New geologic mapping and SHRIMP U-Pb zircon data in the Peninsular Ranges batholith, Baja California, Mexico: Evidence for a suture?

Scott E. Johnson
Department of Earth and Planetary Sciences, Macquarie University, Sydney, New South Wales 2109, Australia

Marcus C. Tate
Department of Earth and Planetary Sciences, Macquarie University, Sydney, New South Wales 2109, Australia

C. Mark Fanning
Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

ABSTRACT
Geologic and SHRIMP U-Pb zircon studies in the Sierra San Pedro Mártir area of northern Baja California, Mexico, suggest that the western and eastern parts of the Peninsular Ranges batholith originated as separate arcs. They are now juxtaposed along a well-exposed ductile thrust (Main Mártir thrust) marked by an age discontinuity of at least 10 to 15 m.y., and sharp changes in rock type, metamorphic grade, and deformation history. The east-dipping thrust, and adjacent highly deformed rocks, were stitched by 108–97 Ma plutons that were generated in a region of crustal thickening formed during juxtaposition of the two arcs. Lack of chemical, isotopic, and geologic evidence for continentally derived rocks in the western arc may preclude an origin by rifting of the continental margin, or development of the arc on a prism of continentally derived sediments adjacent to the continental margin. Instead, the western arc may have originated as an island arc above a subduction zone outboard of North America. If so, a second, concurrent subduction zone along the North American margin must have driven convergence and suturing of the two arcs, and the Main Mártir thrust may mark a nonterminal suture within a wider convergence-related deformation zone that formed ca. 115–108 Ma.

INTRODUCTION AND GEOLOGIC SETTING
The Jurassic to Cretaceous Peninsular Ranges batholith (Fig. 1) contains one of the world’s best-preserved, most completely exposed, and readily accessed transitions between adjacent island (western) and continental-margin (eastern) arcs. A boundary of variable width between western and eastern parts of the batholith is known from geologic, petrological, geochemical, and isotopic gradients or discontinuities along its northern 900 km (e.g., Gastil et al., 1975; Todd et al., 1988; Silver and Chappell, 1988; Gastil, 1993). Although interpretations vary, most workers previously considered the boundary to be a suture between North America and a fringing arc, the two originally separated by a backarc extensional basin (Gastil et al., 1978, 1981; Rangin, 1978; Phillips, 1993; Busby et al., 1998) or a basin of unspecified origin (Todd et al., 1988; Griffith and Hoobs, 1993). Alternatively, Walawender et al. (1991) and Thompson and Girty (1994) suggested that the batholith may have formed in situ across a poorly understood, pre-Triassic boundary between oceanic and continental crust. The boundary between the eastern and western parts of the batholith is well exposed northwest of the Sierra San Pedro Mártir pluton (Fig. 1), where it is expressed as an east-dipping ductile thrust (Main Mártir thrust) that juxtaposes rocks of different age, type, metamorphic grade, and deformation history. In this paper we present geologic mapping and SHRIMP (sensitive high-resolution ion microprobe) U-Pb zircon ages that provide new constraints on the age and origin of this structure (Fig. 1). On the basis of work in this area, we suggest that the thrust may mark a nonterminal suture (Dewey, 1977) within a broad deformation zone that formed during collision of the western island arc with North America ca. 115–108 Ma.

NEW MAPPING AND SHRIMP U-Pb ZIRCON AGES
Figure 1 shows the current results of an ongoing mapping, geochemical, and SHRIMP geochronological program in the Sierra San Pedro Mártir region of Baja California. On the basis of this work we outline the following key observations and relationships.

1. Prebatholithic rocks in the southwest half of the study area (Fig. 1) form part of the Early Cretaceous Alisitos Formation (Allison, 1974; Gastil et al., 1975). Volcanogenic rocks of unknown age in the southwest (yellow in Fig. 1) are dominated by pyroclastic deposits, volcanic flows and breccias, and volcaniclastic rocks, all of which underwent lower greenschist facies regional metamorphism. Marine volcano-sedimentary basinal assemblages to the east (pale blue in Fig. 1) contain similar rocks, in addition to reef limestones and calc-silicate and argillitic rocks. Metamorphic conditions vary from lower greenschist facies in the west to upper greenschist facies or lower amphibolite facies in the east, adjacent to the Main Mártir thrust. Silver et al. (1963) found Albian fossils in the study area (Fig. 1), and demonstrated that these volcano-sedimentary rocks are directly along strike of the late Aptian to early Albian type section at Punta China, 100 km to the northwest.

2. Prebatholithic rocks in the northeast third of the study area (green in Fig. 1) are separated from the Alisitos Formation by the Main Mártir thrust, and include volcanic, volcaniclastic, tuffaceous, calc-silicate, quartzo-feldspathic, and sillimanite-bearing pelitic rocks, all of which have been metamorphosed to at least upper amphibolite facies with locally abundant migmatite. On the basis of fossils in the Alisitos Formation, and SHRIMP...
U-Pb zircon ages (Fig. 1), these rocks predate the Alisitos Formation by at least 10–15 m.y. These older rocks have been intruded by variably deformed sheets and plutons of Early Cretaceous age (ca. 127–135 Ma), and we suggest that they all formed part of a continental arc on the margin of North America that was active from at least 140 Ma.

3. A strong eastward-increasing deformation gradient occurs across the study area. Westernmost volcanogenic rocks of the Alisitos Formation are gently folded, and regional tectonic foliations are rare. Deformation intensity increases markedly within 200 m of the contact between the two major packages of the Alisitos Formation, which is marked as an east-dipping contractional fault in Figure 1. Volcanic rocks on the west side of the contact show abundant brittle shears with associated folds, whereas marbles locally present on the east side show annealed mylonitic microstructures. This faulted contact continues south of the Sierra San Pedro Mártir pluton, and is apparently continuous with the Rosarito fault described by Schmidt (1996). From west to east in the volcano-sedimentary rocks (pale blue in Fig. 1), fold axes rotate progressively from gently plunging to down-dip. Deformation within and east of the Main Mártir thrust was intense and resulted in widespread mylonites showing consistent east over west shear sense. Only one phase of regional ductile deformation and folding has been recognized in the Alisitos Formation, whereas the older rocks east of the thrust contain folded foliations and lineations, indicating that they had a more complex deformation history.

4. The two major subdivisions of the Alisitos Formation host different types of intrusive rocks. In the southwest, recently recognized magmatic ring complexes contain gabbro, mafic core sheets, and tonalite that weathers pink (Johnson et al., 1999; Tate et al., 1999). The tonalite probably formed in situ by mixing of low-pressure (~2.3 kbar) andesite fractionates and trondhjemitic partial melts derived from the contact aureole (Tate et al., 1999). In the volcano-sedimentary rocks (pale blue in Fig. 1), homogeneous intrusions of hornblende-biotite tonalite that weathers white are associated with bodies containing variable amounts of gabbro, diorite, and tonalite. The white-weathered tonalites also intrude the Main Mártir thrust (e.g., the Cerro de Costilla complex in Fig. 1), as well as metavolcanic, metasedimentary, and metamylonitic rocks east of it. These tonalites are younger than those associated with the ring complexes to the west, and our preliminary modeling suggests that they may have formed at source-region pressures of ~10 kbar by mixing of andesite fractionation products with batch melts of garnet-bearing amphibolites. Although they occurred at deeper crustal levels, these fractionation and mixing processes closely resembled those involved with the ring-complex tonalites.

In summary, the relationships described here and shown in Figure 1 indicate that age, lithological, deformational, and metamorphic discontinuities occur across the Main Mártir thrust. This structure corresponds to the boundary between the western and eastern prebatholithic rocks in this area, as originally proposed by Gastil et al. (1975). The thrust and adjacent highly deformed rocks were stitched by a distinctive phase of tonalite plutons and gabbro-bearing intrusive complexes that have chemical and isotopic affinities with the western part of the batholith.

TECTONIC EVOLUTION

We propose the following history (Fig. 2) for development and stitching of the boundary between the western and eastern parts of the batholith, as exposed in the study area (Fig. 1).

1. Voluminous Early Cretaceous orthogneisses, sheeted intrusions, and plutons that intrude volcanogenic rocks east of the Main Mártir thrust suggest that an east-facing subduction zone and related magmatic arc were active along the continental margin. Our SHRIMP U-Pb zircon data in these Early Cretaceous intrusive rocks indicate possible inheritance that may be as old as 180 Ma (see footnote 1), and when combined with ages reported by Thompson and Girty (1994) they suggest that magmatism in the eastern arc may date to Late Triassic or Early Jurassic. Our SHRIMP data indicate that the eastern arc was active until ca. 127 Ma. Although they must be taken as a preliminary data set, these various age determinations may indicate that the continental-margin arc was active for at least ~60–80 m.y. prior to being intruded by the mid-Cretaceous stitching plutons.

2. The Alisitos island arc was probably established ca. 140 Ma (Silver and Chappell, 1988) above an east- or west-facing subduction zone (Fig. 2A). The volcano-sedimentary part of the Alisitos Formation (pale blue in Fig. 1) accumulated in a deep- to shallow-marine basin on the eastern flanks of the subaerial Alisitos arc. In the area of Figure 1, no quartz, granodiorite, or metamorphic clasts have been found in these rocks (Silver et al., 1963). Thus, although it seems probable that the basin received some arc-derived detritus from the continental margin, there is no published evidence in the study area for continuously derived material.

3. Between ca. 115 and 108 Ma, the basin between the island arc and continental margin closed (Fig. 2B), and the two arcs were juxtaposed along the Main Mártir thrust, which shows characteristics of a nonterminal suture zone (Dewey, 1977). Suturing and the main phase of related deformation were largely completed by ca. 108 Ma in the study area, as indicated by the age of the San José pluton, which postdates much or most of the regional tight folding of the Alisitos Formation. Intrusion of the Main Mártir thrust by the Cerro de Costilla complex (Fig. 1) and lack of evidence for post-intrusion deformation within and around the complex indicate that the thrust was inactive by ca. 103 Ma.

4. We speculate that crustal thickening during collision placed lower crustal garnet-bearing amphibolites at appropriate depths for partial melting, and that these partial melts mixed at depth with andesite fractionates to form the stitching tonalites, which then ascended and were emplaced at middle to upper crustal levels. Late in this phase of plutonism, oceanic and continental sources were both available for magma generation along a linear belt parallel to, and just east of, the Main Mártir thrust. The combination of these two sources resulted in the voluminous Sierra San Pedro Mártir pluton and other La Posta-type plutons that thoroughly stitched the suture over a distance of ~900 km (Walawender et al., 1990; Kimbrough and Gastil, 1997).

5. Considerable displacement along the Main Mártir thrust, combined with substantial ductile shortening over a wide area, was followed by rapid denudation east of the thrust. This denudation exposed metamorphic rocks that equilibrated at pressures of as much as 5.5 kbar (Rothstein, 1997), and led to abundant plutonic and metamorphic clasts in Cenomanian to middle Turonian conglomerates on the western margin of the peninsula (e.g., Busby et al., 1998; Kimbrough et al., 1998).

DISCUSSION

The tectonic model outlined herein requires the Alisitos arc to initiate outboard of the North American margin, which is consistent with published chemical and isotopic data from the batholith that show no compelling evidence for a continental component in western arc intrusions (e.g., Silver and Chappell, 1988; Tate et al., 1999). Our determinations show that western belt plutons (e.g., San José and Potrero) and ring complexes (e.g., Burro and Zarza) always have 87Sr/86Sr ≤ 0.7040, and εNd ≥ +3.7, and no inherited zircon ages have been found in these bodies. The lack of evidence for a continental component in western arc intrusions may conflict with previous models that generate the western arc by backarc rifting of the continental margin (e.g., Gastil et al., 1978, 1981; Busby et al., 1998), because they require that basement of the western arc be partly or entirely composed of continentally derived rocks.

Although a suture zone was proposed in the southern California part of the batholith by Todd et al. (1988), there is apparently no equivalent structure to the Main Mártir thrust that separates island-arc volcanic rocks in the west from continentally derived rocks in the east. In alternative models, Walawender et al. (1991) and Thompson and Girty (1994) proposed that the Cretaceous batholith developed in situ over a poorly understood, pre-Triassic boundary between oceanic and continental crust. Walawender et al. (1991) suggested that a single subduction zone outboard of the continental margin caused the western arc to develop on oceanic crust, and SHAWLING...
Variable gabbro, diorite and tonalite; some hypabyssal hornblende-biotite tonalite.

Probable magmatic ring complexes and calderas.

Mafic cone-sheet assemblages.

Trend lines of bedding in Alisitos Fm., and bedding or foliation east of Alisitos Fm.

K-feldspar-bearing granitoids.

Alisitos Fm.; volcanic and volcaniclastic rocks.

Calc-silicate, volcaniclastic and sedimentary rocks, tuffs, migmatic, orthogneisses, sheeted intrusions, mylonites.

Orthogneiss, 133.9 ± 1.5 Ma

Orthogneiss, 127.8 ± 1.6 Ma

Orthogneiss, 102.5 ± 1.6 Ma

Sierra San Pedro Mártir pluton, 87 ± 4/-1 Ma (TIMS)

Potrero pluton, 102.5 ± 1.6 Ma

San José pluton, 113.6 ± 1.0 Ma

Burro complex, 113.8 ± 1.0 Ma

Zarza complex

Encinosa complex, 110.4 ± 1.6 Ma

Cerro de Costilla complex, 103.0 ± 1.0 Ma

San José pluton

Main Mártir Thrust

~140-110 Ma

~115-97 Ma

Sierra San Pedro Mártir pluton is derived from both western oceanic and eastern continental sources.

Figure 1. Preliminary geologic map and accompanying cross section of 1200 km² in Sierra San Pedro Mártir area, northern Baja California, Mexico. U-Pb zircon ages were determined by using SHRIMP II machine at Research School of Earth Sciences, Australian National University, Australia. Regional map shows location of study area and extent of exposed Peninsular Ranges batholith (colored). Thermal ionization mass spectrometry (TIMS) age for Sierra San Pedro Mártir pluton is from Ortega-Rivera et al. (1997). Moho in cross section projected south from Ichinose et al. (1996).

Figure 2. Possible convergence history between western island arc and North American continental margin to form geologic relationships in Figure 1.

A: Development of Alisitos arc, possibly on older arc rocks; final phase of Alisitos Formation entered marine basin between converging island and continental arcs.

B: Arc collision, development of suture, waning of deformation, and final emplacement of plutons that stitch the suture.

Gabbros and metaluminous granitoids, some of which fed ring complexes and calderas.
of the subduction angle ca. 105 Ma caused an eastward step in the locus of magmatism resulting in the La Posta-type plutons.

Models of in situ batholith development require that the western arc was initiated, and remained, adjacent to the continental margin. Although a model of this type could potentially be applied to the study area (Fig. 1), it would need to incorporate the following observations. (1) The contact between the Alisitos Formation and continuously derived rocks is a well-exposed ductile thrust, and rocks on either side differ in age, origin, metamorphic grade, and deformation history. (2) Existing SHRIMP U-Pb zircon studies on western arc plutons show no evidence for inherited ages (this study; Tate et al., 1998; Premo et al., 1998), and therefore do not support the arc being built on a wedge of continentally derived sediments. (3) U-Pb zircon ages from various parts of the batholith suggest that the western and eastern arcs operated separately over specific time intervals, and simultaneously over others, indicating major shifts in the position, width, and type of active magmatism.

CONCLUSIONS

In the Sierra San Pedro Mártir region of Baja California, the Main Mártir thrust juxtaposes rocks of different age, type, metamorphic grade, and deformation history. We suggest that this east-dipping ductile thrust is a major structure within a broad zone of intense deformation that formed by collision of the Cretaceous Alisitos island arc with the North American continental margin ca. 115–108 Ma. The thrust and broad deformation zone were stitched by mid-Cretaceous plutons that formed in response to collision-relate crustal thickening. Geological relationships and U-Pb zircon geochronology suggest that a continental-margin arc was active prior to, and concurrent with, development of the Alisitos arc. This is consistent with a two-subduction-zone model, in which the Alisitos arc originates above a subduction zone in the Farallon plate, outboard of North America, and a second, concurrent subduction zone under the continental margin drives convergence.

ACKNOWLEDGMENTS

This work was supported by a Large Grant (A39700451) and Queen Elizabeth II Research Fellowship from the Australian Research Council, and grant 4311PT from the Consejo Nacional de Ciencia y Tecnologia of México (to Johnson). We thank P. Morgan, S. R. Paterson, K. L. Schmidt, S. E. Shaw, R. H. Vernon, and M. L. Williams for helpful reviews of the manuscript.

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Manuscript received November 17, 1998
Revised manuscript received April 26, 1999
Manuscript accepted May 5, 1999