Forearc-basin sedimentary response to rapid Late Cretaceous batholith emplacement in the Peninsular Ranges of southern and Baja California

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ABSTRACT

The eastern Peninsular Ranges batholith is dominated by voluminous La Posta–type tonalite-granodiorite intrusions that compose half of the magmatic arc at present erosion level. Zircon U-Pb and hornblende $^{40}Ar/^{39}Ar$ results from these intrusions indicate that they were emplaced in a remarkably narrow interval (99–92 Ma) that closely followed cessation of west-directed compression of the arc system. Emplacement of the La Posta suite coincided with a major pulse of coarse-grained sediment into the adjacent forearc basin in early Cenomanian to middle Turonian time. Paleontologic control, and plutonic age and detrital zircon U-Pb data demonstrate the virtual absence of a time lag between magma emplacement and sedimentary response. The tight linkage between magmatism, arc exhumation, and sediment delivery to the forearc indicates that development of major erosional topography in the arc was driven by thermal and mechanical effects associated with large-volume batholith emplacement.

Keywords: forearc basin, batholith, Peninsular Ranges, geochronology.

INTRODUCTION

The emplacement of continental-margin batholiths is an important mechanism of crustal growth. However, the dynamic link between the timing and magnitude of magma addition to the middle and lower crust and upper crustal responses such as uplift, erosion, and sedimentation is not well understood. Intrusion of continental-margin batholiths can trigger vertical crustal displacements, leading to large-magnitude uplift and erosion of the magmatic arc as well as basin subsidence and sediment accumulation in adjacent marginal basins (e.g., Renne et al., 1993; House et al., 1998). The Cretaceous Peninsular Ranges batholith of southern and Baja California and adjacent forearc basin strata in the Vizcaino Peninsula region of Baja California present an excellent example of the dynamic link between large-volume batholith emplacement, arc denudation, and forearc basin sedimentary response. An intriguing aspect of this process is the virtual absence of a time lag between batholith emplacement and rapid basin infilling. This paper documents the synchronicity of these events and provides insight into the middle to upper crustal response to large-volume magma emplacement along continental margins.

PENINSULAR RANGES BATHOLITH

The ~800-km-long Peninsular Ranges batholith has axially distinct western and eastern zones based on age, petrology, style and depth of emplacement, prebatholithic wall rock, and geophysical parameters (Gastil, 1975; Gromet and Silver, 1987; Silver and Chappell, 1988; Fig. 1[1]). Western intrusions are older (ca. 140–105 Ma), range from gabbro to monzogranite, have relatively primitive island-arc geochemical affinities, and are variably overprinted by subsolidus ductile deformation. These plutons occur as relatively small sheet and diapirs that were shallowly emplaced into the Early Cretaceous supracrustal volcanic and sedimentary sequence.

In contrast, the eastern Peninsular Ranges batholith is dominated by relatively homogeneous tonalite and low-K granodiorite emplaced as a series of large nested intrusive centers and smaller isolated intrusions referred to as the La Posta suite (Silver and Chappell, 1988; Walawender et al., 1990). The intrusions contain metaluminous hornblende-bearing tonalite margins and weakly peraluminous low-K granodiorite cores containing inherited zircon. The overall assemblage is remarkably similar in composition to tonalite-trondhjemite-granodiorite gneiss terranes that compose a major component of Archean continental crust (Kimbrough et al., 1998).

The La Posta suite composes ~47% of the total surface exposure of plutonic rocks within the 800-km-long batholith. U-Pb zircon data indicate that most of these intrusions were emplaced in a surprisingly brief interval (99–92 Ma; Fig. 1). Additional $^{40}Ar/^{39}Ar$ ages from hornblende define a slightly younger age range than the U-Pb zircon data, consistent with the lower closure temperatures, and further support a narrow range of emplacement ages for the La Posta bodies. The enormous outcrop area (15 000 km^2) and the narrow emplacement interval for the La Posta tonalite-trondhjemite-granodiorite suite indicate unusually high magma-production rates (75–100 km^3/km/m.y.) for the Peninsular Ranges batholith from ca. 99 to 92 Ma (Silver and Chappell, 1988; Kimbrough et al., 1998). These rates are comparable to the Columbia River flood basalt province and are one to two orders of magnitude higher than those deduced by Francis and Rundle (1976) for the Coastal and Cordillera Blanca batholiths of Peru.

The western and eastern zones of the Peninsular Ranges batholith are locally juxtaposed by a series of synbatholithic west-vergent Early Cretaceous ductile thrust faults that separate rocks with contrasting metamorphic grade and deformational history (Johnson et al., 1999; Fig. 1). In the Sierra San Pedro Matir region, these west-vergent contractional structures form the western flank of an ~20-km-wide doubly vergent fan structure

[1]GSA Data Repository item 2001052, Hornblende $^{40}Ar/^{39}Ar$ results, zircon U-Pb data, SHRIMP U-Pb data, and paleontology data used to construct figures, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, Colorado 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

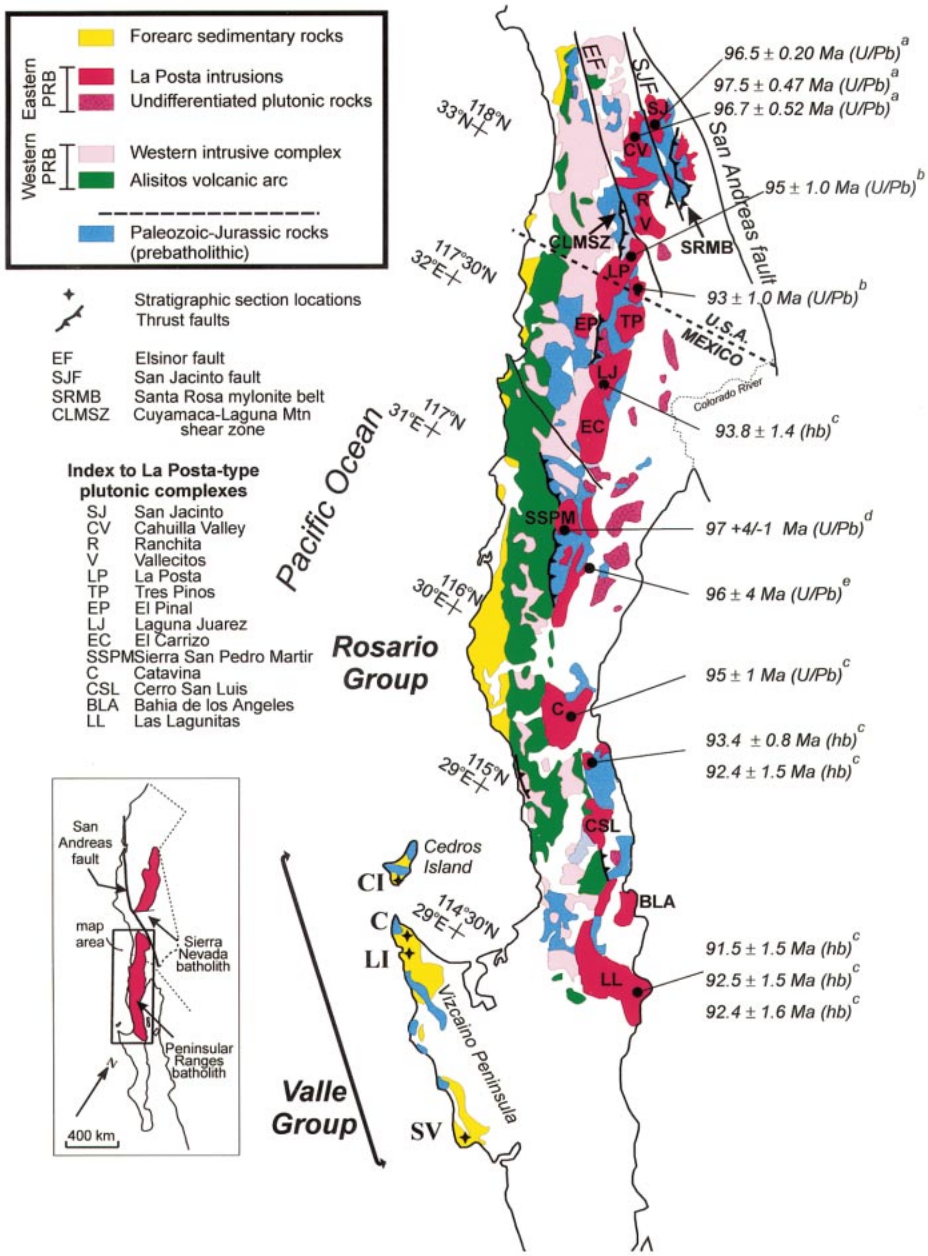

Figure 1. Schematic geologic map of Peninsular Ranges batholith (PRB) and adjacent forearc sedimentary strata modified principally from Gastil et al. (1975) and Krummenacher et al. (1975). U-Pb zircon (U/Pb) and $^{40}Ar/^{39}Ar$ hornblende (hb) ages for La Posta suite intrusions are summarized from a—Premo et al. (1998); b—Walawender et al. (1990); c—GSA Data Repository (see text footnote 1); d—Ortega-Rivera et al. (1997); e—Measures (1996). Surface exposure of 99–92 Ma La Posta–type plutons accounts for half of batholith at present erosion level. Distribution of Vizcaino–Cedros Valle Group stratigraphic columns in Figure 2 are indicated.

(Schmidt et al., 1999). This fan-like structure appears to be a through-going element in the Baja California segment of the Peninsular Ranges batholith. Contemporaneous crustal shortening is recorded to the west of the thrust belt by shallow-level kilometer-scale upright to west-vergent folds and related axial-plane faults in supracrustal volcanic and sedimentary rocks (Fig. 1; Gastil et al., 1975). Synbatholithic crustal shortening occurred from ca. 115 to 108 Ma in the Sierra San Pedro Martir region (Johnson et al., 1999) and from 118 to 105 Ma north of the border (Todd et al., 1988; Thomson and Girty, 1994).

La Posta–type plutons postdate this Early Cretaceous episode of contractional deformation. They are intruded across the fan-like structure in the east-central Peninsular Ranges batholith and stitch thrust faults that separate western and eastern zone rocks. The locus of La Posta–type intrusive centers corresponds closely to the most deeply exhumed part of the Peninsular Ranges batholith. Middle to upper amphibolite facies mineral assemblages (2–6 kbar) within characteristically migmatitic wall rock indicate 5–20 km emplacement depths for Lat Posta–type plutons north of lat 30°N (Todd et al., 1988; Grove, 1993; Rothstein, 1997). South of lat 30°N, emplacement depths for La Posta–type intrusions are somewhat shallower (5–15 km), upper greenschist facies and lower amphibolite facies assemblages being more prevalent (Gastil et al., 1975; Rothstein, 1997).

Available thermochronologic data indicate that La Posta–type plutons were significantly exhumed (>10 km) immediately following emplacement (Lovera et al., 1999; Schmidt et al., 1999). Final denudation of the eastern Peninsular Ranges batholith occurred in the Late Cretaceous–early Tertiary, perhaps in response to Laramide flat subduction beneath southwestern North America (Goodwin and Renne, 1991; Grove, 1993; Schmidt et al., 1999; Lovera et al., 1999; Axen et al., 2000).

PENINSULAR RANGES FOREARC

Peninsular Ranges forearc basin strata comprise two main belts of rock, the Rosario Group and the Valle Group (Fig. 1). The Rosario Group comprises relatively thin (1–2 km) sequences of Turonian to Maastrichtian fluvial to shallow- to deep-marine strata that lap unconformably onto the eroded western flank of the batholith. The Valle Group comprises thick successions (3–12 km) of Aptian-Albian to Eocene, mainly deep-marine strata overlying Triassic to Lower Cretaceous ophiolite, backarc, and island-arc rocks (e.g., Smith and Busby, 1993). It can be divided into at least three distinct subbasins across its 200-km-long outcrop belt, including northern and southern subbasins on the Vizcaino Peninsula that are separated by a paleobasement high, and a third subbasin centered on Cedros Island (Figs. 1 and 2). Each of these subbasins contains a thick, early Cenomanian to middle Turonian coarse clastic sequence bounded above and below by thick, shale-dominated strata (Fig. 2). This impressive pulse of clastic sedimentation represents a rapid and regionally extensive progradation of coarse clastic detritus into the deep-marine portion of the forearc basin.

The thickest and most complete record of the major Cenomanian-Turonian progradation is provided by the Campito and Los Indios sections in the northern Vizcaino subbasin, where a basal 150–300-m-thick broad apron of granule to pebble conglomerate overlies basin-plain shales of the Los Chapunes Formation (Patterson, 1984). These deposits are overlain by a thick succession of sand-rich turbidites that coarsen upward into channel-

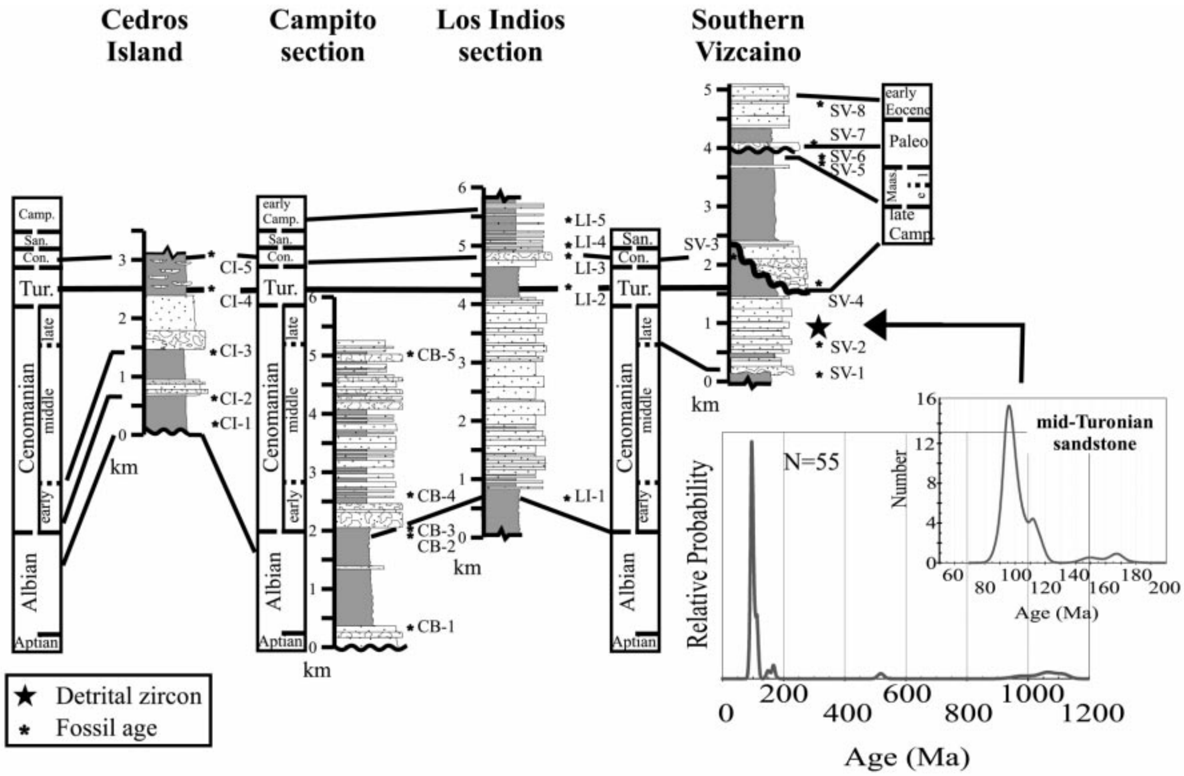

Figure 2. Stratigraphic sections of Valle Group. Graphic columns contrast shale-dominated intervals from sandstone- and conglomerate-dominated intervals. Section names refer to Cedros Island, northern (Campito and Los Indios) and southern Vizcaino subbasins; localities shown in Figure 1. Inset shows relative probability plots of detrital zircon U-Pb data. Note major unimodal peak at 96 Ma. Detrital zircon and fossil ages are available in GSA Data Repository (see text footnote 1).

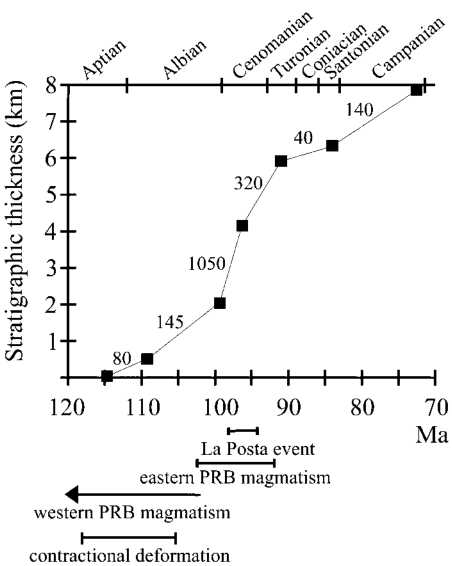

Figure 3. Stratigraphic thickness versus time for Valle Group, northern Vizcaino Peninsula, in relation to structural and magmatic events in source region. Numbers refer to stratigraphic accumulation rates (in m/m.y.). Note thick coarse-grained interval of Valle Group deposited from ca. 99 to 92 Ma, coincident with emplacement and unroofing of La Posta suite. PRB is Peninsular Ranges batholith.

ized sandstone and conglomerate deposited in an inner-fan valley or deep submarine fan. The average grain size in Campito section conglomerates increases upward and reaches a maximum in the middle Cenomanian. The coarsest interval contains numerous boulder beds (maximum clast size of 2.5 m), which we interpret as having been deposited within a steep-gradient inner-fan channel. This observation indicates that the fan apex had prograded into the basin axis by middle Cenomanian time.

The Cenomanian-Turonian clastic influx in the Los Indios section is recorded in the progradation of >3 km of medium- to thick-bedded sand-rich turbidites over underlying slope deposits. Progradation of coarse-grained sandstone and conglomerate into the Cedros Island subbasin was coincident with the initiation of extensional deformation. Shallow crustal attenuation is linked to concomitant uplift of blueschist-grade metamorphic rocks (Smith and Busby, 1993).

The tight link between denudation of La Posta–type intrusions in the magmatic arc and rapid cycling of sediment into the forearc basin is highlighted by U-Pb detrital zircon ages from a Turonian biotite-rich quartzofeldspathic sandstone from the southern Vizcaino section (Fig. 2). The depositional age is tightly defined as 92–91 Ma by the presence of both the middle Turonian ammonite index species *Collignoniceras Woolgarii* in overlying strata and Turonian foraminifera in underlying strata. The sample is dominated by 100–90 Ma grains (30 of 55), as reflected by the single dominant peak ca. 96 Ma in the cumulative probability plot in Figure 2. Note that 15 of the grains overlap the depositional age within analytical uncertainty. Such rapid cycling of sediment into the forearc basin is also required by detrital K-feldspar results from forearc strata of similar age from the northern Peninsular Ranges batholith (Lovera et al., 1999).

DISCUSSION

The enormous influx of Cenomanian to early Turonian coarse-grained sediment containing La Posta age plutonic debris into the forearc basin indicates that significant uplift and erosion of the Peninsular Ranges batholith was virtually synchronous with massive intrusion of the eastern batholith at this time (Fig. 3). Rapid unroofing rates are required to generate high-gradient sediment-transport systems capable of delivering abundant meter-sized boulders and great volumes of sand and gravel to the deep-marine axis of the basin. Our stratigraphic results indicate that high relief and steep gradients must have persisted for at least 5 m.y. Sustained Cenomanian to early Turonian denudation at mean rates of 1.0 km/m.y. is also evident in the northern Peninsular Ranges batholith (Lovera et al., 1999), clearly indicating that magmatic inflation of the batholith at 99–92 Ma was strongly coupled with arc exhumation and sediment delivery to the forearc. The middle Turonian condensed-section marker bed (Fig. 2) closely corresponds to a peak sea-level highstand, one of the highest in the Phanerozoic and widely recognized in the Western Interior Seaway (e.g., Kauffman and Caldwell, 1993). The coincidence of the Cenomanian to middle Turonian sediment pulse with a first-order sea-level maximum underscores the importance of tectonically driven erosional topography in the Peninsular Ranges magmatic arc.

The existence of a causal relationship between the major clastic sediment pulse in the Pensinsular Ranges batholith forearc and emplacement of large-volume tonalite-granodiorite batholiths in the eastern Peninsular Ranges batholith was first proposed by Gastil (1975). Busby et al. (1998) related the rapid influx of coarse-grained sediment into the basin to an accelerated compressional-strain regime ca. 105–95 Ma that generated high-standing erosional topography in the arc. Although west-directed contractional deformation of the batholith may have driven initial subsidence of the forearc system, we consider it unlikely that crustal shortening alone is responsible for the dramatic deep-water sediment pulse recorded in the Vizcaino basin during Cenomanian-Turonian time. Widely distributed contractional deformation in the Peninsular Ranges was largely complete by ca. 105 Ma and therefore predated the Cenomanian-Turonian basin-infilling event by ~5–10 m.y. Moreover, there is no evidence to suggest that large-scale shortening accompanied emplacement of La Posta–type intrusions. The undeformed character of La Posta bodies suggests that the stress regime across the arc during emplacement of La Posta suite magmas was neutral or perhaps extensional (Thompson and Girty, 1994), to accommodate the rapidly added volume of new crust.

Is continental growth via arc magmatism a gradual process, or is it intermittent? High magma-flux rates associated with the tonalite-trondhjemite-granodiorite La Posta–type batholiths suggest that, at least in Phanerozoic continental-margin batholiths, intermittent nonsteady-state processes may have played a profound role. The high flux rate associated with La Posta tonalite-trondhjemite-granodiorite magmatism produced buoyant silicic crust, potentially >20 km in thickness, over a 5 m.y. interval, indicating a transient episode in which energy and mass transfer within the arc operated at dramatically different scales than during normal steady-state subduction-zone magmatism. Thermal and mechanical gradients associated with large-volume magma emplacement created gravitational and tectonic stresses in the upper crust that appear to have controlled arc denudation and forearc-basin sedimentation independent of stresses associated with adjacent plate interactions. The development of continental arc systems clearly results from the complex interplay between tectonics, magma emplacement, various uplift mechanisms, and climate. The Peninsular Ranges forearc basin, however, may represent an end-member example in which erosional topography was driven primarily by large-volume magma emplacement.

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REFERENCES CITED

Axen, G.J., Grove, M., Stockli, D., Lovera, O.M., Rothstein, D.A., Fletcher, J.M., Farley, K., and Abbott, P.L., 2000, Thermal evolution of Monte Blanco Dome; low-angle normal faulting during Gulf of California rifting and late Eocene denudation of the eastern Peninsular Ranges: Tectonics, v. 19, p. 197–212.

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

Francis, P.W., and Rundle, C.C., 1976, Rates of production of the main magma types in the central Andes: Geological Society of America Bulletin, v. 87, p. 474–480.

Gastil, R.G., 1975, Plutonic zones in the Peninsular Ranges of southern California and northern Baja California: Geology, v. 3, p. 361–363.

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.

Goodwin, L.B., and Renne, P.R., 1991, Effects of progressive mylonitization on Ar retention in biotites from the Santa Rosa mylonite zone, California, and thermochronologic implications: Contributions to Mineralogy and Petrology, v. 108, p. 283–297.

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, v. 28, p. 77–125.

Grove, M., 1993, Thermal histories of southern California basement terranes [Ph.D. thesis]: Los Angeles, University of California, 419 p.

House, M.A., Wernicke, B.P., and Farley, K.A., 1998, Dating topography of the Sierra Nevada, California, using apatite (U-Th)/He ages: Nature, v. 396, p. 66–69.

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.

Kauffman, E.G., and Caldwell, W.G.E., 1993, The Western Interior basin in space and time, *in* Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin: Geological Association of Canada Special Paper 39, p. 297–434.

Kimbrough, D.L., Gastil, R.G., and Magistrale, H., 1998, Enormous Late Cretaceous magma flux associated with TTG batholith emplacement: Eastern Peninsular Ranges batholith of southern and Baja California: Geological Society of America Abstracts with Programs, v. 30, no. 7, p. A-258.

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, v. 86, p. 760–768.

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, v. 104, p. 29 419–29 438.

Measures, M.A., 1996, Geology of the Agua Caliente region, southeast Sierra San Pedro Martir, Baja California, Mexico [M.S. thesis]: San Diego, California, San Diego State University, 105 p.

Ortega-Rivera, A., Farrar, E., Hanes, J.A., Archibald, D.A., Gastil, R.G., Kimbrough, D.L., Zentilli, M., Lopez Martinez, M., Feraud, G., and Ruffet, G., 1997, Chronological constraints on the thermal and tilting history of the Sierra San Pedro Martir pluton, Baja California, Mexico, from U/Pb, $^{40}Ar/^{39}Ar$, and fission-track geochronology: Geological Society of America Bulletin, v. 109, p. 728–745.

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, v. 39, p. 161–172.

Premo, W., Morton, D.M., Snee, L., Naeser, N.D., and Fanning, C.M., 1998, Isotopic ages, cooling histories, and magmatic origins for Mesozoic tonalitic plutons from the N. Peninsular Ranges batholith, S. California: Geological Society of America Abstracts with Programs, v. 30, no. 5, p. 59–60.

Renne, P.R., Tobisch, O.T., and Saleeby, J.B., 1993, Thermochronologic record of pluton emplacement, deformation, and exhumation at Courtright shear zone, central Sierra Nevada, California: Geology, v. 21, p. 331–334.

Rothstein, D.A., 1997, Metamorphism and denudation of the eastern Peninsular Ranges batholith, Baja California Norte, Mexico [Ph.D. thesis]: Los Angeles, University of California, 445 p.

Schmidt, K.L., Paterson, S.R., and Blythe, A.E., 1999, Linked but temporally distinct episodes of tectonism, magmatism, and exhumation in the Cretaceous Peninsular Ranges: Geological Society of America Abstracts with Programs, v. 31, no. 7, p. A-482.

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

Smith, D.P., and Busby, C.J., 1993, Mid-Cretaceous crust extension recorded in deep-marine half-graben fill, Cedros Island, Mexico: Geological Society of America Bulletin, v. 105, p. 547–562.

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: Englewood Cliffs, New Jersey, Prentice Hall, p. 894–937.

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.

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