C., 2003, Crustal structure of the Peninsular Ranges batholith from magnetic data: Implications for Gulf of California rifting: Geophysical Research Letters, v. 30p. 51-1-51-4doi: 10.1029/2003GL017159.

Larsen, E.S., 1948, Batholith and associated rocks of Corona, Elsinore and San Luis Rey quadrangles, southern California: Geological Society of America Memoir 29. 182p.

Lewis, J.L., Day, S.M., Magistrale, H., Castro, R.R., Astiz, L., Rebollar, C., Eakins, J., Vernon, F.L., and Brune, J.N., 2001, Crustal thickness of the Peninsular Ranges and Gulf Extensional Province in the Californias, Journal of Geophysical Research, 2001JB000178, p. 13599-13612.

Livaccari, R.F., Burke, K., and S¸engo¨r, A.M.C., 1981, Was the Laramide orogeny related to subduction of an oceanic plateau?: Nature, v. 289, p. 276–278.

Lovera, O.M., Grove, M., Kimbrough, D.L., and Abbott, P.L., 1999, Magnitude and time scales in the exhumation of arc crust: An approach based upon analysis of detrital closure age distributions: Journal of Geophysical Research, 104, 29419–29438.

Mahoney, J.B., Kimbrough, D.L., Grove, M., Jacobson, C.E., Mustard, P.S., 2005, Variations in Late Cretaceous batholith exhumation patterns along the western North American margin. Geological Society of America Abstracts with Programs, v. 37, p. 482. [Placeholder for ms in preparation].

Malin, P.E., Goodman, E.D., Henyey, T.L., Li, Y.G., Okaya, D.A., and Saleeby, J.B., 1995, Significance of seismic reflections beneath a tilted exposure of deep continental crust, Tehachapi Mountains, California: Journal of Geophysical Research, v. 100, p. 2069-2087.

Maruyama, S., Liou, J.G., and Terabayashi, M., 1996. Blueschists and eclogites of the world and their exhumation. International Geological Review, 38, 485-594.

Mattinson, J. M., 1986. Geochronology of high-pressure - low-temperature Franciscan metabasites: A new approach using the U-Pb system. In: Blueschists and Eclogites (Ed. Evans, B.W. and Brown, E.H.), Geol. Soc. America Memoir 164, p. 95-106.

Mattinson, J.M., and Hill, D.J., 1976, Age of plutonic basement rocks, Santa Cruz Island, in D.G. Howell ed., Aspects of the geologic history of the California Continental borderland, Pacific Section American Association of Petroleum Geologists Miscellaneous Publications, v. 24, p. 53-58.

McDougall, I., and Harrison, T.M., 1999, Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ method, second edition: New York, Oxford University Press, 269 p.

McDowell, F.W., Roldán-Quintana, J., and Connelly, J.N., 2001, Duration of Late Cretaceous–early Tertiary magmatism in east-central Sonora, Mexico. Geological Society of America Bulletin, v. 113, p. 521–531.

McWilliams, M.O., and Howell, D.G., 1982, Exotic terranes of western California: Nature, v. 297, p. 215–217.

Mojzsis S. J. and Harrison T. M., 2002, Establishment of a 3.83 Ga magmatic age for the Akilia tonalite (southern West Greenland). Earth and Planetary Science Letters. v. 202, p. 563–576.

Moore, T E, 1986, Petrology and tectonic implications of the blueschist-bearing Puerto Nuevo melange complex, Vizcaino Peninsula, Baja California Sur, Mexico Geological Society of America Memoir 164, pp.43-58.

Moore, T.E., 1985, Stratigraphic and tectonic signifcance of the Mesozoic tectonostratigraphic terranes of the Vizcaíno peninsula, Baja California Sur, Mexico, *in* Howell, D.G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, p. 315.329.

Morgan, J.R.' Kimbrough, D. L., Grove, M., 2005, Detrital U/Pb zircon ages from the Peninsular Ranges Mesozoic flysch belt of southern and Baja California, Peninsular Geological Society, VII International Meeting, Abstract with Program, p. xx.

Nicholson, C., Sorlien, C. C., Atwater, T., Crowell, J. C., and Luyendyk, B. P., 1994, Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault system: Geology, v. 22, p. 491–495.

Nilsen, T. H., and Abbott, P. L., 1981, Paleogeography and sedimentology of Upper Cretaceous turbidites, San Diego, California: American Association of Petroleum Geologists Bulletin, v. 65, p. 1256-1284.

Nordstrom, C. E., 1970, Lusardi Formation--a post-batholithic Cretaceous conglomerate north of San Diego, California: Geological Society of America Bulletin, v. 81, p. 601-605.

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. Geological Society of America Special Paper 374: Tectonic evolution of northwestern Mexico and the Southwestern USA, p. 297–335.

Page, B.M., 1970, Sur-Nacimiento fault zone of California: Continental margin tectonics: Geological Society of America Bulletin, 81, 667–690.

Page, B.M., 1981, The southern Coast Ranges, *in* Ernst, W.G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 329–417.

Page, B.M., 1982, Migration of Salinian composite block, California, and disappearance of fragments: American Journal of Science, v. 282, p. 1694–1734.

Patterson, D.L., 1984, Los Chapunes and Valle sandstones: Cretaceous petrofacies of the Vizcaino basin, Baja California, Mexico, *in* Frizzell, V.A., Jr., ed., Geology of the Baja California Peninsula: Pacific Section, Society of Economic Paleontologists and Mineralogists, 39, 161–172.

Peacock, S.M., 1987. Creation and preservation of subduction-related metamorphic gradients. J. geophys. Res. 92, 12,763-12,781.

Peacock, S.M., 1992, Blueschist-facies metamorphism, shear heating, and P-T-t paths in subduction shear zones. J. Geophys. Res. 97, 17693-17707.

Peacock, S.M., Rushmer, T., Thompson, A.B., 1994, Partial melting of subducting oceanic crust. Earth and Planetary Science Letters, v. 121, p. 227-244.

Peterson, G. L., and Nordstrom, C. E., 1970, Sub-La Jolla unconformity in vicinity of San Diego, California: American Association of Petroleum Geologists Bulletin, v. 54, n. 2, p. 265-274.

Pickett, D.A., and Saleeby, J.B., 1993, Thermobarometric constraints on the depth of the exposure and conditions of plutonism and metamorphism at deep levels of the Sierra Nevada batholith, Tehachapi Mountains, California: Journal of Geophysical Research, v. 98, p. 609–629.

Platt, J. P. 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Geol. Soc. America Bull., 97, 1037-1053.

Platt, J.P., 1975, Metamorphic and deformational processes in the Franciscan Complex, California: Some insights from the Catalina Schist terrane. Geol. Soc. America Bull., 86, 1337-1347.

Platt, J.P., 1976, The petrology, structure, and geologic history of the Catalina Schist terrain, southern California. University of California Publications Geological Sciences 112, 111 pp.

Rothstein, D.A., and Manning, C.E., 2003, Geothermal gradients in continental magmatic arcs; constraints from the eastern Peninsular Ranges Batholith, Baja California, Mexico. Geological Society of America Special Paper 374: Tectonic evolution of northwestern Mexico and the Southwestern USA, p. 337–354.

Rubatto, D., 2002, Zircon trace element geochemistry, partitioning with garnet and the link between U-Pb ages and metamorphism: Chemical Geology, v. 184, p. 123-138.

Saleeby, J.B., 2003, Segmentation of the Laramide Slab - evidence from the southern Sierra Nevada region Geological Society of America Bulletin v. 115, p. 655-668.

Saleeby, J.B., and Sharp, W.D., 1980, Chronology of the structural and petrologic development of the southwest Sierra Nevada foothills, California: Geological Society of America Bulletin, Part II, 91, p. 1416–1535.

Schmidt, K.L., and Paterson, S.R., 2002, A doubly vergent, fan structure in the Peninsular Ranges batholith: Transpression or complex flow along a crustal-scale discontinuity? Tectonics, v. 21, p. 14-1 – 14-19.

Schmidt, K.L., Wetmore, P.H., Johnson, S.E., and Paterson, S.R., 2002, Along-strike variation in the origin of an ocean-continent basement join in the Mesozoic Peninsular Ranges batholith: to what degree does an island arc collision drive orogeny?, *in* Barth, A., ed., Geological Society of America Special Paper v. 365, p. 49-72.

Scholl, D W; von Huene, R; Vallier, T L; Howell, D G, 1980, Sedimentary masses and concepts about tectonic processes at underthrust ocean margins Geology, vol.8, p.564-568.

Sedlock, R L, 1988a, Metamorphic petrology of a high-pressure, low-temperature subduction complex in west-central Baja California, Mexico. Journal of Metamorphic Geology, 6, 205-233.

Sedlock, RL, 1988b, Tectonic setting of blueschist and island-arc terranes of west central Baja California, Mexico, Geology, 16, 623-626.

Shaw, S.E., Todd, V.R., and Grove, M., 2003, Jurassic peraluminous gneissic granites in the axial zone of the Peninsular Ranges, southern California. Geological Society of America Special Paper v. 374, p.157–183.

Shervais, J.W., Murchey, B.L., Kimbrough, D.L., Renne, P.R., and Hanan, B., 2005, Radioisotopic and biostratigraphic age relations in the Coast Range Ophiolite, northern California: Implications for the tectonic evolution of the Western Cordillera. Geological Society of America Bulletin: v. 117, p. 633–653.

Silver, L.T., and Chappell, B.W., 1988, The Peninsular Ranges batholith: An insight into the evolution of the Cordilleran batholiths of southwestern North America: Royal Society of Edinburgh Transactions: Earth Sciences, v. 79, p. 105-121.

Smith, D P, Busby, C J, 1993, Mid-Cretaceous crust extension recorded in deepmarine half-graben fill, Cedros Island, Mexico, Geol. Soc. America Bull., 105, 547-562.

Sorensen, S. S., 1988b. Petrology of amphibolite-facies mafic and ultramafic rocks from the Catalina Schist, southern California: metasomatism and migmatization in a subduction zone metamorphic setting. J. metamorphic Geol. v. 6. pp. 405-435.

Sorensen, S.S., 1986, Petrologic and geochemical comparison of the blueschist and greenschist units of the Catalina Schist terrane, southern California. Geological Society of America Memoir 164: 59-75.

Sorensen, S.S., 1988a, Tectonometamorphic significance of the basement rocks of the Los Angeles Basin and the California Continental Borderland. in Ernst, W.G., Ed., Metamorphism and Crustal Evolution of the Western United States, Rubey Volume VII: 998-1022.

Sorensen, S.S., and Barton, M.D., 1987, Metasomatism and partial melting in a subduction complex: Catalina Schist, southern California. Geology 15: 115-118.

Sorensen, S.S., and Grossman, J.N., 1989, Enrichment of trace elements in garnet amphibolites from a paleo-subduction zone: Catalina Schist, southern California. Geochimica et Cosmochimica Acta 53, 3155-3177.

Sorensen, S.S., 1985, Petrologic evidence for Jurassic island arc-like basement rocks in the southwestern Tranverse ranges and California continental borderland. Geological Society of America Bulletin v. 96, p. 997-1006.

Staude, J.M., and Barton, M.D., 2001, Jurassic to Holocene tectonics, magmatism, and metallogeny of northwestern Mexico. Geological Society of America Bulletin, v. 113, p. 1357–1374.

Stern, R.J., and Bloomer, S.H., 1992, Subduction zone infancy: Examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs: Geologic Society of America Bulletin, v. 104, p. 1621.1636.

Stern, T., Bateman, P.C., Morgan, B.A., Newell, M.F., and Peck, D.L., 1981, Isotopic U-Pb ages of zircon from the granitoids of the central Sierra Nevada, California: U.S. Geological Survey Professional Paper 1185, 17 p.

Stock, J., and Molnar, P., 1988, Uncertainties and implications of the Late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific plates: Tectonics, v. 7, p. 1339–1384.

Stuart, C J, 1979, Middle Miocene paleogeography of coastal southern California and the California borderland: Evidence from schist-bearing sedimentary rocks, in Armentrout, J M, Cole, M R, and Terbest, H Jr., editors, Cenozoic paleogeography of the western United States, SEPM Pacific Coast Field Guide 3, 29-44.

Sundberg, F. A. and Cooper, J. D., 1978, Late Cretaceous depositional environments, northern Santa Ana Mountains, Southern California, in Howell, D. G., and McDougall, K. A., eds., Mesozoic Paleogeography of the Western United State :Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium 2, p. 535-546.

Suppe, J. and Armstrong, R.L., 1972, Potassium-Argon dating of Franciscan metamorphic rocks. American Journal of Science, v. 272, p. 217-233.

Suppe, J., 1970, Offset of late Mesozoic basement terrains by the San Andreas fault system: Geological Society of America Bulletin, v. 81, p. 3253–3258.

Taylor, H. P., 1986, Igneous rocks; 2, Isotopic case studies of Circum-Pacific magmatism, in Valley, J. W., Taylor, H. P., Jr., and O'Neil, J. R., eds., Stable Isotopes in High-Temperature Geological Processes: Mineralogical Society of America, p. 273-317.

ten Brink, U S, Zhang, J, Brocher, T M, Okaya, D A, Klitgord, K D, Fuis, G S, 2000, Geophysical evidence for the evolution of the California inner continental borderland as a metamorphic core complex. J. Geophys. Res., 105, 5835-5857.

Thomson, C.N., and Girty, G.H., 1994, Early Cretaceous intra-arc ductile strain in Triassic-Jurassic and Cretaceous continental margin arc rocks, Peninsular Ranges, California, Tectonics, v.13, p.1108-1119.

Todd, V. R., Erskine, B. G., and Morton, D. M., 1988, Metamorphic and tectonic evolution of the northern Peninsular Ranges Batholith, southern California, in Ernst, W. G., ed., Metamorphism and Crustal Evolution of the Western United States, Rubey Volume VII: Prentice-Hall, Englewood Cliffs, New Jersey, p. 894-937.

Todd, V.R., and Shaw, S.E., 1985, S-type granitoids and an I-S line in the Peninsular Ranges batholith, southern California: Geology, v. 13, p. 231-233.

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. Special Paper 374: Tectonic evolution of northwestern Mexico and the Southwestern USA: v. 374, p. 185–235.

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. Geological Society of America Special Paper

374: Tectonic evolution of northwestern Mexico and the Southwestern USA, v. 374, p. 275–295.

Usui, T., Nakamura, E., Kobayashi, K., Maruyama, S. and Helmstaedt, H., 2003, Fate of the subducted Farallon plate inferred from eclogite xenoliths in the Colorado Plateau. Geology, v. 31, p. 589–592.

Vedder, J. G., 1987, Regional geology and petroleum potential of the southern California Borderland, in Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins: Beaufort Sea to Baja California, edited by D. W. Scholl, A. Grantz, and J. G. Vedder, Circum-Pacific Council for Energy and Mineral Resourses, Houston, Texas, p. 403–447.

Vedder, J.G., Howell, D.G., and McLean, H., 1983, Stratigraphy, sedimentation, and tectonic accretion of exotic terranes, southern Coast Ranges, California, *in* Watkins, J.S., and Drake, C.L., eds., Studies in continental margin geology: American Association of Petroleum Geologists Memoir 34, p. 471–496.

von Huene, R., and D. W. Scholl (1991), Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust, Rev. Geophys., v. 29, p. 279–316.

von Huene, R., and D. W. Scholl, 1993, The return of sialic material to the mantle indicated by terrigeneous material subducted at convergent margins, Tectonophysics, 219, 163– 175.

von Huene, R., and S. Lallemand (1990), Tectonic erosion along the Japan and Peru convergent margin, Geol. Soc. Am. Bull., v. 102, p.704–720.

Wakabayashi, J., 1990, Counterclockwise P-T-t paths from amphibolites, Franciscan Complex, California: relics from the early stages of subduction zone metamorphism: Journal of Geology, v. 98, p. 657-680.

Wakabayashi, J., 1992, Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California: Journal of Geology, v. 100, p. 19-40.

Wakabayashi, J., 1999, Subduction and the rock record: Concepts developed in the Franciscan Complex, California: in Sloan, D., Moores, E.M., and Stout, D. eds., Classic Cordilleran Concepts: A View From California, Geological Society of America Special Paper 338, p. 123-133.

Walawender, M.J., Gastil, R.G., Clinkenbeard, J.P., McCormick, W.V., Eastman, B.G., Wernicke, R.S., Wardlaw, M.S., Gunn, S.H., and Smith, B.M., 1990, Origin and evolution of the zoned La Posta–type plutons, eastern Peninsular Ranges batholith, southern and Baja California,: *in* Anderson, J.L., ed., The nature and origin of Cordilleran magmatism: Geological Society of America Memoir 174, p. 1–18.

Weaver, D.W., and Nolf, B., 1969, Geology of Santa Cruz Island (map), *in* Weaver, D.W., ed., Geology of the northern Channel Islands, southern California borderland: PacificSection, American Association of Petroleum Geologists Special Publication, scale 1:24 000.

Wetmore, P.H. , Herzig, C., Schultz, P.W., Alsleben, H, Paterson, S.R., and Schmidt, K.L., 2003, Cretaceous Tectonic Evolution of the Western Zone of the Peninsular Ranges Batholith of Southern and Baja California, *in* Johnson, S.E., Paterson, S.R., Girty, G.H., and Fletcher, J, eds., Geological Society of America Special Paper v. 374, p. 93-116.

Wetmore, P.H., Schmidt, K.L., Paterson, S.R. and Herzig, C., 2002, Tectonic implications for the along-strike variation of the Peninsular Ranges batholith, southern and Baja California. Geology, v. 30, p. 247–250.

Williams I. S. and Claesson S., 1987, Isotopic evidence for the Precambrian provenance and Caledonian metamorphism of high grade paragneisses from the Seve Nappes, Scandinavian Caledonides. Contributions to Mineralalogy and Petrology, v. 97, p. 205–217.

Wood, D.J., and Saleeby, J.B., 1997, Late Cretaceous-Paleocene extensional collapse and disaggregation of the southernmost Sierra Nevada batholith: International Geology Review, v. 39, p. 973-1009.

Woodford, A.O., 1924, The Catalina Metamorphic Facies of the Franciscan series: University of California Pub. Geol. Sciences, v. 15, n. 3, p. 49-68.

Woodring, W.P., and Popenoe, W.P., 1942, Upper Cretaceous formations and faunas of southern California: Amer. Assoc. Petroleum Geologists Bulletin, vol. 26, no. 2, p. 166-176.

Woodring, W.P., Bramlette, M.N., and Kew, W.S.W., 1946, Geology and paleontology of the Palos Verdes Hills, California, U.S.G.S. Professional Paper 207, 145 pp.

Wright, T.L., 1991, Structural geology and tectonic evolution of the Los Angeles Basin, California, in Active Margin Basins, edited by K.T. Biddle, AAPG Memoir 52, 35-134.

Wright, J.E., and Fahan, M.R., 1988, An expanded view of Jurassic orogenesis in the western United States Cordillera: Middle Jurassic (pre-Nevadan) regional metamorphism and thrust faulting within an active arc environment, Klamath Mountains, California, Geological Society of America Bulletin, v. 100, p. 859–876.

Yeats, R.S., 1968, Southern California structure, seafloor spreading, and history of the Pacific Basin: Geological Society of America Bulletin, v. 79, p. 1693-1702.

Yerkes, R.F., McCulloh, T.H., Schoellhamer, J.E., and Vedder, J.G., 1965, Geology of the Los Angeles basin, California – An introduction, U.S.G.S. Professional Paper 420-A, 57 pp.

Zandt, G., Gilbert, H., Owens, T.J., Ducea, M., Saleeby, J., and Jones, C.H., 2004, Active foundering of a continental arc root beneath the southern Sierra Nevada in California, Nature, v. 431, p. 41-46.

FIGURES

Figure 1 Geologic setting of the Catalina Schist. Location map provided in upper left shows the distribution of high-pressure/temperature subduction complexes and Cretaceous-tertiary batholiths in southwestern North America. The offshore distribution of subduction complexes is estimated primarily from Crouch and Suppe (1993), Bohannon and Geist (1998), Sedlock, 1988a,b, Bonini and Baldwin (1998), and Fletcher et al., (2006). The box outlines the location of southern California continental borderland. The simplified map of borderland shown in the lower right is based upon Bohannon and Geist (1998) while cross section Y-Y' is after Crouch and Suppe (1993). Symbols P & P' denote formerly contiguous rocks prior to Middle Miocene rifting. Box shows location of Catalina Island. The geologic map and cross section X-X' of Catalina Island in the upper left are after Platt (1976). The distribution of lawsonite albite and actinolite albite rocks is from Altheim et al. (1999). Note that epidote blueschist and epidote amphibolite rocks are distinguished from Platt's (1976) greenschist unit.

Figure 2 Geologic map of the Peninsular Ranges batholith modified after Gastil et al., (1975) and Kimbrough et al., (2001). Generalized stratigraphic relationships of forearc region in the northern Vizcaino peninsula modified after Kimbrough et al. (2001), Kimbrough and Moore (2003) and references cited within these papers. Simplified stratigraphy of northern Santa Ana mountains modified after Lovera et al. (1999) and references cited therin. Western limit of forearc refers to E-dipping detachment system associated with borderland rifting between Santa Ana Mountains and El Rosario. South of the Vizcaino peninsula, the San Benitos-Tosco-Abreojos fault zone bounds the forearc. In the intervening region, the western limit of the forearc has been estimated from areo magnetic mapping of Langenheim and Jachens (2003).

Figure 3 (A) Measured zircon U-Pb age vs. Th/U of Cretaceous forearc sedimentary rocks of the Peninsular Ranges batholith. Data from Mahoney et al. (2005) demonstrates that virtually all detrital igneous zircons derived from the Peninsular Ranges have Th/U > 0.1 (see also Williams and Claesson, 1987). (B) Equivalent plot for zircon results from the Catalina Schist amphibolite unit. Based upon cathodoluminescence imaging and other criteria, we regard a Th/U = 0.1 as a meaningful cutoff to distinguish analyses in which the sputter pit overlapped metamorphic zircon growth (open symbols). The filled symbols represent detrital grains that we consider to be largely unaffected by metamorphic zircon growth (see also Kröner et al., 1994; and Rubatto, 2002). Zircon results with Th/U < 0.1 have been excluded from all subsequent plots and calculations.

Figure 4 Probability plots of detrital zircon U-Pb age distributions from major units of the Catalina Schist on Catalina Island. (A) amphibolite (B) epidote amphibolite (C) epidote blueschist (D) lawsonite blueschist (E) actinolite albite (F) lawsonite albite. Note that we use a split horizontal axis at 300 Ma and that elative probability plots between 300-3000 Ma have a 2x scaling factor to improve resolution of the overall age distribution, (G) True scale cumulative probability specta for all units.

Figure 5 Estimated temperature-time histories for major units of the Catalina Schist. (A) amphibolite (B) epidote amphibolite (C) epidote blueschist (D) lawsonite blueschist (E) actinolite albite (F) lawsonite albite (G). Yellow circles represent measured detrital zircon U-Pb ages. Maximum bounds upon the depositional age of the sedimentary protolith represent average and standard deviation of U-Pb ages of five youngest zircons with Th/U > 0.1. Data sources for other thermochronometry include Suppe and Armstrong (1972), Mattinson (1986), Grove and Bebout (1995), and Anczkiewicz et al. (2004). Note that we have varied the bulk closure temperatures assigned to micas from 400°C for coarse grained muscovites within the high-grade units to 300°C for finer grained, less retentive white mica within lawsonite albite rocks.

Figure 6 (A) Cumulative probability plots for detrital zircon U-Pb age distributions from Peninsular Ranges forearc strata (data from Mahoney et al., 2005). Note striking provenance shift between early and Late Cretaceous strata for the Vizcaino region. Early Cretaceous strata have not been identified from the northern Peninsular Ranges forearc. Blue line represents detrital zircon results from the lawsonite blueschist and lower grade rocks of the Catalina Schist for reference. (B) Cumulative probability plots illustrating strong similarity of detrital zircon U-Pb age distributions of lawsonite blueschist and lower grade rocks of the Catalina Schist to Turonian strata from the Santa Ana Mountains (Mahoney et al., 2005) and the oldest recognized representative of the Pelona and related schists (San Emigdio Mountains). Schist from this locality structurally underlies the the southwestern-most tail of the Sierra Nevada batholith (Grove et al., 2003a; see Fig. 1 for location).

Figure 7 Relative probability plot of zircon U-Pb results obtained from Tithonian marine volcanic strata from the northwestern margin of the Peninsular Ranges. These rocks were formerly considered to represent the Santiago Peak volcanics but are now recognized to be older and structurally beneath the Early Cretaceous volcanic arc (e.g., Herzig and Kimbrough, 1991). The older volcanics represent a potential source for 140-150 Ma zircon in the Catalina Schist.

Figure 8 (A) Relative probability plot of detrital zircon U-Pb age results from Jurassic-Triassic flysch host rocks from the northern Peninsular Ranges batholith (Morgan et al., 2005). Four widely separated samples represent the Bedford Canyon Formation, French Valley Group, and Julian Schist in southern California and the Vallecitos Group in northwestern Baja California. (B) Relative probability plot of detrital zircon U-Pb age results from the Catalina Schist amphibolite unit. (C) Cumulative probability plot of flysch host rocks and Catalina Schist illustrating the strong similarity in their detrital zircon U-Pb age distributions.

Figure 9 Ternary mixing simulation of the detrital zircon age distribution of major tectonic units of the Catalina Schist (see Fletcher et al., 2006 for details of modeling process). (A) Cumulative probability plot illustrating the three end members used in the calculations: 1-Triassic-Jurassic flysch wallrocks of northern Peninsular Ranges (Morgan et al., 2005), 2-Late Jurassic-Early Cretaceous volcanic arc (Alsleben et al., 2005; D.L. Kimbrough, unpublished data), and 3-Late Cretaceous forearc (Mahoney et al., 2005). Results from the Catalina Schist are shown for reference. (B) Best-fit results for indicated tectonic units of the Catalina Schist. Note the general trend away from Peninsular Ranges wallrock and volcanic zircon signature exhibited by the oldest accreted units toward pluton-dominated zircon provenance that characterizes the youngest rocks within the Catalina Schist. (C) – (F) show cumulative probability plots for best-fit solutions for amphibolite, epidote amphibolite, epidote blueschist, and lawsonite blueschist and lower grade Catalina Schist. With the exception of the epidote amphibolite results, all best-fit mixtures agree with measured distributions to within 95% confidence using Kolmorgorov-Smirnoff statistic (see Fletcher et al., 2006 for explanation of how the K-S statistic is calculated for this type of data).

Figure 10 Subduction erosion model for the formation of the Catalina Schist. (A) Geometry for northern Peninsular Ranges is based upon better preserved southern forearc which was not severely affected by Miocene rifting. The backarc extension and sedimentation shown are inferred from geologic relationships within east-central Peninsualr ranges and formerly adjacent mainland Mexico. Note that detrital zicon results from Early Cretaceous volcanic sediments (Alsleben et al., 2005) require close proximity to southwestern North America. (B) Initial underthrusting of Early Cretaceous forearc beneath northwestern Peninsular Ranges and amphibolite facies metamorphism and anatexis at 115 Ma. Note that amphibolite unit stalls beneath western batholith at a position well-separated from active subduction zone. Coherent metagabbro underlying the amphibolite unit on Catalina Island is inferred to represent underthrust arc-ophiolite basement from the forearc. Evidence for intra-arc shortening at this time is detailed within the text. (C) Progressive formation of subcrustal duplex beneath northwestern Peninsular Ranges from continued collapse of Early Cretaceous forearc. Deposition, underthrusting, and peak metamorphism of epidote amphibolite rocks takes place between 113-97 Ma. Note that shortening in the backarc region preconditions the crust for deep melting (> 40 km) to generate La Posta magmatism at 95 Ma. (D) Final assembly of the Catalina Schist between 100-95 Ma. Deposition, underthrusting, metamorphism, and cooling of the epidote blueschist and lower grade rocks takes place over an interval too short to be resolved by our methods (i.e., < 2-4 m.y.). Deep, garnet-involved, melting to generate La Posta magmatism is facilitated by overthickened arc-ophiolite basement in the former backarc, focused asthenispheric counter flow caused by initiation of flat subduction and eastern relocation of magmatic arc, and massive devolatilization of deep underplated Catalina Schist within the subduction channel. (E) Impact of Laramide flat subduction upon northern Peninsualr Ranges. Deep crustal and lithospheric mantle root of La Posta plutonic belt is swept away between 80-65 Ma, caused renewed deep exhumation of eastern Peninsular Ranges batholith.

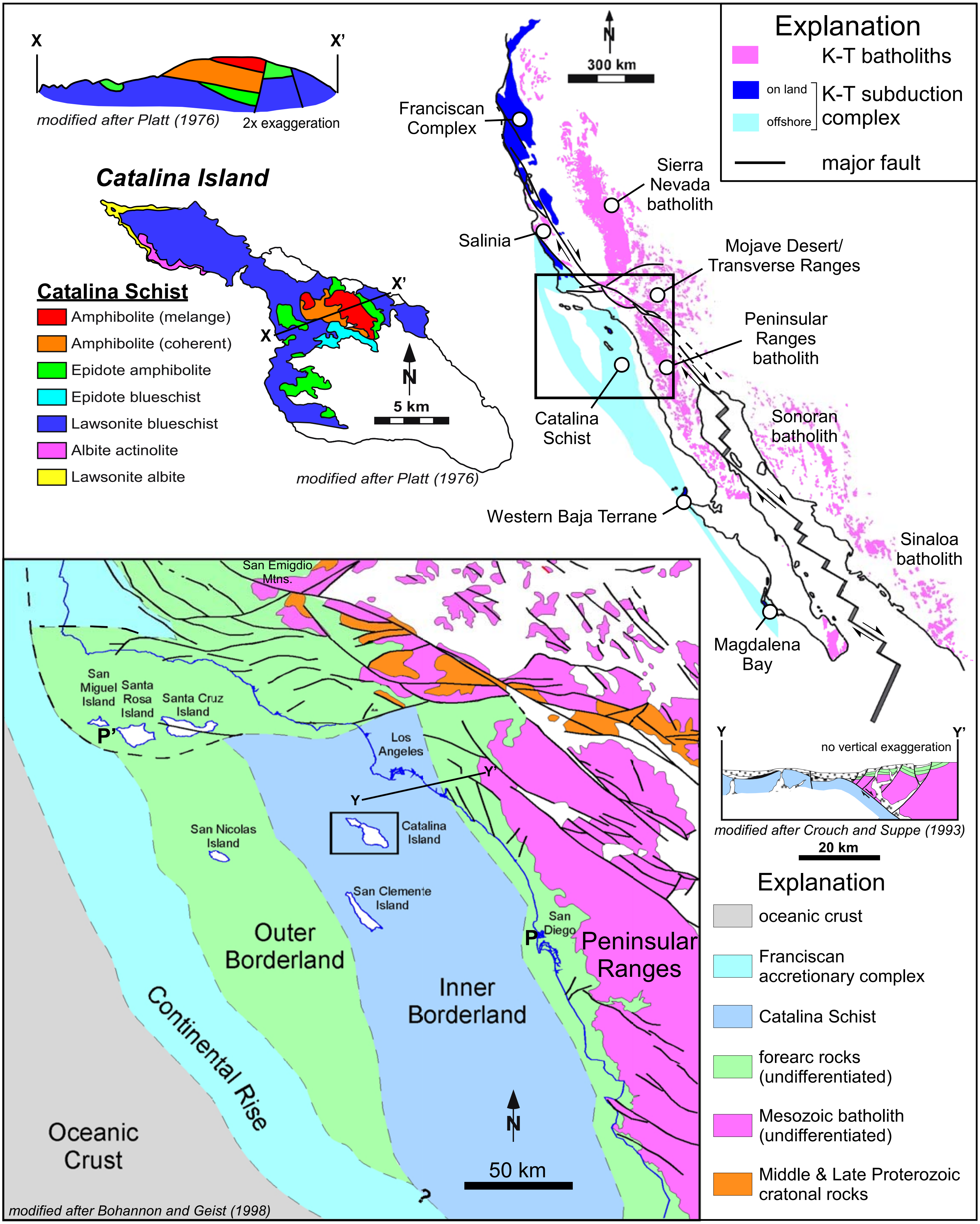
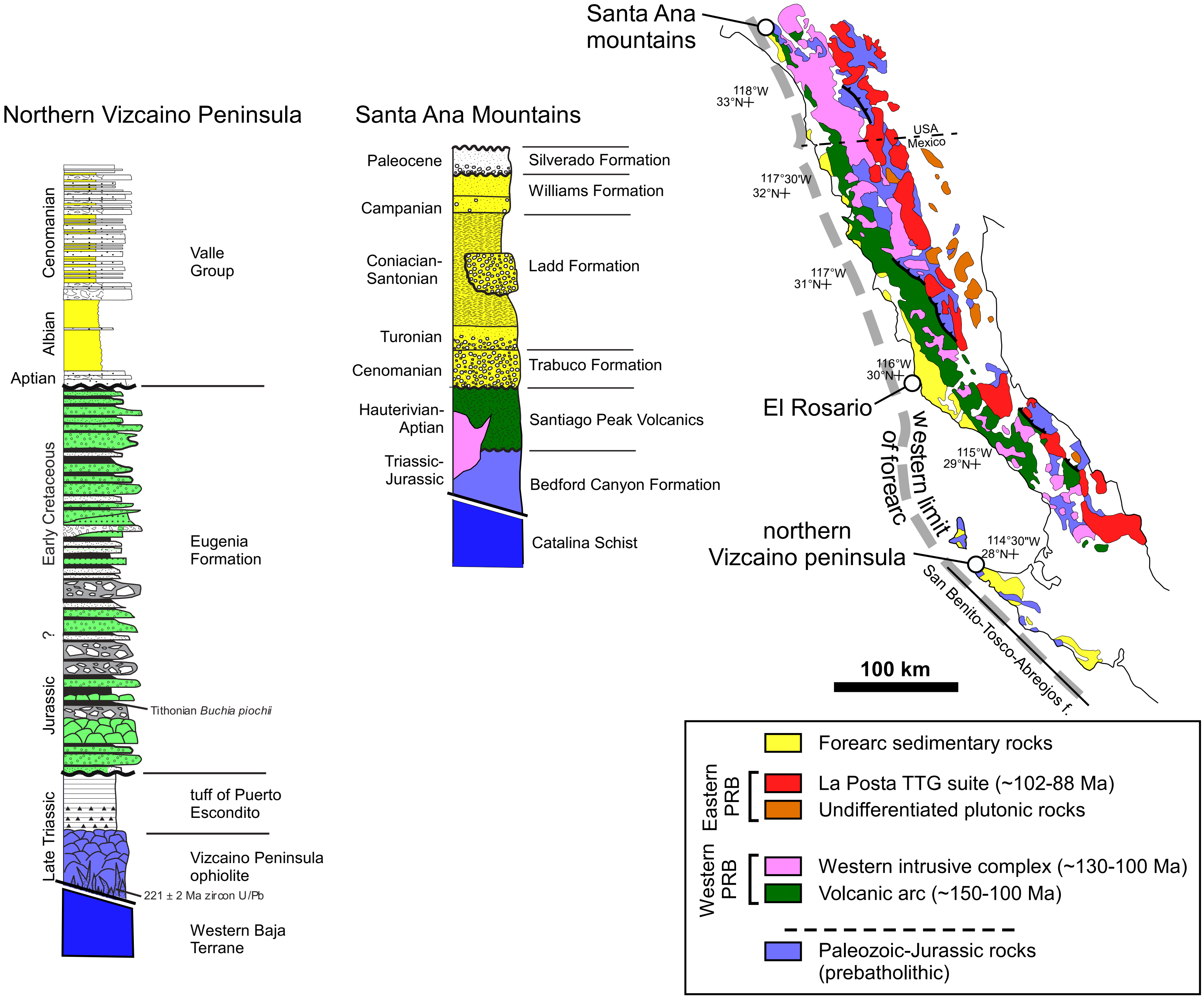

X
X'
modified after Platt (1976)
2x exaggeration
Catalina Island
Catalina Schist
Amphibolite (melange)
Amphibolite (coherent)
Epidote amphibolite
Epidote blueschist
Lawsonite blueschist
Albite actinolite
Lawsonite albite
X'
X
N
5 km
modified after Platt (1976)
N
300 km
Franciscan Complex
Sierra Nevada batholith
Salinia
Mojave Desert/ Transverse Ranges
Peninsular Ranges batholith
Catalina Schist
Sonoran batholith
Western Baja Terrane
Sinaloa batholith
Magdalena Bay
Explanation
K-T batholiths
on land
offshore
K-T subduction complex
major fault
San Emigdio Mtns.
San Miguel Island
Santa Rosa Island
Santa Cruz Island
P'
Los Angeles
Y'
Y
Catalina Island
San Nicolas Island
San Clemente Island
San Diego
P
Outer Borderland
Inner Borderland
Peninsular Ranges
Continental Rise
Oceanic Crust
N
50 km
?
modified after Bohannon and Geist (1998)
Y
Y'
no vertical exaggeration
modified after Crouch and Suppe (1993)
20 km
Explanation
oceanic crust
Franciscan accretionary complex
Catalina Schist
forearc rocks (undifferentiated)
Mesozoic batholith (undifferentiated)
Middle & Late Proterozoic cratonal rocks

Figure 1

Figure 2


Northern Vizcaino Peninsula
Cenomanian
Albian
Aptian
Early Cretaceous
?
Jurassic
Late Triassic
Valle
Group
Eugenia
Formation
Tithonian *Buchia piochii*
tuff of Puerto
Escondito
Vizcaino Peninsula
ophiolite
221 ± 2 Ma zircon U/Pb
Western Baja
Terrane
Santa Ana Mountains
Paleocene
Campanian
Coniacian-
Santonian
Turonian
Cenomanian
Hauterivian-
Aptian
Triassic-
Jurassic
Silverado Formation
Williams Formation
Ladd Formation
Trabuco Formation
Santiago Peak Volcanics
Bedford Canyon Formation
Catalina Schist
Santa Ana
mountains
118°W
33°N
USA
Mexico
117°30'W
32°N
117°W
31°N
116°W
30°N
El Rosario
Western limit
of forearc
115°W
29°N
northern
Vizcaino peninsula
114°30"W
28°N
San Benito-Tosco-Abreojos f.
100 km
Forearc sedimentary rocks
Eastern
PRB
La Posta TTG suite (~102-88 Ma)
Undifferentiated plutonic rocks
Western
PRB
Western intrusive complex (~130-100 Ma)
Volcanic arc (~150-100 Ma)
Paleozoic-Jurassic rocks
(prebatholithic)

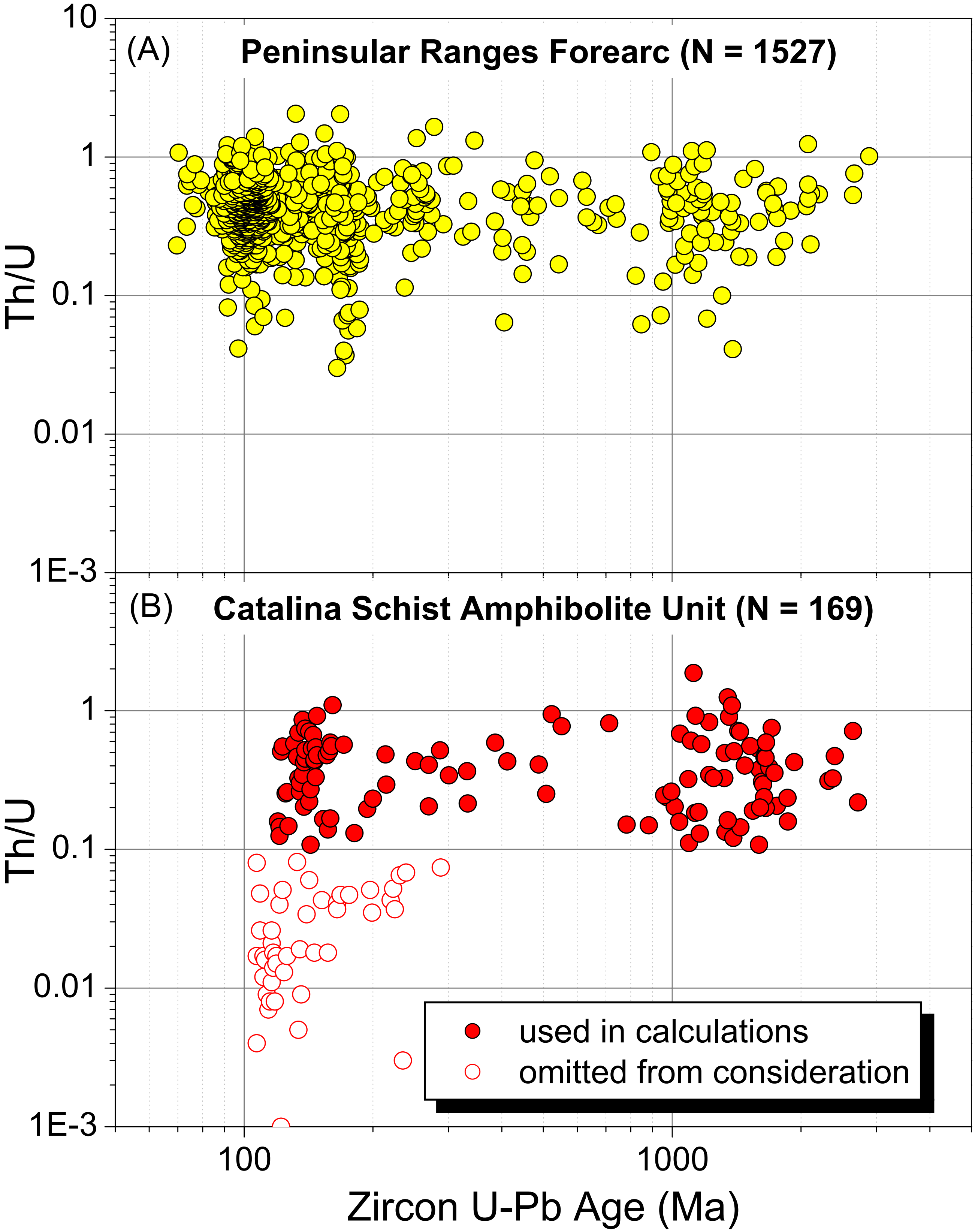

(A)
Peninsular Ranges Forearc (N = 1527)
(B)
Catalina Schist Amphibolite Unit (N = 169)
used in calculations
omitted from consideration
Th/U
10
1
0.1
0.01
1E-3
100
1000
Zircon U-Pb Age (Ma)

Figure 3

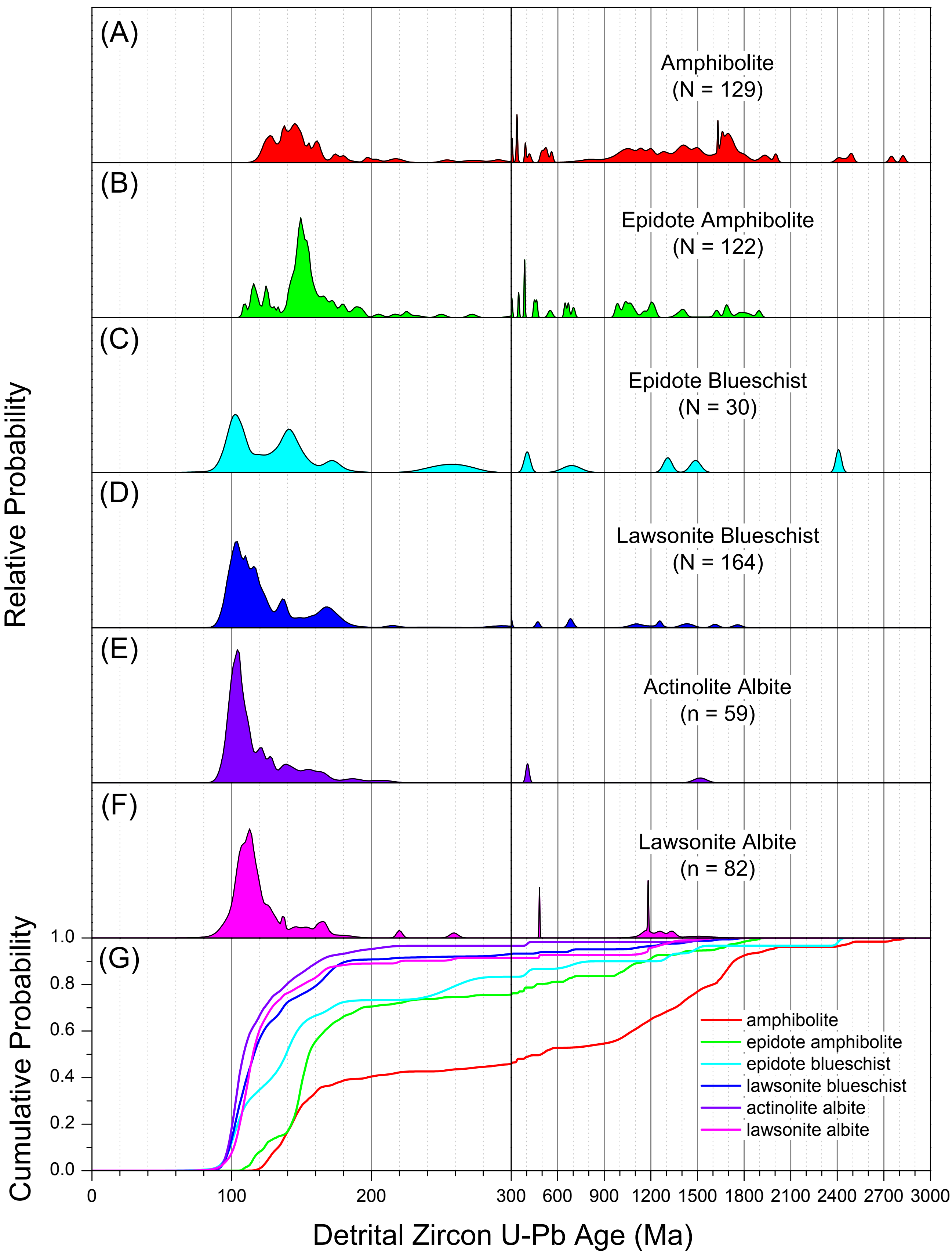
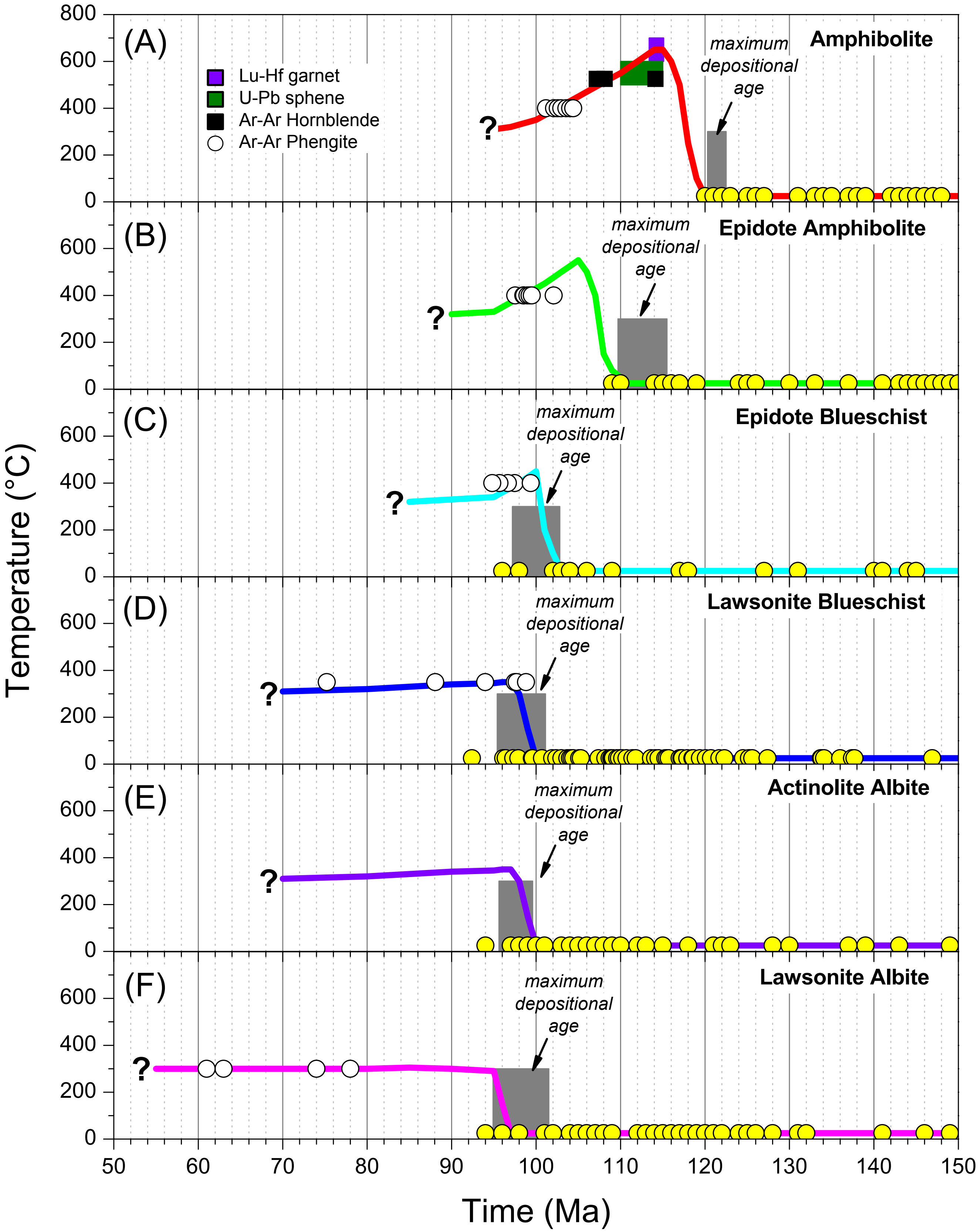
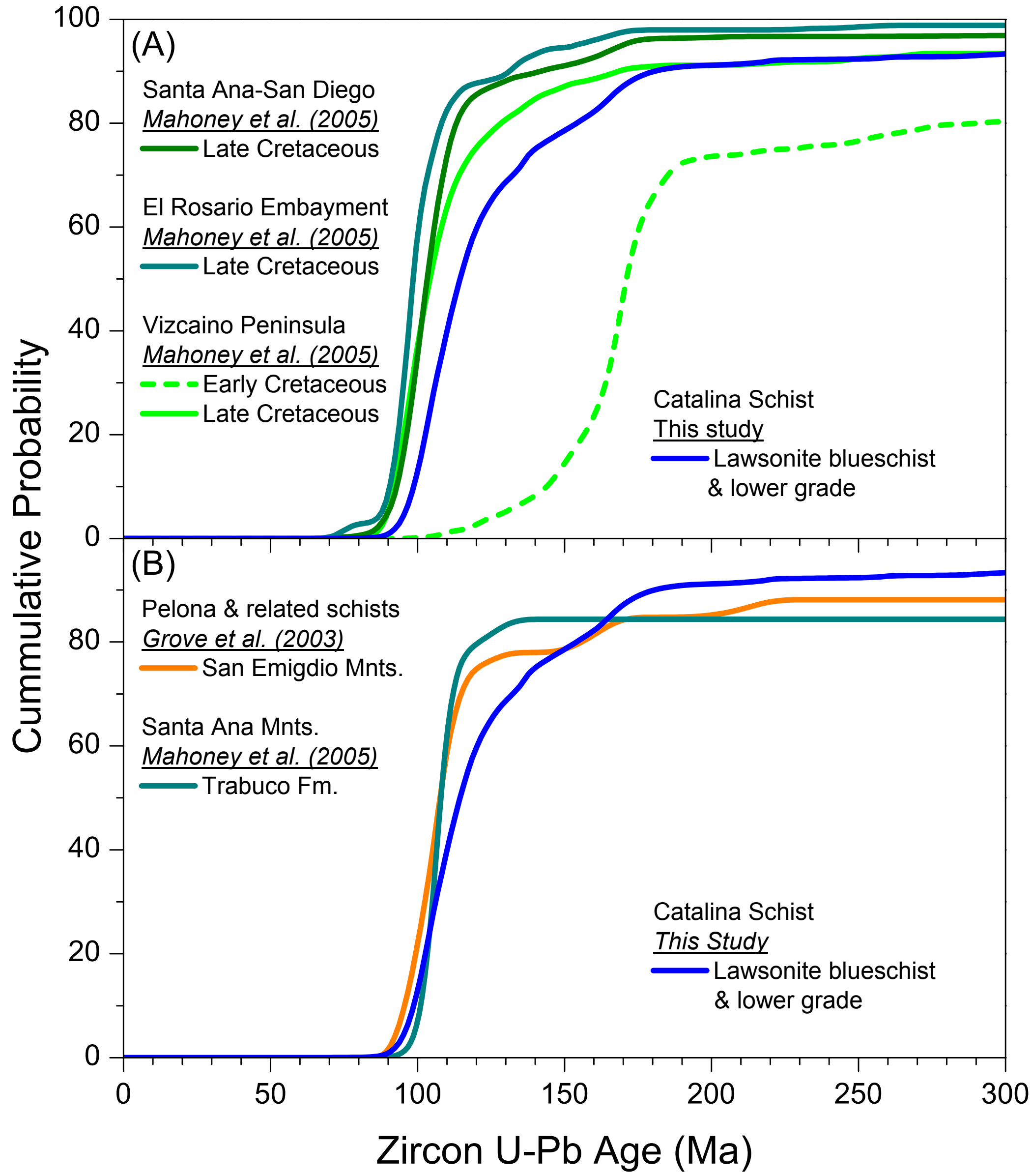

(A)
Amphibolite
(N = 129)
(B)
Epidote Amphibolite
(N = 122)
(C)
Epidote Blueschist
(N = 30)
(D)
Lawsonite Blueschist
(N = 164)
(E)
Actinolite Albite
(n = 59)
(F)
Lawsonite Albite
(n = 82)
(G)
Relative Probability
Cumulative Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
600
900
1200
1500
1800
2100
2400
2700
3000
amphibolite
epidote amphibolite
epidote blueschist
lawsonite blueschist
actinolite albite
lawsonite albite
Detrital Zircon U-Pb Age (Ma)

Figure 4



(A)
Amphibolite
Lu-Hf garnet
U-Pb sphene
Ar-Ar Hornblende
Ar-Ar Phengite
maximum depositional age
(B)
Epidote Amphibolite
maximum depositional age
(C)
Epidote Blueschist
maximum depositional age
(D)
Lawsonite Blueschist
maximum depositional age
(E)
Actinolite Albite
maximum depositional age
(F)
Lawsonite Albite
maximum depositional age
?
Temperature (°C)
Time (Ma)
0
200
400
600
800
50
60
70
80
90
100
110
120
130
140
150

Figure 5



(A)
Santa Ana-San Diego
Mahoney et al. (2005)
Late Cretaceous
El Rosario Embayment
Mahoney et al. (2005)
Late Cretaceous
Vizcaino Peninsula
Mahoney et al. (2005)
Early Cretaceous
Late Cretaceous
Catalina Schist
This study
Lawsonite blueschist
& lower grade
(B)
Pelona & related schists
Grove et al. (2003)
San Emigdio Mnts.
Santa Ana Mnts.
Mahoney et al. (2005)
Trabuco Fm.
Catalina Schist
This Study
Lawsonite blueschist
& lower grade
Cummulative Probability
Zircon U-Pb Age (Ma)
0
20
40
60
80
100
0
50
100
150
200
250
300

Figure 6

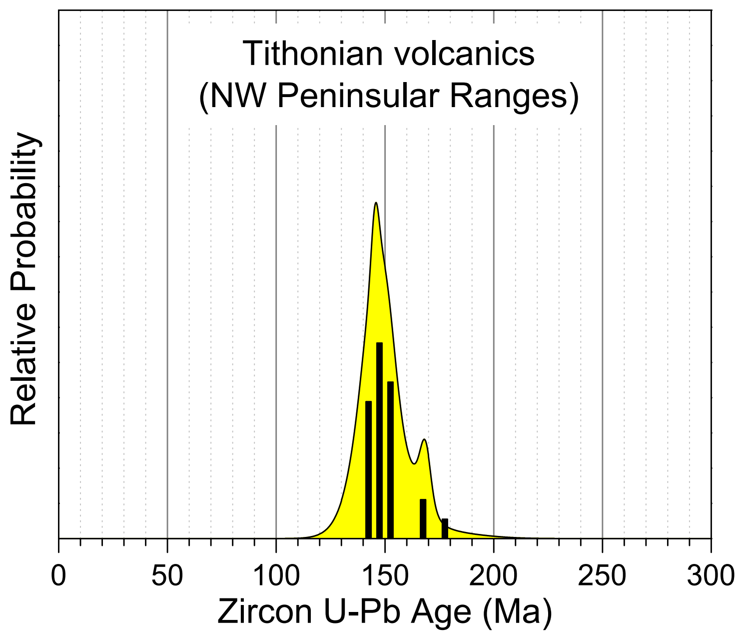
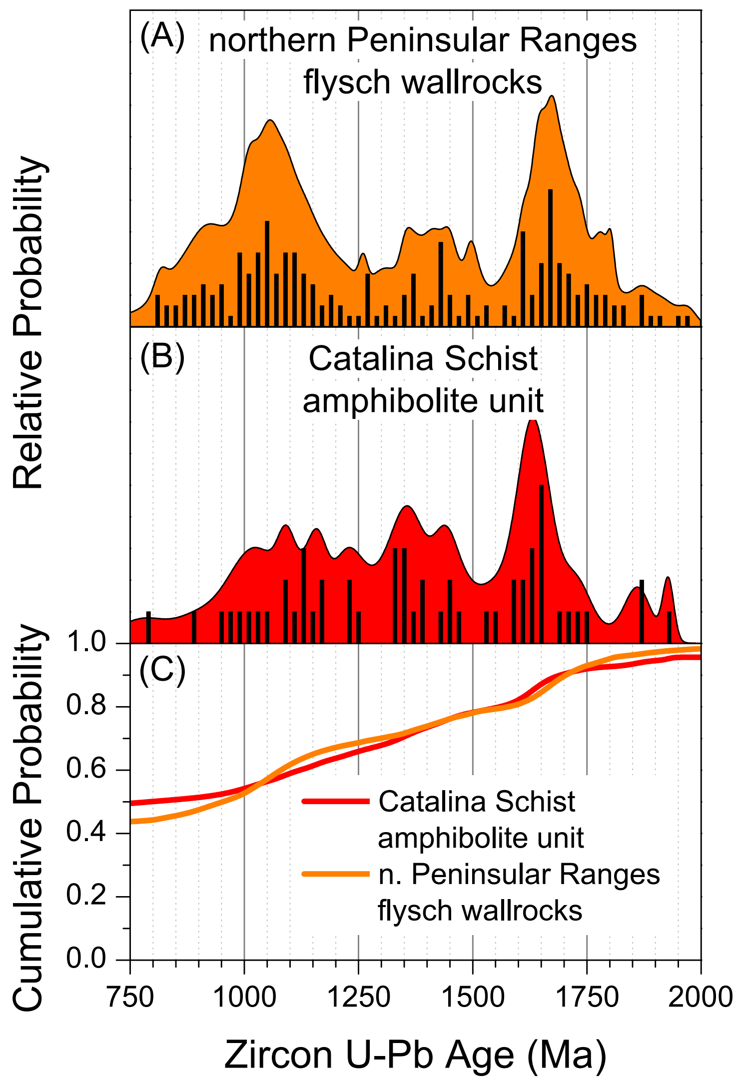
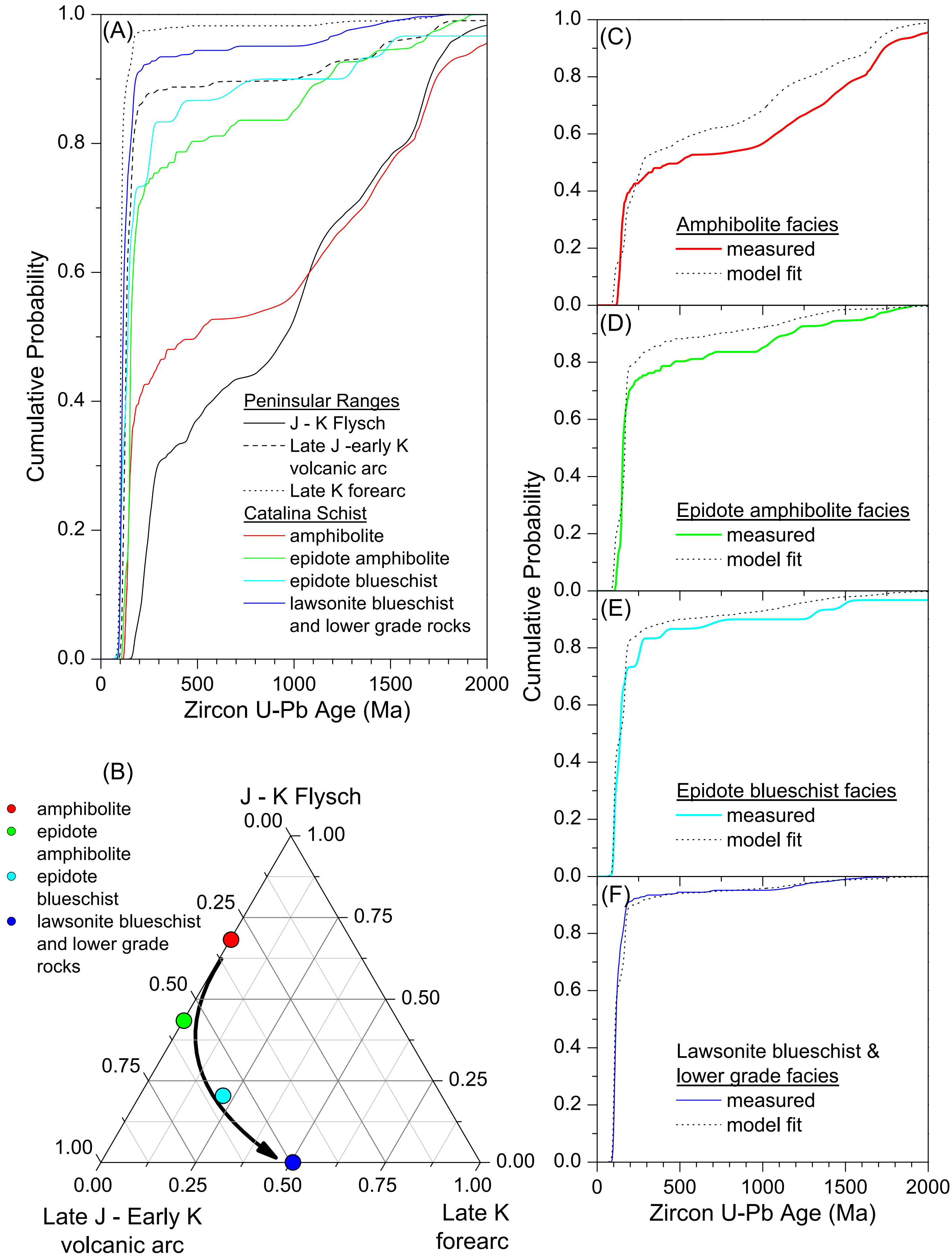

Tithonian volcanics
(NW Peninsular Ranges)
Relative Probability
0
50
100
150
200
250
300
Zircon U-Pb Age (Ma)

Figure 7



(A) northern Peninsular Ranges flysch wallrocks
(B) Catalina Schist amphibolite unit
(C)
Relative Probability
Cumulative Probability
1.0
0.8
0.6
0.4
0.2
0.0
750
1000
1250
1500
1750
2000
Zircon U-Pb Age (Ma)
Catalina Schist amphibolite unit
n. Peninsular Ranges flysch wallrocks

Figure 8



(A)
Cumulative Probability
Zircon U-Pb Age (Ma)
Peninsular Ranges
J - K Flysch
Late J -early K volcanic arc
Late K forearc
Catalina Schist
amphibolite
epidote amphibolite
epidote blueschist
lawsonite blueschist and lower grade rocks
(B)
J - K Flysch
Late J - Early K volcanic arc
Late K forearc
amphibolite
epidote amphibolite
epidote blueschist
lawsonite blueschist and lower grade rocks
(C)
Amphibolite facies
measured
model fit
(D)
Epidote amphibolite facies
measured
model fit
(E)
Epidote blueschist facies
measured
model fit
(F)
Lawsonite blueschist & lower grade facies
measured
model fit

Figure 9

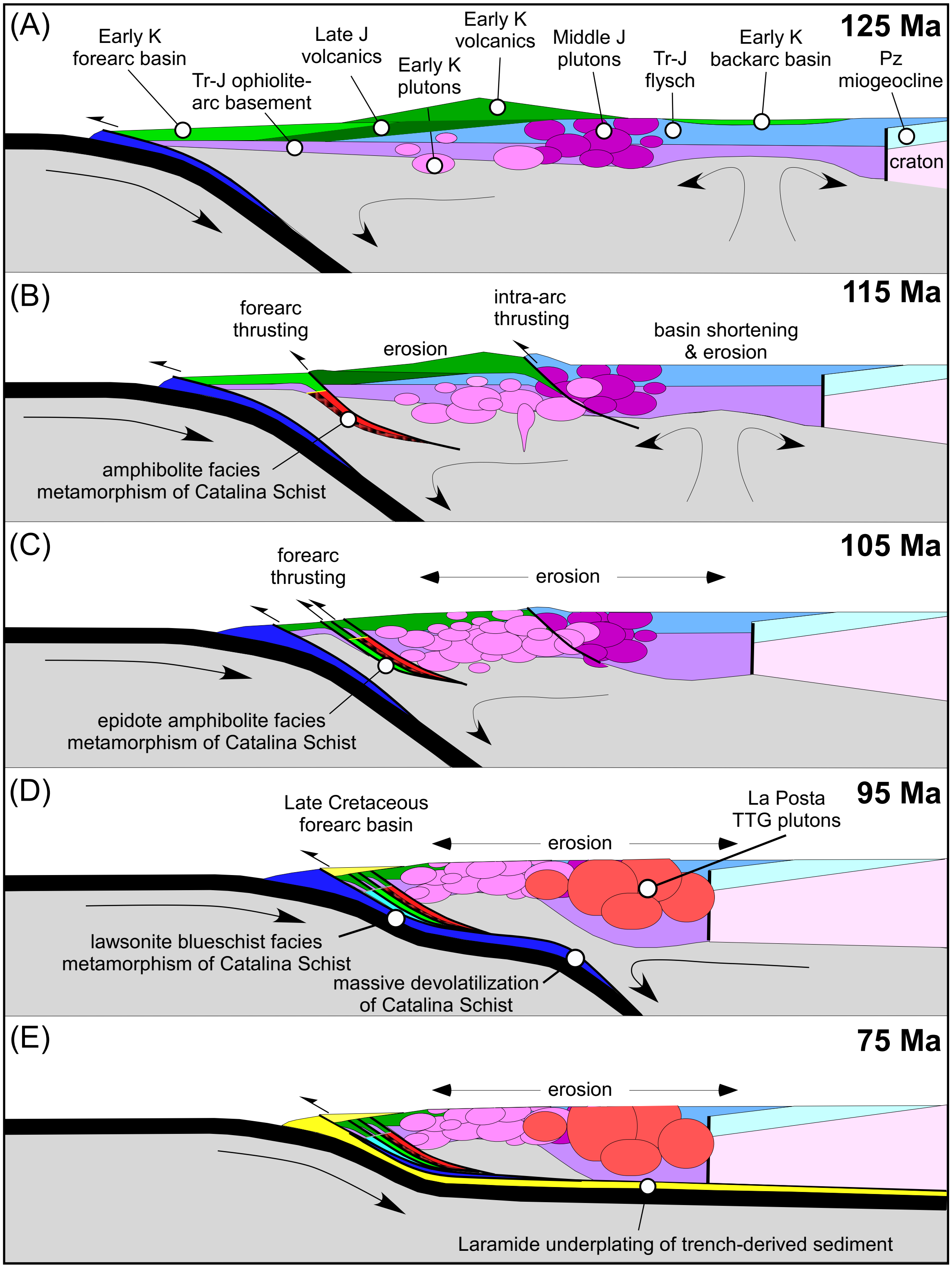

(A)
125 Ma
Early K
forearc basin
Tr-J ophiolite-
arc basement
Late J
volcanics
Early K
plutons
Early K
volcanics
Middle J
plutons
Tr-J
flysch
Early K
backarc basin
Pz
miogeocline
craton
(B)
115 Ma
forearc
thrusting
erosion
intra-arc
thrusting
basin shortening
& erosion
amphibolite facies
metamorphism of Catalina Schist
(C)
105 Ma
forearc
thrusting
erosion
epidote amphibolite facies
metamorphism of Catalina Schist
(D)
95 Ma
Late Cretaceous
forearc basin
erosion
La Posta
TTG plutons
lawsonite blueschist facies
metamorphism of Catalina Schist
massive devolatilization
of Catalina Schist
(E)
75 Ma
erosion
Laramide underplating of trench-derived sediment

Figure 10