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Mesozoic tectonic evolution of the Peninsular Ranges of southern and Baja California

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ABSTRACT

The Mesozoic evolution of the Peninsular Ranges of southern California, USA, and Baja California, México, remains a controversial aspect of Cordilleran tectonics with multiple, often mutually exclusive, models potentially viable. A fundamental reason for the lack of agreement between the proposed tectonic models is that they are based on one dimensional, arc perpendicular observations of the batholith from widely separated locations on opposite sides of the ancestral Agua Blanca fault, an active strike-slip fault with an earlier Mesozoic history. North of the ancestral Agua Blanca fault, the Late Triassic through Jurassic was characterized by deep to moderately deep marine sedimentation of continentally derived turbidite sequences of the Bedford Canyon Complex. These strata were deformed within an accretionary prism setting and were subsequently uplifted and beveled by subaerial erosion. During the Early Cretaceous the continental margin arc associated with the earlier-formed accretionary prism migrated westward and developed within and on the Bedford Canyon Complex.

South of the ancestral Agua Blanca fault Jurassic strata are only preserved locally in the central zone. During the Early Cretaceous this part of the arc subsided below sea level and became the site of turbidite sedimentation before being uplifted and dominated by the deposition of submarine sediment, succeeded by subaerial volcanics derived from the continental margin arc present in the central and eastern zones. Outboard, the Alisitos arc, developed through and on oceanic crust, began to impinge upon the continental margin in the Early Cretaceous (ca. 115 and 108 Ma). During accretion of the Alisitos arc across the Main Mártir thrust and ancestral Agua Blanca fault, the Late Triassic–Jurassic accretionary prism (correlative to the Bedford Canyon Complex) was structurally removed from between the arc and the continent by forcible subduction. If

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this model is correct, it implies that the Late Cretaceous uplift of the central zone of the Peninsular Ranges batholith, both north and south of the ancestral Agua Blanca fault, was not driven by accretion-related deformation at the trench.

Keywords: Peninsular Ranges batholith, Santiago Peak arc, Alisitos arc, Agua Blanca fault, Mesozoic, tectonics.

INTRODUCTION

The Mesozoic tectonic evolution of the Peninsular Ranges province of southern California, USA, and Baja California, México, remains a poorly constrained component of North American Cordilleran geology. Although a variety of tectonic models have been proposed, they differ in their most fundamental aspects, such as whether or not arc-continent collision occurred (e.g., Todd et al., 1988; Thomson and Girty, 1994). Differences between these models, at least in part, result from models being based on observations made in locations separated by faults that are interpreted to have been active during the Mesozoic. The presence of these faults calls into question the validity of extrapolating the findings of local, one-dimensional studies to the entire Peninsular Ranges and beyond (e.g., Dickinson and Lawton, 2001). To address some of the long-standing geologic problems associated with the Peninsular Ranges we present a compilation of multiple data sets from several widely distributed parts of the central and western Peninsular Ranges to identify along-strike variations in the character of this region and to provide better constraint to the Mesozoic tectonic evolution.

This study is an expansion of results reported in Wetmore et al. (2002). There, evidence was presented to support the conclusion that during the Early Cretaceous the western zone of the Peninsular Ranges (defined below) evolved as two distinct tectonic blocks, a continental margin arc to the north and an island arc to the south. The two arcs were ultimately joined due to the accretion of the southern island arc near the end of the Early Cretaceous. In this paper the details of the Mesozoic depositional, structural, and paleogeographical evolution of the Peninsular Ranges are discussed to fully describe, evaluate, and justify the earlier proposed model.

GEOLOGIC BACKGROUND

The geology of the Peninsular Ranges is intrinsically tied to the Peninsular Ranges batholith, which forms the core of this province. The Peninsular Ranges batholith is the southernmost segment of a chain of North American Mesozoic batholiths that extend from Alaska to the southern tip of Baja California. It is exposed from the Transverse Ranges in southern California to as far as the 28th parallel. Recent studies have also correlated the intrusives of the Los Cabos block in southernmost Baja California Sur with those of the Peninsular Ranges batholith to the north (Kimbrough et al., 2002). To the east, the Peninsular Ranges batholith is bounded by the San Andreas–Gulf of California transform-rift system. To the west, the batholith is bounded by the Continental Borderlands, a collage of Mesozoic rocks variably formed and deformed within trench, forearc, and arc tectonic settings (e.g., Sedlock et al., 1993). Paleogeographic relationships between the Continental Borderlands and the Peninsular Ranges are highly speculative due to the Mesozoic and Cenozoic history of a series of strike-slip faults within the Borderlands (e.g., Busby et al., 1998), some of which may coincide with active structures (e.g., Legg et al., 1991).

The Peninsular Ranges batholith is a world-class example of a laterally zoned batholith; it has a mafic western (outboard) zone and a felsic eastern zone. Several data sets document the existence of east-west transitions between eastern, central, and western batholith-parallel zones (Fig. 1). These data include rare earth elemental (REE) abundances (Gromet and Silver, 1987); oxygen isotopic signatures (Taylor and Silver, 1978); and Sr initial ratios and ε_{Nd} determinations from plutonic rocks (DePaolo, 1981). In addition, the Fe-Ti oxide mineralogy of the batholith exhibits an east-west transition where plutons of the western zone contain magnetite and ilmenite while those of the eastern zone contain the latter mineral phase (Gastil et al., 1990).

The above plutons intrude four major lithostratigraphic belts that parallel the long axis of the batholith (Gastil, 1993). These are, from east to west, Late Precambrian to Permian miogeoclinal strata, Ordovician to Permian (Early Triassic?) slope basin deposits, (Late?) Triassic to Cretaceous "back-arc" sedimentary rocks, and Jurassic(?) to Cretaceous arc volcanics. The Peninsular Ranges has thus been subdivided into three zones (eastern, central, and western), the trends of which parallel the batholith (Fig. 1). Typically, the eastern zone includes miogeoclinal and slope basin deposits, the central zone "back-arc" sedimentary rocks, locally overlying slope basin strata, and the western zone volcanic arc rocks (Gastil, 1993).

These across-strike variations of the host rock stratigraphy and batholith have been interpreted to reflect a change in basement composition (e.g., DePaolo, 1981; Silver and Chappell, 1988), where the primitive western zone, with its island arc signature, is underlain by oceanic lithosphere, and the eastern zone is underlain by older lithosphere of continental composition. These observations and interpretations have provided the foundations for a series of tectonic models that seek to explain the juxtaposition of these disparate lithospheric types.

Tectonic Models for the Mesozoic Evolution of the Peninsular Ranges Batholith

The models most often proposed for the Mesozoic tectonic evolution of the Peninsular Ranges batholith may be distilled down to three end members: (1) a single, eastward-migrating arc developed across a pre-Triassic join between oceanic and

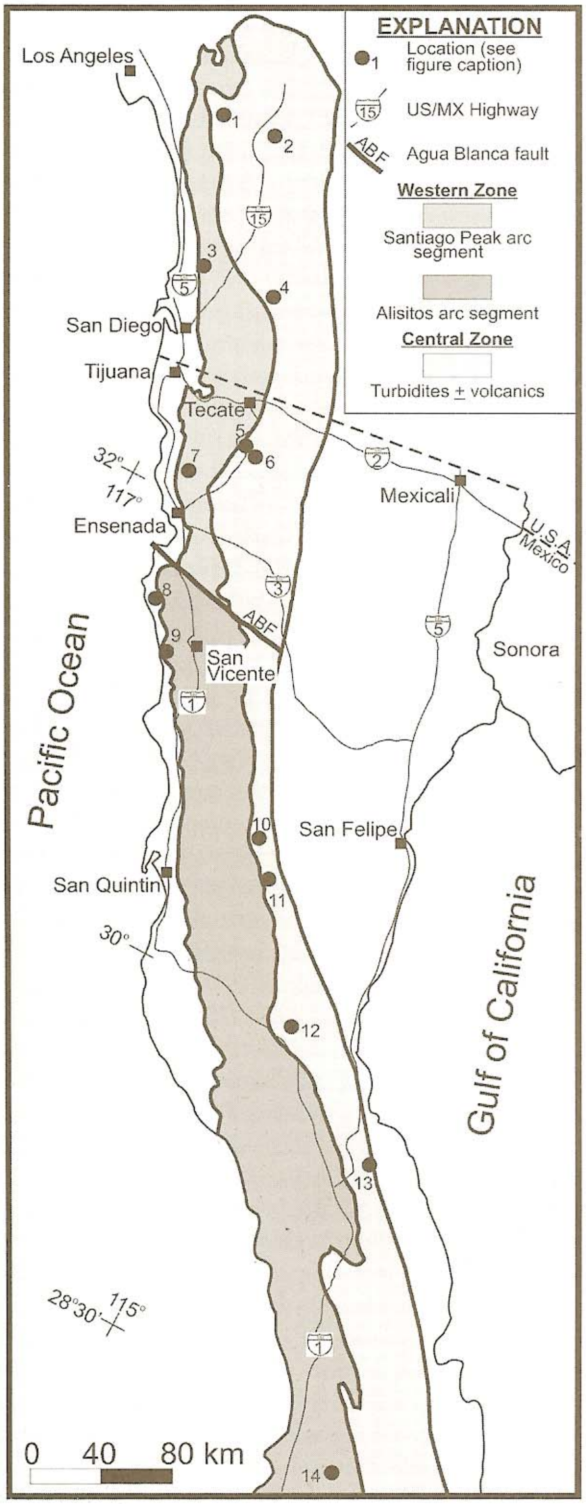

Figure 1. Map of southern California and Baja California Norte showing western and central zones of Peninsular Ranges batholith and localities discussed in text (modified from Gastil, 1993). Locations: 1—Santa Ana Mountains; 2—Winchester area; 3—central San Diego County; 4—eastern San Diego County; 5—Rancho San Marcos; 6—Rancho Vallecitos; 7—Cañon La Mision; 8—Punta China; 9—Erendira; 10—northern Sierra San Pedro Mártir; 11—southern Sierra San Pedro Mártir; 12—El Marmol; 13—Sierra Calamajue; 14—El Arco.

continental lithospheres (Walawender et al., 1991; Thomson and Girty, 1994); (2) an exotic island arc accreted to the North American margin across a non-terminal suture (Johnson et al., 1999a; Dickinson and Lawton, 2001); and (3) the reaccretion of a rifted and fringing arc to the North American margin (Gastil et al., 1981; Busby et al., 1998).

Models requiring the western zone of the Peninsular Ranges batholith to have been initially rifted from the continental margin and subsequently reaccreted are generally based on regional observations of stratigraphy and structure. However, the specific geometric requirements a rift-reaccretion model implies are inconsistent with existing data sets. For example, a rift-reaccretion model requires that a basin form between the arc and the continental margin, implying that the ages of strata should oldest within the arc and the continent and youngest in the basin. However, as discussed below, the ages of the stratigraphy of the Peninsular Ranges decrease continuously toward the west.

The observations that led to the single migrating arc (Thomson and Girty, 1994) and exotic arc (Johnson et al., 1999a) models were derived from studies of the Peninsular Ranges batholith in southern California and the Sierra San Pedro Mártir, México (Fig. 1), respectively. These two areas are separated by the Agua Blanca fault, an active dextral strike-slip fault south of Ensenada, México (e.g., Allen et al., 1960; Rockwell et al., 1989; Suarez-Vidal et al., 1991). Gastil et al. (1981), on the basis of observed differences in the apparent age and environment of deposition of the volcanics on either side of the Agua Blanca fault, identified it as an inherited structure with a Mesozoic origin as a transform fault. Gastil et al. (1981), thus, divided the western zone into northern and southern arc segments called the Santiago Peak and Alisitos, respectively. In their model, the fault is interpreted as having accommodated the diachronous accretion of the two arc segments to the western margin of North American.

Since the Gastil et al. (1981) study, our understanding of the geology of the Peninsular Ranges has improved substantially through numerous studies of the regional geology. However, few have followed up on the apparent discontinuity within the western and central zone of the batholith across the Agua Blanca fault. Here we focus on the along-strike variation in the Peninsular Ranges north and south of the Agua Blanca fault with particular attention paid to the temporal evolution of sedimentation and deformation within the central zone and the structural relationships of the central zone strata to western zone volcanics. We will use these observations to constrain the tectonic evolution of the Peninsular Ranges batholith during the Late Triassic through the Early Cretaceous and will reevaluate recently proposed models (e.g., Busby et al., 1998; Dickinson and Lawton, 2001) for the Peninsular Ranges batholith evolution.

PENINSULAR RANGES NORTH OF THE AGUA BLANCA FAULT

The pre-batholithic stratigraphy of the central and western zones of the Peninsular Ranges north of the Agua Blanca fault range in age from Late Triassic through Early Cretaceous. They can be subdivided into pre-Cretaceous and Cretaceous groups on the basis of general lithology, deformational history, and depositional setting. Those of the older group largely represent turbidite sequences (e.g., Germinario, 1993) subsequently deformed within an accretionary prism adjacent to the North American continental margin (e.g., Criscione et al., 1978). The Early Cretaceous sequences are generally the volcanic products of the western arc developed on and through the older accretionary prism.

Late Triassic through Jurassic: Turbidite Sedimentation and Deformation

Late Triassic through Jurassic sedimentary strata have been described from several locations in both southern and Baja California north of the Agua Blanca fault and have commonly been given local formational names. In the north, from west to east, these are the Bedford Canyon Formation, French Valley Formation, Julian Schist, and, further south, the Vallecitos Formation. In this group we also include the volcaniclastic-rich turbidite sequences of central San Diego County (Fife et al., 1967; Balch et al., 1984) west of exposures of the Julian Schist for reasons discussed below. Collectively, these strata have long been interpreted to be a correlative group of deep to moderately deep submarine fan deposits (Gastil, 1993).

Bedford Canyon Formation

The Bedford Canyon Formation, exposed in the Santa Ana Mountains of Orange and Riverside Counties of southern California, is the most well-studied of the middle Mesozoic turbidite sequences. The formation is dominated by alternating lithic and feldspar-rich sandstones (litharenites to lithic arkoses) and shales, with lesser amounts of limestone, conglomerate, chert, pebbly mudstones, and tuffaceous sequences (Moscoso, 1967; Moran, 1976). Additionally, isolated exposures of serpentinite occur along fault contacts within the formation (Moran, 1976; Criscione et al., 1978; Herzig, 1991). Deformation of the Bedford Canyon Formation is characterized by disrupted bedding, well-formed bedding-parallel foliation, and a second axial planar foliation associated with abundant tight to isoclinal folds, and ubiquitous small faults, typically subparallel to bedding and with some ramp-flat geometries.

The age of the Bedford Canyon Formation has been difficult to resolve because the formation is, in general, poorly fossiliferous with the exception of several allochthonous (olistostromal?) limestone blocks that contain Bajocian to Callovian (176.5 to 159.4 Ma) fossils (Silberling et al., 1961; Imlay, 1963, 1964; Moscoso, 1967). Moscoso (1967) noted that the ages of these fossils become older towards the east (Fig. 2). The age of deposition for the Bedford Canyon Formation, therefore, may be constrained as being between Bajocian (176.5 Ma, Gradstein et al., 1994) and the age of the overlying basal unit of the Santiago Peak Volcanics (127 ± 2 Ma; Herzig, 1991). Isotopic studies of the Bedford Canyon Formation are similar with a 175.8 ± 3.2 Ma Rb/Sr whole-rock isochron age (Criscione et al., 1978). The lower intercept age of 210 ± 49 Ma derived from a mixed detrital zircon population (Bushee et al., 1963; Gastil and Girty, 1993) is also consistent with a Middle Jurassic age of deposition for the Bedford Canyon Formation.

French Valley Formation

The French Valley Formation crops out east of the Elsinore fault near Winchester, California (Fig. 1). It is dominated by immature sandstones and shales with lesser amounts of conglomerate and chert as well as horizons composed of olistostromes (Schwartz, 1960), all indicative of a medium to deep submarine fan depositional setting. The French Valley Formation has been isoclinally folded and pervasively cleaved.

The age of the French Valley Formation may be Late Triassic, as indicated by bivalves (Lamb, 1970). Detrital zircons yield a U/Pb lower intercept age of 285 ± 130 Ma (Gastil and Girty, 1993). However, a Rb/Sr whole-rock isochron age of 151 ± 11 Ma (Davis and Gastil, 1993) appears far too young and may reflect a subsequent metamorphic event rather than the age of deposition.

Julian Schist

The Julian Schist of eastern San Diego County (Fig. 1) is composed predominantly of sandstones and shales with minor

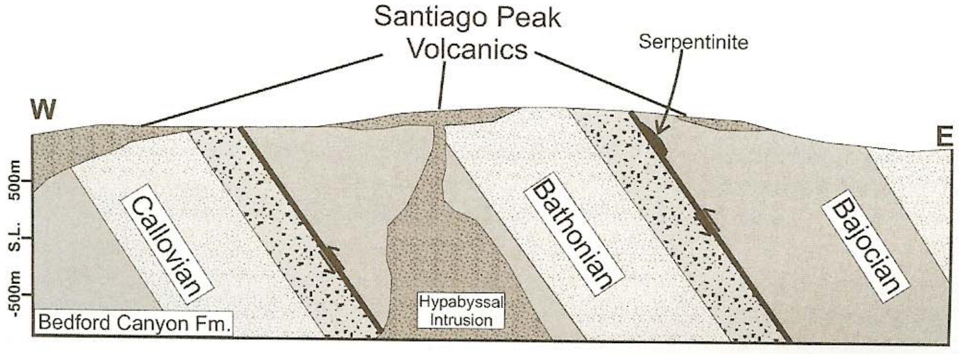

Figure 2. Schematic cross section through the Santa Ana Mountains based on our own field observations and age constraints from Moscoso (1967).

amounts of carbonate and other lithologies (Germinario, 1993). The depositional environment, therefore, is inferred to have been within the distal and medial portions of a deep to moderately deep submarine fan. Unlike many of the other correlative formations the Julian Schist has been metamorphosed to amphibolite grade and strongly deformed by the emplacement of multiple intrusives and episodes of deformation associated with the Cuyamaca Laguna Mountain Shear Zone (Thomson and Girty, 1994).

The age of the Julian Schist is poorly constrained. Only one fossil has ever been reported from these strata, the imprint of an ammonoid that was interpreted to be Triassic (Hudson, 1922). Unfortunately, the sample was subsequently lost. U/Pb analyses of detrital zircons collected from the Julian Schist are strongly discordant with a poorly constrained lower intercept at ca. 260 Ma (Gastil and Girty, 1993). However, this lower intercept is at least consistent with the age of the Harper Creek gneiss, which had a tonalite to granite protolith (Leeson, 1989) and intruded the Julian Schist at 156 ± 16 Ma (Girty et al., 1993).

Contact relationships with younger stratigraphy, such as the Santiago Peak Volcanics, have not been described for the Julian Schist. Thus, correlation of tectonic events observed elsewhere (e.g., Santa Ana Mountains) cannot be unambiguously established in the eastern part of San Diego County.

Vallecitos Formation

Further south, the Vallecitos Formation, described from the Rancho Vallecitos and Rancho San Marcos areas in northern Baja California (Fig. 1; Reed, 1993), is characterized by lithologies and internal structures similar to those of other turbidite sequences further north. Reed (1993) interprets recrystallized sandstones and shales within the formation to have been deposited in the distal portions of a submarine fan. The presence of pebbly mudstones and large (5 km^2) olistostromal blocks of Ordovician miogeoclinal strata (Lothringer, 1993; Gehrels et al., 2002) further indicate proximity to a slope of the continental margin. U/Pb analysis of detrital zircons from these Ordovician strata by Gehrels et al. (2002) indicates a North American source, providing a definitive tie between the Mesozoic turbidite sequences and the continent.

Deformation and metamorphism of the Vallecitos Formation is variable and largely dependent upon proximity to the multiple large intrusive bodies present near Rancho Vallecitos (Reed, 1993; Sutherland and Wetmore, unpubl. mapping). Away from intrusives, recrystallization, cleavage, bedding-parallel faulting, and folding are perceived to be only slightly more intense than conditions observed for the Bedford Canyon Formation in the Santa Ana Mountains.

The age of the Vallecitos Formation, like that of more northerly formations, is not well defined. Gastil and Girty (1993) report the lower intercept of a mixing line formed from U/Pb analyses of detrital zircons collected from the formation to be 369 ± 59 Ma. A Rb/Sr whole-rock isochron age of 206 ± 12 Ma is suggested by Davis and Gastil (1993), indicating a possible Late Triassic age of deposition.

Tres Hermanos–Santa Clara Area

The descriptions of the southernmost exposures of turbidite sequences north of the Agua Blanca fault are from the Tres Hermanos–Santa Clara area (Fig. 1; Chadwick, 1987). Sandstone- and shale-dominated strata of this area have been intruded by several plutonic bodies that have imparted a strong metamorphic overprint as well as a significant component of emplacement-related deformation. Chadwick (1987) reports the presence of earlier-formed northwest-trending structures that include tight and isoclinal folds and associated foliation within the turbidite sequences.

Isotopic ages for the Tres Hermanos–Santa Clara strata are similar to those described for the Vallecitos Formation. U/Pb analyses of detrital zircons yield a lower intercept of 302 ± 61 Ma and a Rb/Sr isochron age of 167 ± 9 Ma (Chadwick, 1987), suggesting a slightly younger Early Jurassic age of deposition. The ages of intrusive bodies within these strata are all Early Cretaceous (132 ± 1.25 Ma or younger; Chadwick, 1987), approximately the same age as the Santiago Peak Volcanics, and thus they do not constrain the age of these pre-Cretaceous strata well.

Central San Diego County Volcaniclastics

Exposed in central San Diego County (Fig. 1) are a series of volcaniclastics, deposited in a submarine environment (named the Santiago Peak volcaniclastics by Balch et al. (1984)), that have long been correlated with the Santiago Peak Volcanics (Fife et al., 1967; Balch et al., 1984). Based on depositional environment, structural relationship to younger volcanic sequences, and age of these strata, we believe that they are better correlated with the pre-Cretaceous continentally derived turbidite sequences (e.g., the Bedford Canyon Formation) for reasons discussed below.

These volcaniclastics are epiclastically reworked breccias composed of andesites, dacites, and latites of similar composition to the Santiago Peak Volcanics. However, the deposits are exposed in sections containing turbidites, sandstones, and shales that are interpreted to have been deposited in medial to distal submarine fans (Balch et al., 1984) similar to those of the Bedford Canyon Formation. The Santiago Peak Volcanics, sensu stricto, on the other hand, are interpreted to have been deposited in a subaerial environment.

The volcaniclastic-rich sandstones and shales in central San Diego Country are characterized by a penetrative bedding parallel foliation, tight and locally overturned(?) folds, and brittle faults, all of which are truncated along the structural top of the section by an erosional surface. Overlying these volcaniclastic-rich turbidite sequences across an angular unconformity are volcanics that dip moderately and do not possess the deformational features of the underlying volcaniclastic and turbidite sequences. This relationship is remarkably similar to that observed between the Bedford Canyon Formation and the Santiago Peak Volcanics in the Santa Ana Mountains (described below).

The age of the strata in central San Diego was established by Fife et al. (1967) as Tithonian based upon the presence of the fossil *Buchia Piochii*. A recent U/Pb zircon age of ca. 152 Ma from a volcanic flow (dike?) within the package of volcaniclastic-rich turbidites is consistent with the fossil age (Anderson, 1991). Thus, given that the basal unit of the Santiago Peak Volcanics in the type section of the sequence yields an age of 127 ± 2 Ma (Herzig, 1991), correlation between the strata of central San Diego County and the Santiago Peak Volcanics is unfounded and a more appropriate correlation is made with the Bedford Canyon Formation.

The above descriptions of the turbidite sequences of the central zone north of the Agua Blanca fault reveal consistent features throughout this region. These include similar lithologies and inferred depositional environment, style and magnitude of deformation, presence of olistoliths, detrital zircon populations that indicate a source that included Precambrian to Triassic exposures, and a general depositional age that ranges between Late Triassic and Jurassic. The identification of volcaniclastic layers within these strata is common only within those formations that are clearly identified as being deposited in the Jurassic (e.g., Bedford Canyon Formation and the volcaniclastic-rich turbidite sequences of central San Diego County). Additionally, a general east-to-west younging of the strata is indicated for the southern California sequences. That is, the French Valley Formation, which contains Early Triassic fossils, is east of the Bedford Canyon Formation, which is Jurassic and which exhibits an intraformational westward younging (Bajocian on the east to Callovian on the west; Fig. 2). Similarly, the Triassic Julian Schist in eastern San Diego County is east of the volcaniclastic-rich turbidites of central San Diego County, which yield Tithonian fossils. Because of the similarities between all of these formations, we propose that they should be incorporated under a single group named the Bedford Canyon Complex.

Early Cretaceous: Development of the Santiago Peak Arc

The Early Cretaceous arc volcanic strata of the western zone north of the Agua Blanca fault are dominated by the Santiago Peak Volcanics. Rocks of similar stratigraphic position, such as the Estelle Mountain Volcanics, exposed east of the San Andreas fault east of the Santa Ana Mountains, named the Temescal Wash quartz latite porphyry by Larsen (1948), possess almost identical ages, contact relationships, petrologies, geochemistries, and degree of deformation to those described for the Santiago Peak Volcanics (Herzig, 1991). Hence, it seems practical to include all such units with the Santiago Peak Volcanics.

The most extensive studies of the Santiago Peak Volcanics have been completed in the Santa Ana Mountains (Larsen, 1948; Peterson, 1968; Gorzolla, 1988; Herzig, 1991) and central and northern San Diego County (Hanna, 1926; Adams, 1979; Tanaka et al., 1984; Anderson, 1991; Reed, 1992; Carrasco et al., 1993). South of the international border, where exposures are substantially better than to the north, studies have been completed in Cañon La Mision (Meeth, 1993) and the Ensenada area (Schroeder, 1967). Together these studies provide a relatively coherent picture of the volcanic products of the Early Cretaceous arc that existed along the western side of the Peninsular Ranges batholith north of the Agua Blanca fault.

Lithology and Petrochemistry of the Santiago Peak Volcanics

The Santiago Peak Volcanics are composed of flows, volcaniclastic breccias, welded tuffs, hypabyssal intrusions, and relatively rare epiclastic deposits (Larsen, 1948; Schroeder, 1967; Adams, 1979; Gorzolla, 1988; Herzig, 1991; Reed, 1992; Carrasco et al., 1993; Meeth, 1993). The volcanics are inferred to be subaerially deposited based on the abundance of accretionary lapilli and preserved paleosols, as well as the apparent absence of pillow lavas, thick and laterally extensive epiclastic deposits, and other marine deposits.

A relatively large body of geochemical data exists for northern exposures of the Santiago Peak Volcanics (e.g., Hawkins, 1970; Tanaka et al., 1984; Gorzolla, 1988; Herzig, 1991; Reed, 1992; Meeth, 1993), and, when combined with that for intrusive bodies from the same arc segment (e.g., Taylor and Silver, 1978; DePaolo, 1981; Gromet and Silver, 1987; Silver and Chappell, 1988; Carollo and Walawender, 1993), a coherent picture of the generation and evolution of magmas from the region may be drawn. Many of the early geochemical investigations focused on the intrusive suites and variations in the REE and isotopic compositions across the batholith (e.g., Taylor and Silver; 1978; DePaolo, 1981; Gromet and Silver, 1987). These studies identify a relatively primitive western zone underlain by oceanic lithosphere juxtaposed with a relatively evolved central/eastern zone underlain by transitional to continental lithosphere.

Major and trace element data, as well as isotopic data from the Santiago Peak Volcanics, indicate that they, like the plutons that intrude them (e.g., DePaolo, 1981), were derived from a depleted, oceanic mantle source (Herzig, 1991). However, some significant modification of the magmas is indicated by observed low Ni concentrations and slightly more evolved Nd and Sr isotopic values for the rhyolites. Such observations are suggestive of fractional crystallization of olivine and clinopyroxene, which was likely promoted by the hydrous character of the magmas (e.g., Nicholls and Ringwood, 1973), as well as the assimilation of some minor amounts of radiogenic crustal material. The most likely assimilant, at least near the level of extrusion, would have been continentally derived turbidite sequences, such as the Bedford Canyon Complex, which have an isotopic signature consistent with a continental provenance (Criscione et al., 1978). Assimilation, however, is not perceived to be significantly more than ~10% for even the most felsic units because of the relatively consistent concentrations of the incompatible elements (Herzig, 1991; Herzig and Wetmore, unpubl. data).

One hundred and seventeen whole rock geochemical analyses of the Santiago Peak Volcanics define a wide range of lava types from basalts to rhyolites (Fig. 3). Major elemental determinations of lava type indicate that the Santiago Peak arc was most likely a continental margin arc rather than an island arc (e.g., Todd et al., 1988). For example, although the mean lava type is andesite, basalts are uncommon and rhyolites comprise ~25% of the samples analyzed. This is in direct contrast with the petrologic characterization of active island arc systems as being largely composed of basalts and basaltic andesites (Marsh, 1979). Fur-

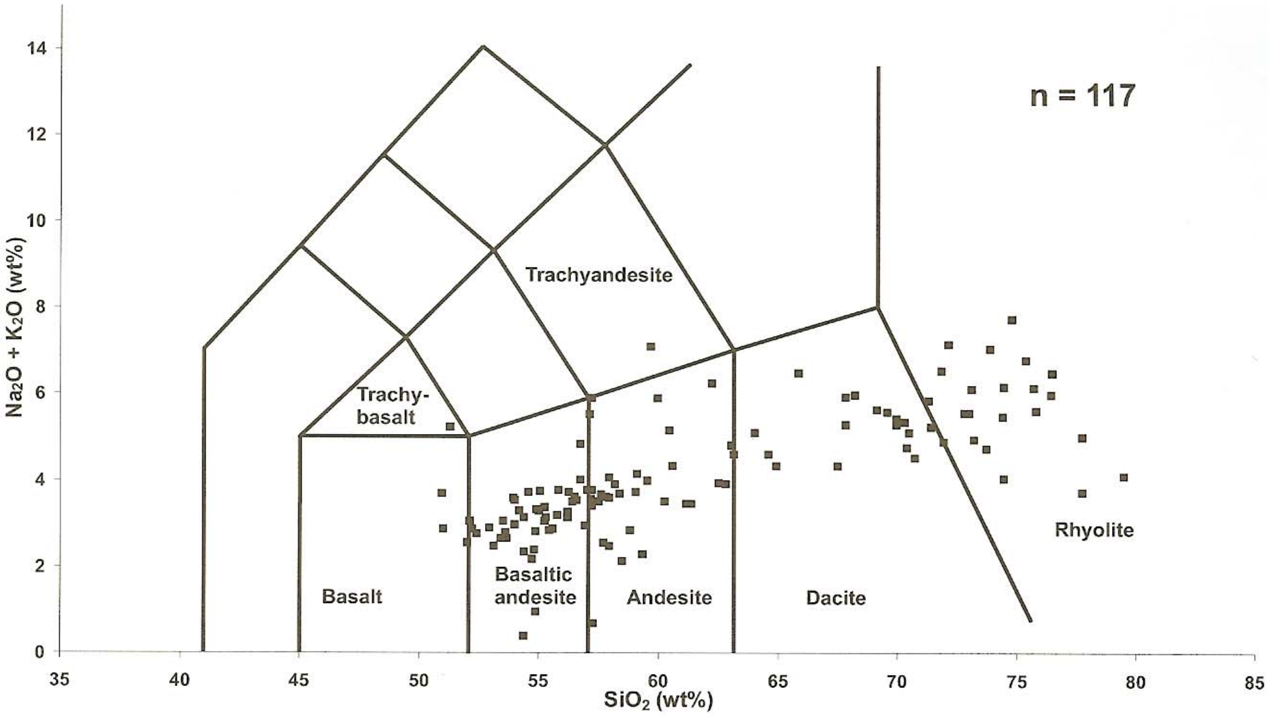

Figure 3. Chemical classification plot of lava types from Santiago Peak Volcanic. Diagram of Le Maitre et al. (1989). Data compiled from Tanaka et al. (1984), Gorzolla (1988), and Herzig (1991).

thermore, rhyolites comprise the basal unit to the Santiago Peak Volcanics in many studied localities (e.g., Santa Ana Mountains; Herzig, 1991). This precludes the possibility that the Santiago Peak arc was long-lived and evolved into a felsic island arc.

Contact Relations between the Santiago Peak Volcanics and the Bedford Canyon Complex

Contact relations between the Santiago Peak Volcanics and the underlying Bedford Canyon Formation in the Santa Ana Mountains are often not well exposed. This fact has led to some erroneous interpretations that have been perpetuated in the literature through the years. Initial descriptions by Larsen (1948) as well as later descriptions by Schoellhamer et al. (1981) indicated a depositional contact between the two stratigraphic units. However, several subsequent studies concluded that the two were juxtaposed across a low-angle fault (e.g., Peterson, 1968; Criscione et al., 1978). Many of the early tectonic models for the Mesozoic evolution of the Peninsular Ranges batholith were thus based on an accretionary juxtaposition of the Santiago Peak arc to the North American continent (e.g., Gastil et al., 1981; Todd et al., 1988). Such interpretations have persisted and can be found the most recent models (e.g., Dickinson and Lawton, 2001).

We have reexamined several key exposures of the contact between the Santiago Peak Volcanics and the Bedford Canyon Complex in the Santa Ana Mountains (Herzig, 1991; M. Sutherland, 2002, personal commun.) in central San Diego County (Wetmore and Herzig, unpubl. mapping), and the Vallecitos area in Baja California (Sutherland and Wetmore, unpubl. mapping). In each area, several observations strongly suggest that this contact is an angular unconformity. At each exposure the moderately well-formed cleavage and folds, characteristic of the Bedford Canyon Complex strata, were oriented at high angles to, and truncated at, the contact (Fig. 4, A–C). In the Santa Ana Mountains and Vallecitos area, an uncleaved conglomerate composed of chert and/or sandstone pebbles in a muddy matrix is locally preserved along the contact. Also in the Santa Ana Mountains, the basal flows of the Santiago Peak Volcanics contain accidental sandstone and greywacke clasts from the underlying Bedford Canyon Formation. Additionally, Herzig (1991) reports that feeder dikes within the Bedford Canyon Formation may be traced directly into flows of the overlying Santiago Peak Volcanics (Fig. 4D).

Geochronology of the Santiago Peak Volcanics

Recent U/Pb geochronology studies of the Santiago Peak Volcanics by D.L. Kimbrough (San Diego State University) and his students (Anderson, 1991; Meeth, 1993; Carrasco et al., 1995) yield mildly discordant ages that range from 128 to 116 Ma. For example, a welded tuff that unconformably overlies the Bedford Canyon Formation in the Santa Ana Mountains and is inferred to be the basal unit of the Santiago Peak Volcanics yielded a U/Pb zircon age of 127 ± 2 Ma (Anderson, 1991;

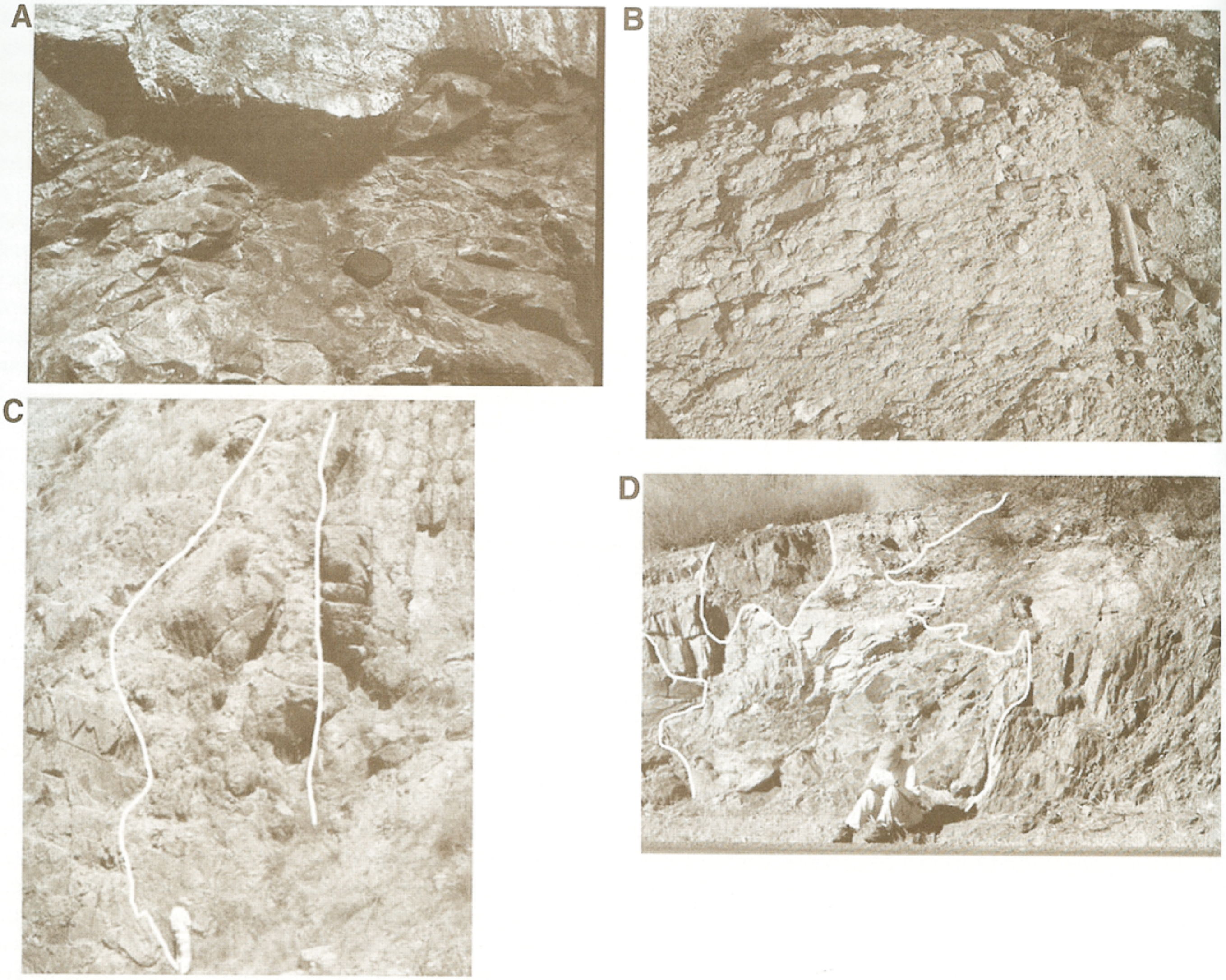

Figure 4. A: Contact between Bedford Canyon Formation and Santiago Peak Volcanics (top) in Santa Ana Mountains. B: Basal conglomerate exposed along contact between Bedford Canyon Formation and Santiago Peak Volcanics in Santa Ana Mountains. C: Contact between Vallecitos Formation (left) and Santiago Peak Volcanics (right) with basal conglomerate preserved along contact. Steep dip of contact results from rotation in structural aureole of nearby pluton. D: Hypabyssal intrusion of Santiago Peak Volcanics feeding overlying flows.

Herzig, 1991). The 116 Ma age, derived from a sample 200 m below the mapped top of the Santiago Peak Volcanics section in the Cañon La Mision area (Fig. 1; Meeth, 1993), is assumed to be a minimum age for the end of Santiago Peak arc magmatism. Overlying the Santiago Peak Volcanics are course clastic forearc strata of Late Cretaceous age (e.g., Rosario Formation). Thus, the true termination of Santiago Peak volcanism is at some time between 116 Ma and the Late Cretaceous.

Observed discordance in the U/Pb zircon analyses of the Santiago Peak Volcanics and associated plutonics provide further evidence that the Santiago Peak arc was a continental margin arc and not an island arc. Anderson (1991) suggests that the observed discordances resulted from both minor lead loss and some inheritance of radiogenic lead. The possibility of inheritance is also supported by the presence of a small fraction of discolored zircons that did not appear to be consistent with the majority of clear, euhedral zircons. This observation suggests that these discolored crystals are xenocrysts derived from minor amounts of incorporation of the country rock through which the plutons were emplaced (e.g., Bedford Canyon Complex). This is consistent with the observation that sandstone and greywacke xenoliths of apparent Bedford Canyon Formation are entrained within the basal flows and volcaniclastic units of the Santiago Peak (Herzig, 1991). These observed discordances and inferred inheritance occur in study areas for the entire length of the Santiago Peak arc segment including the

San Diego area (Anderson, 1991), and the Cañon La Mision area south of the international border (Meeth, 1993).

Deformation of the Santiago Peak Volcanics

The deformational history of the Santiago Peak Volcanics is one of the most poorly constrained aspects of this part of the Peninsular Ranges. Our mapping in the Santa Ana Mountains and central San Diego County has resulted in the identification of high-angle brittle faults, and gentle to moderately steep tilting and open folding of the volcanics. However, the observed cleavage and ductile strain that characterize the underlying Bedford Canyon Complex are not observed within the Santiago Peak Volcanics. In fact, fabric ellipsoids determined from lithic-rich samples from the Santiago Peak Volcanics do not significantly deviate from those measured in undeformed volcanics (Sutherland et al., 2002).

Mapping of the Santiago Peak Volcanics near Rancho Vallecitos (Sutherland et al., 2002) and north of the active Agua Blanca fault (Figs. 1 and 5B) has resulted in the identification of pronounced tilting and ductile strain, including a pervasive and well-developed cleavage, within the structural aureoles of plutons in both these areas. However, away from these intrusive bodies the minor deformation observed affecting the volcanics is similar to that characterizing exposures north of the international boarder.

In the area of the Agua Blanca fault the Santiago Peak Volcanics are cut discordantly by both the northwest-trending active strike slip structure and an older dip slip fault. The structural trends defined by the axes of open folds, minor west-vergent faults, and the average strike of bedding are truncated at the southern extent of the Santiago Peak Volcanics by what has been mapped as the ancestral Agua Blanca fault (Fig. 5) (Wetmore et al., 2002). This steeply northeast-dipping shear zone parallels the active Agua Blanca fault but is located ~2 km to the south. While some deflection (drag) of these regional trends is observed with proximity to the active structure, no deflection has been observed associated with the older ancestral Agua Blanca fault. Furthermore, no increases in finite ductile strain or in metamorphic grade are observed in proximity to the latter structure.

The above description of the Santiago Peak Volcanics and associated intrusives indicates that the Santiago Peak arc north of the Agua Blanca fault developed atop the Late Triassic through Jurassic Bedford Canyon Complex. Initiation of Early Cretaceous arc magmatism began after the earlier-formed strata were deformed, uplifted, and erosionally beveled as indicated by the truncation of fabrics and structures within the Bedford Canyon Complex at the contact with the overlying volcanics. Evidence supporting a depositional contact between the volcanics and the Bedford Canyon Complex strata includes a basal conglomerate present along the contact, xenoliths and xenocrysts of Bedford Canyon Complex derivation in the Santiago Peak Volcanics, a pronounced break in deformation across the contact without any indication of shear, and hypabyssal intrusions that cross-cut the turbidites and the contact to feed the overlying volcanics.

PENINSULAR RANGES SOUTH OF THE AGUA BLANCA FAULT

South of the Agua Blanca fault there have been considerably fewer geologic investigations of the western and central zones of the Peninsular Ranges. However, those that have been completed describe a Late Triassic through Early Cretaceous history that is markedly different from that to the north of the Agua Blanca fault. The most salient differences south of the ancestral Agua Blanca fault are the lack a Late Triassic through Jurassic accretionary prism (cf., Bedford Canyon Complex) to the south, and that the western and central zones are juxtaposed across a well-defined, east-dipping ductile shear zone (Main Mártir thrust). Below we describe the central and western zones in this region (Fig. 1).

Central Zone

Sierra San Pedro Mártir

The central zone in the Sierra San Pedro Mártir area (Fig. 1) has been the focus of two recent structural studies: Johnson et al. (1999a) in the northern part and Schmidt (2000) in the southern. In each area, the thermal affect of the numerous plutonic bodies has metamorphosed most of the preserved country rock screens to at least amphibolite grade. As such, the age and depositional environments of these prebatholithic strata cannot be constrained unequivocally. However, along the westernmost exposures of the central zone in both the northern and southern Sierra San Pedro Mártir, the strata are comprised of calc-silicates, metavolcanics, and quartzo-feldspathic metapelites.

Plutons that intrude these strata range in age from ca.134 Ma to ca. 97 Ma (Johnson et al., 1999a; Schmidt, 2000) with two major pulses, one between 134 and ca. 128 Ma and the other associated with the Late Cretaceous La Posta event between 100 and 94 Ma (e.g., Walawender et al., 1990). Thus, the age of the host stratigraphy must be greater than ca.134 Ma. Correlation of these strata with the Paleozoic through Early Triassic continental slope basin deposits exposed elsewhere in the central zone south of the Agua Blanca fault is possible, but the presence of a volcanic component is inconsistent with lithologies described for the older strata. Therefore, we suggest that the strata exposed in the westernmost exposures of the Sierra San Pedro Mártir were most likely deposited during the Middle to Late Jurassic, when arc magmatism is known to have been active in eastern parts of the central zone (Schmidt, 2000) and further east in mainland México (e.g., Damon et al., 1983).

Two deformational events are recorded within the prebatholithic strata of the central zone in the Sierra San Pedro Mártir (Schmidt, 2000). The oldest event predates the ca. 134 Ma plutons as host rocks in the middle part of the central zone possess a foliation which is not preserved in the intrusives of the earlier pulse of magmatism. In the western part of the central zone, this earlier fabric is strongly overprinted by mylonitic fabrics associated with the Main Mártir thrust (discussed below), the west-directed shear zone that juxtaposes the central and western

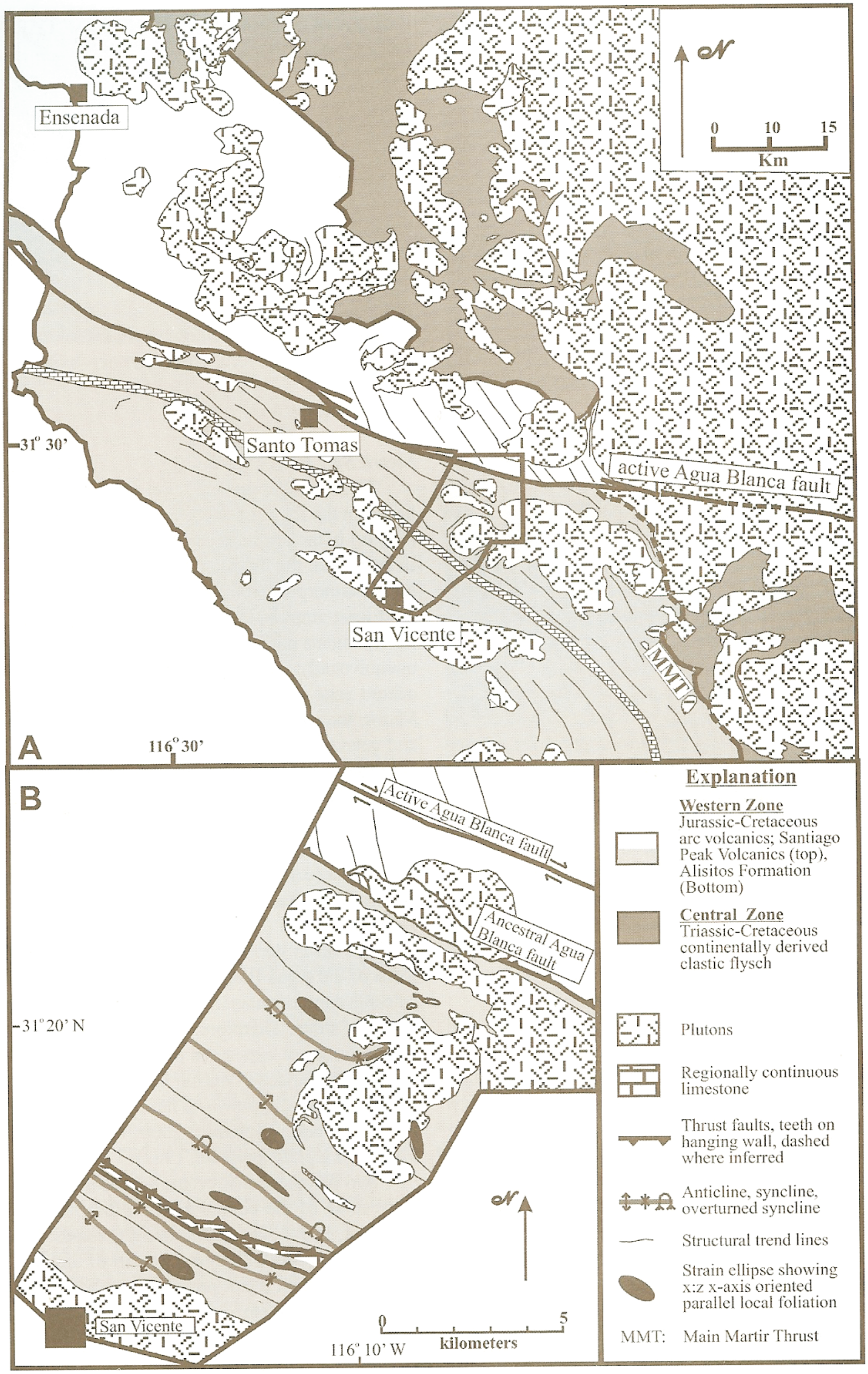

Figure 5. A: Geologic map of Agua Blanca fault based on Gastil et al. (1975); B: Map of northern Alisitos arc northeast of San Vicente (mapping by Wetmore).

zones (Johnson et al., 1999a). Deformation associated with this structure may have initiated as early as ca. 132 Ma, as indicated by igneous sheets and high-temperature subsolidus fabrics in plutons of this age along the western margin of the central zone (Schmidt, 2000).

El Marmol Area

The El Marmol area is located ~80 km south-southeast of the southern Sierra San Pedro Mártir (Fig. 1). Paleozoic to Early Triassic continental slope basin deposits that overlapped older North American miogeoclinal assemblages (Buch and Delattre, 1993; Campbell and Crocker, 1993; Gastil, 1993) are exposed in this part of the central zone. The slope basin stratigraphy is comprised of thin-bedded argillite, sandstones, and cherts with interbedded calcareous quartzarenite and pebble conglomerates with clast compositions of chert and quartzite. These strata are interpreted to have been deposited by sediment gravity flows with intervening intervals of quiescent pelagic sedimentation (Buch and Delattre, 1993).

Paleozoic to Early Triassic strata are overlain with angular discordance by the Early Cretaceous Olvidada Formation in the El Marmol area (Fig. 6; Phillips, 1993). Phillips (1993) describes lower, middle, and upper members of this formation. The lower member is composed of boulder-pebble conglomerate and sandstone, some containing volcanogenic detritus and minor limestones clasts. Phillips (1993) interprets this member to represent shallow marine deposition. The gradationally overlying middle member is composed of rhythmically bedded cherts, sandstones, and shales and is interpreted to represent deep-water slope basin to abyssal plain deposition. These marine strata are unconformably overlain by the upper member of the formation, which consists of cobble conglomerate containing clasts that appear to be derived from the middle member of the formation, and sandstones and shales. The section is capped by vesicular andesites that are interpreted to have been deposited in a subaerial environment.

Deformation of the Paleozoic through Early Cretaceous strata of the El Marmol area includes an overall east-tilting of the entire section as well as two generations of folding (Buch and Delattre, 1993). The first generation of folding appears to affect only the Paleozoic to Early Triassic strata and is characterized by tight to isoclinal folds with northwest-striking, northeast-dipping axial planes. The second generation of folding affects both pre-Cretaceous and Early Cretaceous strata but not Late Cretaceous dikes and sills. Similar to the earlier-formed folds, the second generation are tight to isoclinal but with axial surfaces that strike more westerly than those of the former generation. Tertiary and Quaternary volcanic and sedimentary deposits obscure contact relationships between the strata of the El Marmol area and that of the western zone volcanics.

Sierra Calamajue

The Sierra Calamajue is located ~80 km south-southeast of the El Marmol area. Mapping in this area was completed by Griffith and Hoobs (1993) and is being remapped as part of a regional transect by H. Alsleben (2002, personal commun.). The stratigraphy of the Sierra Calamajue is dominated by metavolcanics and volcaniclastics with subordinate amounts of carbonate, phyllite, chert, and limestone pebble to cobble conglomerate. According to Griffith and Hoobs (1993), the strata in the Sierra Calamajue range from Mississippian through the Early Cretaceous. However, many of the U/Pb age determinations for the volcanic stratigraphy in this part of the central zone are presently being reevaluated by D.L. Kimbrough. An early observation from this work indicates that the analyzed units from this area are that all of the volcanics are Early Cretaceous and contain some component of inherited Precambrian zircons.

Perhaps similar to the El Marmol section, the westernmost exposures in the Sierra Calamajue are comprised of Paleozoic(?) deep marine strata, represented here by the Cañon Calamajue unit (Griffith and Hoobs, 1993). Lower parts of the Cañon Calamajue unit are composed of cherts and phyllites. Near the top of the unit is a limestone cobble conglomerate with a volcaniclastic matrix. The blocks of this conglomerate yield Chesterian age conodonts of North American affinity. However, the allochthonous nature of these blocks suggests that this is a lower age limit and not necessarily the age of deposition for the Cañon Calamajue unit.

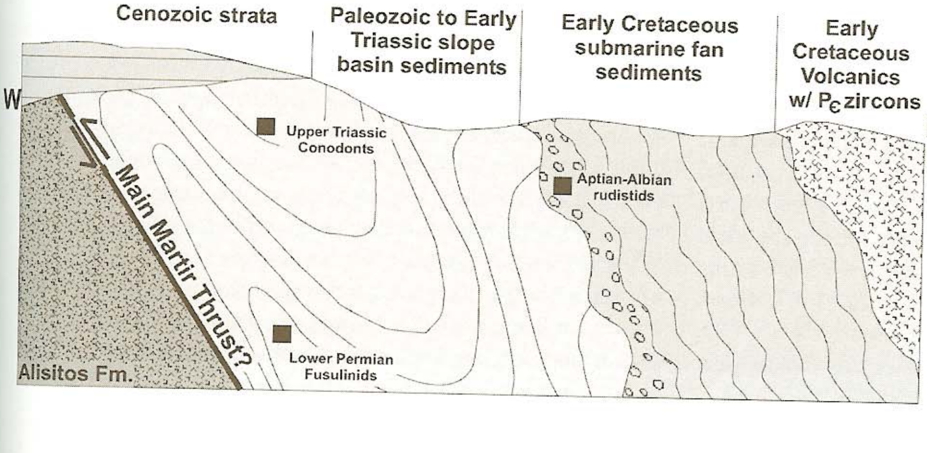

Figure 6. Schematic cross section through El Marmol area based on mapping and descriptions from Buch and Delattre (1993) and Phillips (1993).

Northeast of the Cañon Calamajue unit are a series of metavolcanic units with interbedded limestones juxtaposed with phyllite-dominated units, with lesser volcanics, across northeast-dipping, southwest-vergent thrust faults (Griffith and Hoobs, 1993). Deformation of these units reaches a maximum intensity within Cañon Calamajue, an observation that led Griffith and Hoobs (1993) to suggest that this zone was the suture between North America and the Alisitos arc of the western zone. However, due to the presence of strata with North American provenance and volcanics containing Precambrian zircons west of the faults, alternative interpretations are possible (see Discussion section).

In summary, the along-strike lithologic character of the central zone south of the ancestral Agua Blanca fault does exhibit several differences from place to place, but as a whole it appears to have experienced a broadly similar evolution throughout along its length. For example, while the ratio of volcanics to marine sediments is not the same for any of the two areas, the observation of marine deposition of clastic sediments succeeded by the subaqueous deposition of volcanics is common to all three. This indicates the presence of a basin or basins along the southwestern margin during the latest Jurassic through much of the Early Cretaceous. However, missing from each of these areas are the Late Triassic through Jurassic turbidite sequences that dominate the central zone of the Peninsular Ranges north of the ancestral Agua Blanca fault.

Western Zone

Early Cretaceous arc strata of the western zone of the Peninsular Ranges batholith south of the Agua Blanca fault are included in the Alisitos Formation. Most early studies of the Alisitos Formation focused on stratigraphy, paleontology, and depositional environment (e.g., Allison, 1955, 1974; Silver et al., 1963; Suarez-Vidal, 1986) with many of these studies confined to northernmost exposures. Recent studies have expanded the understanding of the stratigraphy to more southern areas (e.g., Beggs, 1984; Fackler-Adams, 1997) and have begun to focus on the structural/tectonic and magmatic evolution of this part of the Peninsular Ranges (e.g., Goetz, 1989; Johnson et al., 1999a, 1999b; Tate and Johnson, 2000; Tate et al., 1999; Schmidt, 2000; Wetmore et al., 2002).

Alisitos Formation

The Alisitos Formation is composed of reworked or epiclastic volcaniclastics, volcanogenic argillites and sandstones, several primary volcanic flows and breccias, and a regionally extensive prominent limestone/marble member that can be traced continuously from Punta China to the northern Sierra San Pedro Mártir (Silver et al., 1963; Figs. 1 and 5). Subaqueous deposition dominated during the emplacement of the Alisitos Formation based on the observed volcaniclastic lithologies and the abundant fossils preserved within them and the presence of several basaltic lava flows exhibiting pillow structures (Leedom, 1967; Reed, 1967; Allison, 1974; Beggs, 1984; Suarez-Vidal, 1986, 1993; Fackler-Adams, 1997). Subaerial deposition occurs locally near inferred volcanic edifices (Fackler-Adams, 1997).

Petrologic classifications of the volcanics of the Alisitos Formation lack the support of the large geochemical data set that exists for the Santiago Peak Volcanics. However, descriptions from hand samples and thin sections suggest that the two share a similar range in composition (e.g., Fackler-Adams, 1997). However, based on the few published stratigraphic columns (e.g., Leedom, 1967, Allison, 1974), combined with our own mapping near San Vicente (Wetmore, unpubl. mapping; Fig. 1) and in the western part of the Sierra San Pedro Mártir (Schmidt, 2000), we believe that basalts, basaltic andesites, and andesites overwhelmingly dominate and that more siliceous volcanics (e.g., rhyolites) are uncommon.

The presence of moderate- to deep-water clastic and biochemical sediments in the Alisitos Formation is reported by Suarez-Vidal (1986, 1993) and Johnson et al. (1999a). Suarez-Vidal (1993) suggested that the package of clastic sediments that he mapped in an area south of the Agua Blanca fault and near El Arco (Fig. 1) represented a regionally continuous depositional package that comprised the northern and eastern exposures of the Alisitos Formation. In the northern Sierra San Pedro Mártir, Johnson et al. (1999a) mapped a north-northwest–trending belt of equivalent rocks bounded on the west and east by west-vergent thrust faults. Suarez-Vidal (1993) further suggested that the presence of such rocks indicated deposition in a "tectonically quiet" setting, such as a backarc environment.

Paleontological investigations of the Alisitos Formation have consistently yielded Early Cretaceous fauna (e.g., Allison, 1955, 1974; Silver et al., 1963). Some early confusion may have existed concerning the exact age (Aptian-Albian) of some of the fossils, but ultimately an Albian age was determined by Allison (1974). Subsequently, a small number of U/Pb zircon ages have been reported for both of the volcanics as well as for some of the plutons that intrude the Alisitos Formation. Carrasco et al. (1995) and Johnson et al. (2003) report ages from the volcanics of 116 ± 2 and 115 ± 1.1 Ma. Johnson et al. (1999a) further report ages from plutons of the western part of the Sierra San Pedro Mártir area that range from 116.2 ± 0.9 to 102.5 ± 1.6 Ma. None of these U/Pb zircon studies have resulted in the observation of any component of Precambrian inheritance.

The most complete geochemical data sets for the Alisitos arc segment are from the Zarza Intrusive Complex and the San José tonalite of the northern Sierra San Pedro Mártir area reported in Tate et al. (1999) and Johnson et al. (2003; Fig. 1). Similar to data from the Santiago Peak Volcanics, these intrusive bodies yield major and trace element and isotopic signatures that are consistent with melt derivation from within depleted oceanic lithosphere. However, unlike the Santiago Peak Volcanics, interpreted contamination is consistent with assimilation of metabasite (Tate et al., 1999) rather than more silicic continentally derived clastic sedimentary sequences. Combined with the observed lack of any inherited component to the zircons from either intrusive or extrusive igneous rocks, these observations strongly suggest that the basement of the Alisitos arc segment does not contain continentally derived materials (Johnson et al., 1999a; Wetmore et al., 2002).

Structures Attending the Boundaries of the Alisitos Arc

Contact relationships between the Alisitos Formation and the continentally derived clastic sedimentary sequences of the central zone have been described in both the northern and southern Sierra San Pedro Mártir (Goetz, 1989; Johnson et al., 1999a; Schmidt, 2000). In each of these areas the two lithostratigraphic belts are juxtaposed across a large, east-over-west ductile shear zone known as the Main Mártir thrust. A similar structural juxtaposition exists between the Alisitos Formation and the Santiago Peak Volcanics to the north across a newly identified southwest-vergent reverse fault (Wetmore et al., 2002). To the south of the Sierra San Pedro Mártir, the presence of structures clearly juxtaposing the Alisitos Formation with central zone, deep-water sediments and successive volcanics have not, as yet, been clearly identified.

Studies of deformation within the Alisitos Formation have traditionally focused on structures developed along the eastern margin of this part of the western zone (Goetz, 1989; Johnson et al., 1999a; Schmidt, 2000). Strong deformation characterizes each of these areas where west-vergent ductile shear zones place the continentally derived clastic sedimentary sequences over the Alisitos Formation (Figs. 1 and 5). Our reconnaissance work across the Alisitos indicates that the intensity of deformation increases from shallowly west-dipping strata without observed internal fabrics in western exposures to openly folded strata with horizontal axes, moderate- to well-formed cleavages, and intermediate strain intensities (<~40% shortening in the z-direction), and finally to isoclinally folded strata with inclined axes, strongly developed foliations, and large strain intensities (>~60% shortening) adjacent to the Main Mártir thrust. The overall across strike width of this fold and thrust belt is ~25 km (Johnson et al., 1999a; Wetmore et al., 2002). The Main Mártir thrust also corresponds to the transition between intrusives to the west that exhibit no observed inherited older zircons and yield primitive isotopic signatures from those to the east that do possess Precambrian zircons and evolved isotopic signatures (Johnson et al., 1999a). Johnson et al. (1999a) constrain the timing of the main pulse of deformation within this fold-and-thrust belt and across the Main Mártir thrust to be between ca. 115 and 108 Ma.

In the northern part of the arc segment, the fold-and-thrust belt that includes the Main Mártir thrust is deflected into sub-parallelism with the trace of the ancestral Agua Blanca fault (Wetmore et al., 2002). This deflection involves as much as 50° of strike rotation in a counterclockwise sense (i.e., from ~N15°W to N65°W; Fig. 5). Our recent mapping in the area south of the fault (Fig. 5) has resulted in the identification of a pronounced break in strain intensity across a northeast-dipping ancestral Agua Blanca fault. Overall deformation increases dramatically with proximity to the ancestral Agua Blanca fault with folds becoming isoclinal and strain intensities becoming immeasurably large. Shear sense determined from lineation-parallel sections within the underlying Alisitos Formation suggests a strong component of northeast side-up motion across the fault, which is also consistent with the southwest vergence of all folds developed in this region. However, additional kinematic information was obtained from sections perpendicular to the lineation suggesting an additional component of sinistral shear opposite current motion across the nearby active brittle fault.

In summary, the western zone of the Peninsular Ranges south of the ancestral Agua Blanca fault is composed of plutons that intrude the Albian Alisitos Formation, which is characterized by subaqueous volcanic deposits (dominantly basalts and andesites), epiclastically reworked volcanic sediments, and subordinate amounts of carbonate. Geochemical and geochronological studies of the volcanics and plutonics suggest derivation from a depleted mantle source without contamination from continental crust or continentally derived deposits. The northern and eastern boundaries of the Alisitos arc are characterized by broad (>20 km), southwest-vergent fold-and-thrust belts with the Main Mártir thrust and the ancestral Agua Blanca fault juxtaposing the Alisitos arc with the central zone and Santiago Peak Volcanics, respectively.

DISCUSSION

The above descriptions of the western and central zones of the Peninsular Ranges batholith clearly illustrate the dramatic differences north and south of the ancestral Agua Blanca fault. These differences include the following (Table 1): (1) the presence or absence of Late Triassic through Jurassic continentally derived turbidite sequences (north) and/or Early Cretaceous submarine sedimentary strata (south), (2) the environment of deposition of Early Cretaceous western zone volcanics and contact relations between these volcanics and the continentally derived strata of the central zone (depositional, north; fault, south), (3) the presence of xenocrystic Precambrian zircons in plutons and volcanic flows of the western zone (present, north; absent, south), (4) the frequency of lava types of western zone volcanics (abundant rhyolites, north; abundant basalts, south), (5) the general distribution and intensity of deformation within the western zone (minor to moderate, north; 20-km-wide fold-and-thrust belt, south), and (6) the character of deformation associated with the ancestral Agua Blanca fault (truncation, north; deflection into subparallelism, south). We believe that these differences unambiguously indicate that the ancestral Agua Blanca fault is the along-strike continuation of the Main Mártir thrust, as together they served as a nonterminal suture accommodating the juxtaposition of the Alisitos arc segment to the Santiago Peak arc segment and North America. Additionally, the ancestral Agua Blanca fault must have accommodated the tectonic removal of the pre-Cretaceous accretionary prism, which is represented by the Bedford Canyon Complex to the north, prior to Alisitos arc accretion.

An Alternative Tectonic Model

During the Late Triassic through at least the Jurassic, the southwestern margin of North America north of the ancestral Agua Blanca fault was the site of a considerable amount of turbidite sedimentation. These deposits, which contain Precambrian zircons and olistostromal blocks of miogeoclinal quartzite,

TABLE 1. VARIATIONS IN THE PENINSULAR RANGES BATHOLITH NORTH AND SOUTH OF THE AGUA BLANCA FAULT

	North of Agua Blanca fault	South of Agua Blanca fault
Late Triassic–Jurassic clastic turbidites	Yes	No
Early Cretaceous clastic sediments	No	Yes
Depositional environment of Cretaceous arc volcanics	Subaerial	Submarine
Contact relations between Early Cretaceous volcanics and continentally derived sediments of the central zone	Depositional unconformity	Large ductile southwest-vergent shear zone
Inherited zircons	Observed within both volcanics and plutonics	Not observed in either volcanics or plutonics
Lava types	Andesites most abundant, but with ~40% comprised of dacites and rhyolites	Dominated by basalts, basaltic andesites, and andesites, dacites and rhyolites rare
Regional deformation	Weak to moderate, somewhat elevated in southeastern exposures	Intense within fold-and-thrust belt along eastern and northern limits to the Alisitos arc
Deformation associated with Agua Blanca fault	Truncation of regional structures without increases in strain or metamorphism	Regional change in structural trend, high strain intensities and amphibolite? Grade metamorphism

clearly exhibit a North American provenance. The presence of an arc to the east (Damon et al., 1983; Saleeby et al., 1992) active contemporaneously with turbidite sedimentation, combined with observed serpentinite blocks and olistostromes included within the section, suggest that the deformation exhibited by these sequences likely resulted during incorporation into an accretionary prism (Fig. 7, A and B [line A–A′]). Additionally, the westward younging of east-dipping Bedford Canyon Complex strata is consistent with the imbrication of coherent (albeit internally deformed) packages of stratified sediments forming duplexes in an accretionary wedge associated with a west-facing arc (e.g., Lash, 1985; Sample and Fisher, 1986; Sample and Moore, 1987).

Following deposition of the Bedford Canyon Complex and deformation within an accretionary prism setting, the entire section appears to have been uplifted, subaerially exposed, and erosionally beveled (Fig. 7, A and B [line C–C′]). This is consistent with the interpretation that the Santiago Peak Volcanics were deposited in a subaerial environment. A specific uplift event is not necessary to expose these strata to subaerial erosion. Rather, the strata of the Bedford Canyon Complex could have simply moved toward higher elevations as a function of time and the addition of material into the wedge, both scraped off at the toe, as the Bedford Canyon Complex appears to have been, and underplated in a manner similar to the process proposed for the uplift and exhumation of the Cascadia accretionary wedge in Washington state (Brandon et al., 1998).

In addition to uplift of strata within the accretionary prism, a further result of long-term accretion of material to the southwestern margin of North American may have been the apparent westward migration of magmatism that impinged upon the Late Triassic to Jurassic accretionary prism in the Early Cretaceous (Fig. 7A). However, other options could include a steepening of the subducting slab or the initiation of a new subduction zone outboard of an older one.

Regardless of the mechanism that caused the apparent migration, by the Early Cretaceous the Santiago Peak arc was being built on and through the southwestern margin of the North American continent. This interpretation is supported by observed depositional contacts between the volcanics and the continentally derived stratigraphy, xenocrysts of Precambrian zircon in both the volcanics and plutonics, xenoliths of sandstone and greywacke in the volcanic flows, and the presence of intrusions that cut the Bedford Canyon Complex and can be traced directly into the overlying flows of the Santiago Peak Volcanics. Furthermore, while the overall chemistry of the intrusive and extrusive magmas of the Santiago Peak arc are clearly derived from a depleted mantle source, the volcanics have been altered by moderate amounts of assimilation of silicic material and fluid-enhanced fractional crystallization, such that the overall distribution of lava types is strongly skewed away from the typical island arc assemblage and toward more silicic dacites and rhyolites.

Deformation within the Santiago Peak Volcanics is somewhat enigmatic in that the regional deformation is typically very minor (upright, open folds and minor offset (< 50 m), high-angle brittle faults). While part of this deformation may have been Early Cretaceous in age, some proportion of it must be Late Cretaceous or younger, given the steeply west-dipping paraconformity(?) between the Santiago Peak Volcanics and the overlying Late Cretaceous clastic strata of the western Santa Ana Mountains.

South of the ancestral Agua Blanca fault, the fact that Late Triassic through Jurassic sedimentary strata have been preserved only locally (i.e., Sierra San Pedro Mártir) suggests that this part of the Peninsular Ranges was largely emergent during this time

A

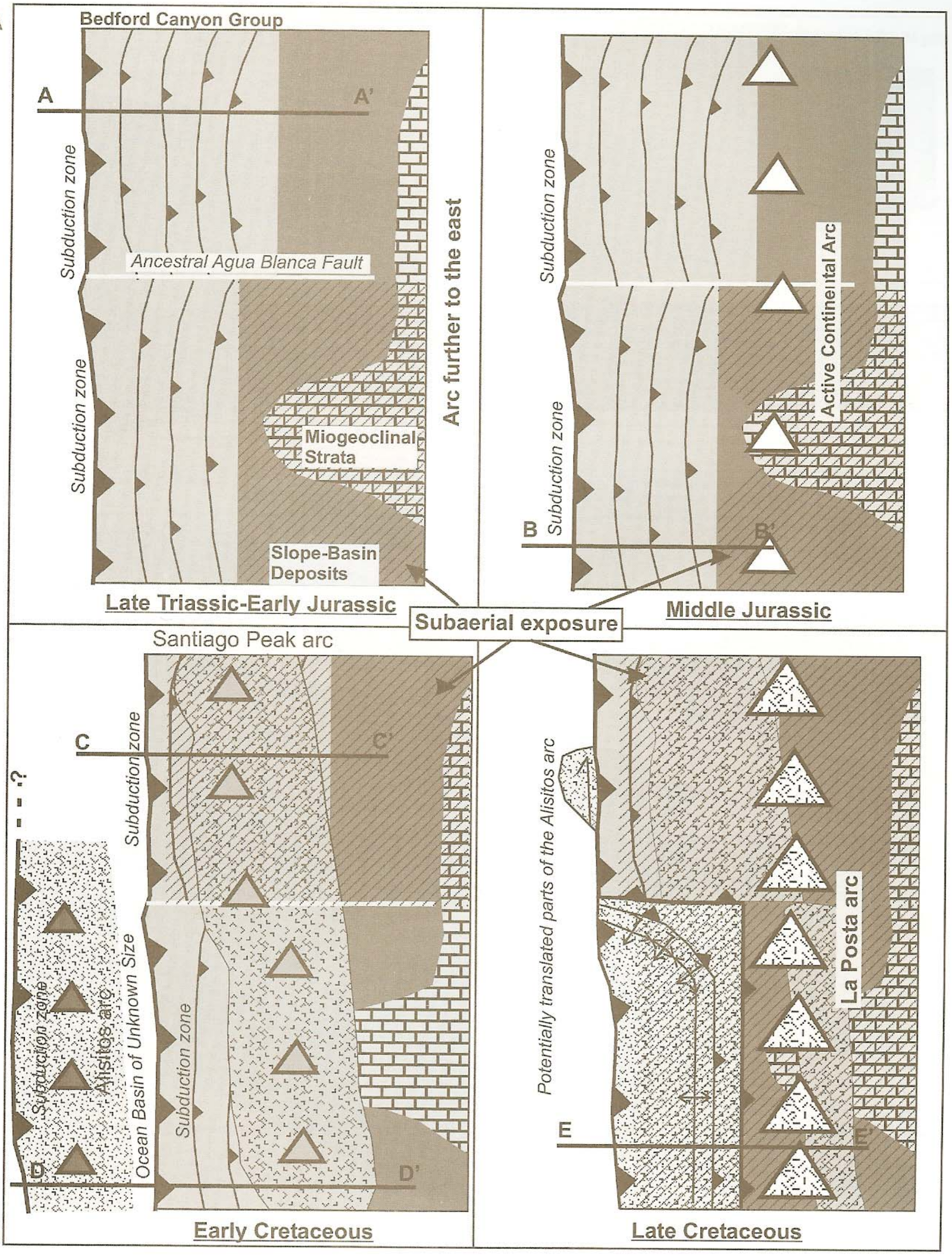

Figure 7 (on this and following page). A: Schematic depiction of Late Triassic through Early Cretaceous tectonic evolution of Peninsular Ranges batholith. B: Cross sections (lines A–A′ and C–C′) through Peninsular Ranges batholith north of ancestral Agua Blanca fault. C: Cross sections (lines B–B′, D–D′, and E–E′) through Peninsular Ranges batholith south of ancestral Agua Blanca fault.

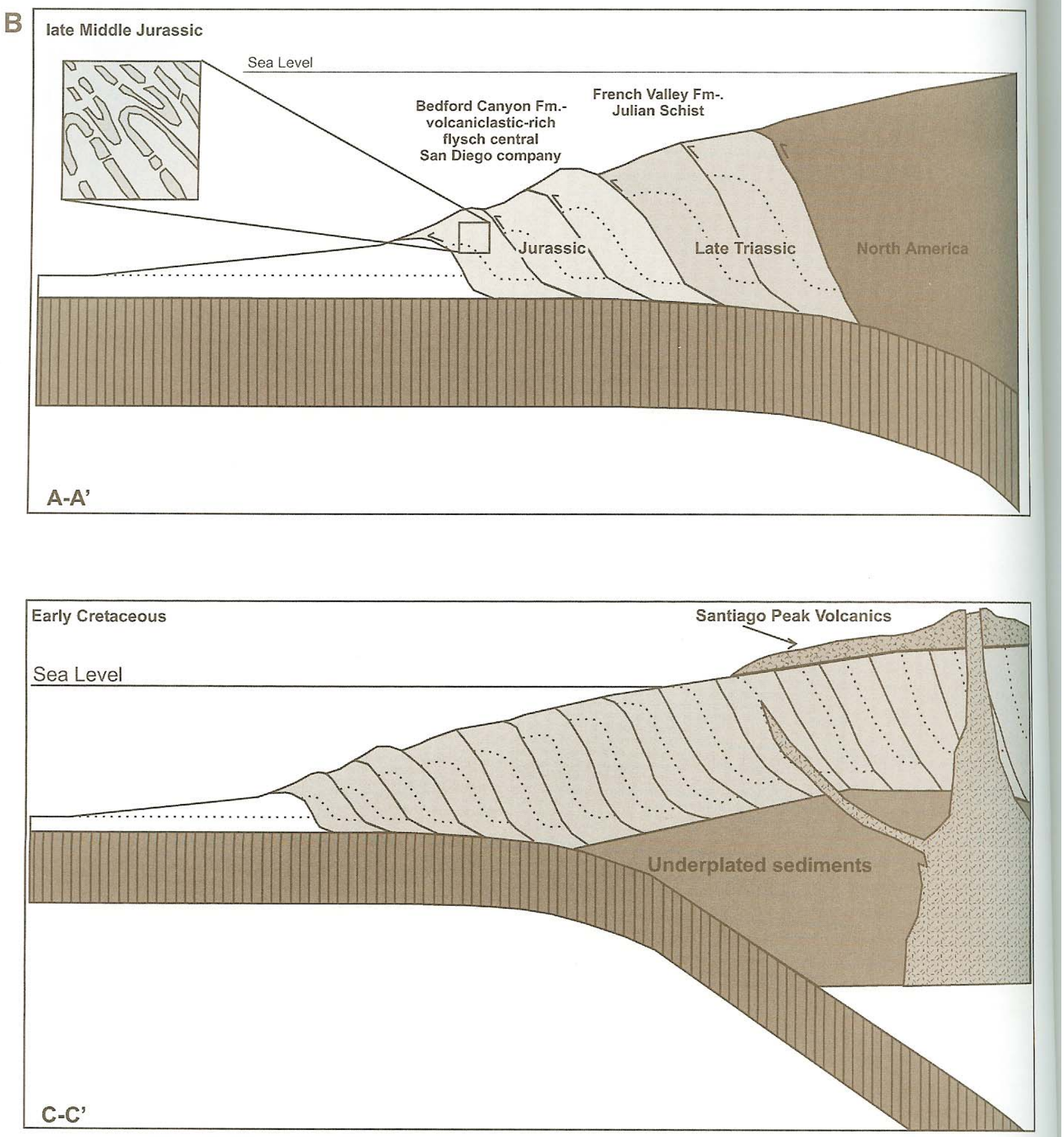

Figure 7. (*continued*)

(Fig. 7, A and C [line B–B′]). However, given that a continental arc did exist in Sonora, México (Ramon et al., 1983) during this time, the trench and accretionary prism represented by the Bedford Canyon Complex to the north of the ancestral Agua Blanca fault should have existed west of the present location of the central zone south of the fault. This is also consistent with the presence of earliest Cretaceous plutonics in the hanging wall of the Main Mártir thrust (Johnson et al., 1999a).

During the Early Cretaceous, the central zone of the Peninsular Ranges batholith south of the Agua Blanca fault subsided

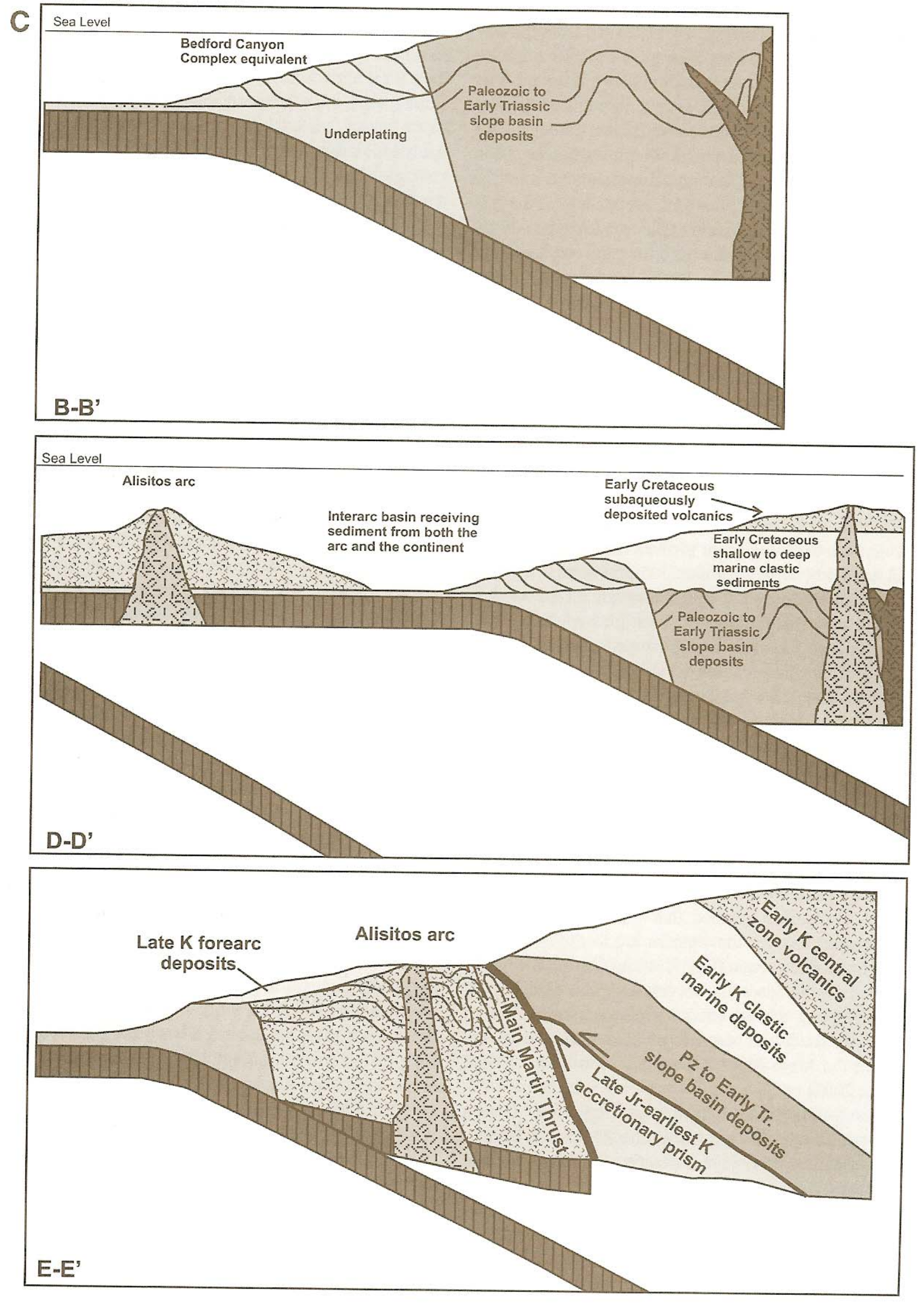

Figure 7. (*continued*)

below sea level and began receiving clastic detritus from the east (Fig. 7, A and C [line D–D′]). This appears to have been a relatively short-lived condition, as later in the Early Cretaceous this basin was filled or uplifted as clastic sedimentation gave way to the deposition of proximally derived volcanics that grade upward from submarine into subaerial deposits. The transition between clastic and volcanic deposits was contemporaneous with the deformation of the clastic strata prior to the deposition of the volcanics. This suggests that termination of the latest Jurassic–Early Cretaceous central zone basin may have, in part, resulted from tectonic closure. Like the Santiago Peak Volcanics, the volcanics of the central zone bear the signature of contamination by continentally derived materials implying derivation from sources within the central zone or from further east.

The volcanics/volcaniclastics of the Alisitos arc south of the Agua Blanca fault were deposited in a submarine environment and are believed to be everywhere in fault juxtaposition with continentally derived strata, including the Santiago Peak Volcanics (Fig. 7A). In fact, volcanic strata of the Alisitos arc exhibit no indication that rocks of continental derivation exist in the basement of this arc, such as the presence of xenocrystic Precambrian zircons in volcanics or plutonics, or evolved magmas, which can be shown to have otherwise assimilated clastic detrital material (e.g., Bedford Canyon Complex). Such observations led Johnson et al. (1999a) to argue that the Alisitos arc originated as an island arc developed on oceanic crust not previously associated with North America. This interpretation is also consistent with the prominence of basalts and andesites as the dominant petrologic types for volcanics of the Alisitos Formation.

The deformation within the Alisitos arc is much more widespread and, along its eastern margin, of greater intensity than that observed within the Santiago Peak arc to the north. Deformation associated with the southwest-vergent fold-and-thrust belt that parallels the Main Mártir thrust, the structure juxtaposing the Alisitos arc with North America–derived strata, suggests a causal link between the two. Goetz (1989), Johnson et al. (1999a), and Schmidt (2000) all concluded that this belt of deformation reflects the accretion of the western arc to the continental margin in the Early Cretaceous (Fig. 7, A and C [line E–E′]). In all of these models, the accretion occurs across an east-dipping subduction zone along the western continental margin. This is consistent with the southwest vergence of all identified structures associated with the Main Mártir thrust (Johnson et al., 1999a; Wetmore et al., 2002).

The fold-and-thrust belt along the ancestral Agua Blanca fault represents a unique feature within the Peninsular Ranges and is best explained by tectonic juxtaposition of the two western zone arc segments. The counterclockwise rotation of structures within the Alisitos arc into subparallelism with the ancestral Agua Blanca fault in the northern part of the arc, along with observed kinematics in this area, suggest that the northern Alisitos was strongly affected by sinistral transpression, opposite to displacements along the active fault. The continuation of southwest-vergent thrusting from the Main Mártir thrust to the ancestral Agua Blanca fault suggests that the latter represents the northward continuation of the former. Therefore, the ancestral Agua Blanca fault is interpreted to be the suture zone that juxtaposes the two arc segments of the western zone (e.g., Wetmore et al., 2002).

Additional Tectonic Considerations

The above tectonic history brings several additional tectonic problems into focus. Deformations observed in eastern San Diego County associated with the Cuyamaca Laguna Mountain Shear Zone and those of the faults in Cañon Sierra Calamajue have been interpreted as sutures juxtaposing western and central zones. However, these interpretations are not reconcilable with the above models; thus, further discussion is necessary. Additionally, the above tectonic model implies that components of the central zone observed north of the ancestral Agua Blanca fault must have been tectonically removed to the south of the fault and that the Late Cretaceous exhumation observed in the central zone along the length of the Peninsular Ranges cannot everywhere be attributed to accretion-related deformation.

Deformation in the Sierra Calamajue was interpreted by Griffith and Hoobs (1993) as resulting from the accretion of the Alisitos arc to the North American margin. However, as noted above, volcanics containing inherited Precambrian zircons and limestone conglomerates yielding North American affinity fossils are observed west of the faults mapped in Cañon Calamajue. These observations are inconsistent with those from the Alisitos Formation in other areas of the Peninsular Ranges. Two alternative explanations for this apparent inconsistency are: (1) these faults do not form the suture, rather the suture likely exists further to the west of the Sierra Calamajue; and (2) continentally derived sediments and volcanics dominated the Early Cretaceous basin that existed between the continent and the Alisitos arc such that these strata were deposited across the intervening trench and onto the Alisitos island arc. The existence of the suture at a more westerly position than the Cañon Calamajue is certainly possible given the overall lack of mapping in this area combined with the large areas to the west of the Sierra Calamajue covered by Tertiary and Quaternary strata. The latter alternative is likewise possible given that the Alisitos arc was largely submerged throughout its depositional history and as the arc got progressively close to North America, the basin between the two continually shrank. However, more detailed study of this part of the Peninsular Ranges is required before these or other potential alternatives can be distinguished.

The Cuyamaca Laguna Mountain Shear Zone is a northwest-striking, east-dipping ductile shear zone exposed in eastern San Diego County (Fig. 1). This structure, which is approximately coincident (±10 km) with many of the major chemical, petrological, and mineralogical transitions between western and central zones (e.g., Silver et al., 1979), has traditionally been identified as an Early Cretaceous suture between North America and the Santiago Peak arc (e.g., Todd et al., 1988). However, a recent study of the structural evolution of the Cuyamaca Laguna Mountain Shear Zone by Thomson and Girty (1994) reinterpreted Early Cretaceous deformation exhibited by the structure as having resulted from strain concentration upon a preexisting lithospheric boundary between oceanic and continental crusts. This interpretation is largely based on the observation that the continentally derived strata of the Julian Schist are present on both sides of the Cuyamaca Laguna Mountain Shear Zone. We believe that the designation of this structure as an intra-arc shear zone by Thomson and Girty (1994) and not an arc-continent suture is consistent with the data present in this paper.

The juxtaposition of the Alisitos arc with the central zone implies that a substantial portion of the western margin of North America in this region must have been removed. This follows from the interpretation that the Alisitos arc, unlike the Santiago Peak arc, did not develop across the former accretionary prism, but rather was built on oceanic crust. Wetmore et al. (2002) proposed two hypotheses to explain the missing accretionary prism: strike-slip translation and subduction. They cite the observed steep lineation with northeast side-up sense of shear along the Main Mártir thrust and lack of kinematic indicators suggesting a component of lateral translation in this area to argue that the missing terrane was most likely subducted beneath the central zone. They further suggest a means of testing this hypothesis through the geochemical study of the Late Cretaceous intrusive bodies present in the central zone of the Peninsular Ranges batholith north and south of the Agua Blanca fault. In this instance, if the accretionary prism south of the Agua Blanca fault was subducted, it should be recorded as an identifiable chemical signature within these magmas (e.g., Ducea, 2001) and be absent from magmas north of the fault.

During the Late Cretaceous, the entire length of the central zone of the Peninsular Ranges batholith experienced an enormous amount of exhumation and denudation (Lovera et al., 1999; Schmidt, 2000; Kimbrough et al., 2001). This uplift and associated deformation has commonly been attributed to the accretion or reaccretion of the western zone of the batholith (e.g., Todd et al., 1988). However, if the above model is correct, then accretion only affected the central zone adjacent to the Alisitos arc and no such mechanism can be called upon to drive the Late Cretaceous event in the central zone adjacent to the Santiago Peak arc. Additionally, the timing of this exhumation event, between 100 and 85 Ma (Schmidt, 2000), is as much as 15 m.y. after the accretion of the Alisitos arc to the continental margin, indicating that even this accretion event was unlikely to have been fully responsible for the observed Late Cretaceous uplift and exhumation in the central zone adjacent to the Alisitos arc.

In the absence of terrane accretion to drive deformation and exhumation within the central zone of the Peninsular Ranges batholith, two alternative models have been proposed: increased coupling between the subducting and overriding plates at the trench (Schmidt et al., 2002) and the thermal-mechanical effects associated with the emplacement of the volumetrically large La Posta suite of plutons (Kimbrough et al., 2001). While the temporal overlap between magmatism, uplift, and exhumation are enticing, the true mechanism(s) for magmatism to drive the latter two processes are simply too vague at present to view the coincidence of these events as one of cause and effect. Additionally, the temporal overlap between the La Posta event and uplift is only partial in that uplift both predates and postdates the magmatic event by several million years each. Conversely, the relative plate motion vectors (Engebretson et al., 1985) indicate a high angle of convergence between North America and subducted oceanic crust from 100 to 85 Ma at relatively high velocities, which is consistent with an increased coupling model. However, additional constraints are required to further resolve the mechanism(s) that drove this Late Cretaceous event.

Alternative Models

Tectonic models discussed in the introduction require some dramatically different processes and tectonic geometries to explain the present configuration of the Peninsular Ranges. These include the rifted-fringing arc model (Gastil et al., 1981; Busby et al., 1998) and the accretion of an exotic, east-facing island arc (Dickinson and Lawton, 2001). The rifted-fringing arc model proposed by Gastil et al. (1981) and Busby et al. (1998) is based on observations made from areas both north and south of the ancestral Agua Blanca fault as well as from the Continental Borderlands terrane.

Rifted-fringing arc models are commonly based on the observation of large amounts of "flysch-like" strata preserved within the central portions of batholiths (e.g., Gastil et al., 1981). Gastil et al. (1981) and Gastil (1993) correlated the turbidite sequences of the central zone for the entire length of the batholith and identified them all as "Triassic-Cretaceous back-arc clastics." The Gastil et al. (1981) model proposes that the entire western zone of the batholith was rifted from the continental margin in the Triassic, allowing for the deposition of these strata. Several objections can be raised against this interpretation. First, if a fragment of the continent were rifted in the Triassic, then the ages of the strata should be older in the western and eastern zones and younger in the central zone. This is not consistent with the age distributions of central zone strata, either north or south of the ancestral Agua Blanca fault. Second, if rifting and the development of a fringing arc occurred in the Triassic, volcanics and plutonics of this age should be present in the western zone. While some Jurassic epiclastically reworked volcaniclastics have been observed in central San Diego County, their volume is far too small to support their interpretation as a Triassic-Jurassic arc. Triassic magmatism may be preserved in eastern San Diego County (e.g., Thomson, 1994), but no evidence supports the existence of an arc of this age in the western zone north or south of the ancestral Agua Blanca fault.

The rifted-fringing arc model proposed by Busby et al. (1998) is based on observations of the western zone in the area south of the ancestral Agua Blanca fault (e.g., Fackler-Adams and Busby, 1998) and stratigraphy preserved in the Continental Borderlands terrane. Busby et al. (1998) partition their model into three phases that correspond to time periods of 220–130 Ma (Phase one), 140–100 Ma (Phase two), and 100–50 Ma (Phase three). In their model, phase one represents the rifting of a fragment of the continental margin to form the extensional fringing arc of phase two, which ultimately becomes reaccreted to the continental margin during phase three. In general, the same objections that were raised against the Gastil et al. (1981) rifted-fringing arc model apply here. However, there are several additional complications from the Busby et al. (1998) model, which are described below.

The identification of an early Mesozoic accretionary prism with continental ties (e.g., Boles and Landis, 1984; Sedlock and Isozaki, 1990) within the Continental Borderlands terrane implies that this terrane must have been adjacent to a continent in the Mesozoic. However, strike-slip translation of this terrane during the Late Cretaceous (e.g., Busby et al., 1998) makes correlations between the Jurassic and Early Cretaceous strata of the Continental Borderlands terrane and the Early Cretaceous arc strata of the western zone of the Peninsular Ranges batholith highly suspect. Presently, no data exist to indicate that the Continental Borderlands were adjacent to the Peninsular Ranges batholith prior to the Late Cretaceous (e.g., Klinger et al., 2000).

Detailed mapping of structures and stratigraphic sequences within the Alisitos arc southeast of San Quintin by Fackler-Adams and Busby (1998) form the basis for events in phases one and two of the Busby et al. (1998) model. It is important to note here that strata and intrusive bodies older than ca. 116 Ma have not been identified within the Alisitos arc. Therefore, none of phase one and only the last 16 m.y. of phase two are potentially represented in this part of the Peninsular Ranges. This 16 m.y. coincides with the time during which we propose that the Alisitos arc is characterized by northeast-southwest–directed shortening associated with its accretion to the continental margin. Fackler-Adams and Busby (1998), however, argue for a rifting arc model based on the presence of northeast-trending dikes and small-offset (<100 m) normal faults, and ~200 m of basalts capping the section. Their interpretation of these observations seems somewhat overstated, given that all extensional features are oriented perpendicular to the extension directions suggested by Busby et al. (1998) and that the magnitudes of fault offset and dike-induced dilation are all very small. Furthermore, the relatively small volume of basaltic lavas termed "rift-related" could just as easily be ocean island basalts. No reported chemical data support the designation of these lavas as rift-related. Similarly, north of the ancestral Agua Blanca fault, the identification of extensional structures and volcanic petrologies have not been reported, even though a greater percentage of the time discussed in the Busby et al. (1998) model is preserved in the rock record.

Finally, if the western zone of the Peninsular Ranges were to have developed as a reaccreted rifted-fringing arc, at least some proportion of the basement of this fringing arc must have be composed of continentally derived materials. It therefore follows that volcanics and plutonics that were emplaced through and deposited on these continental materials should show some contamination, such as that observed in the Santiago Peak Volcanics and associated plutonic units. However, this is not the case for the Alisitos arc. We conclude that models identifying any portion of the western zone of the Peninsular Ranges batholith as having evolved as a rifted-fringing arc are untenable.

Dickinson and Lawton (2001) recently proposed a tectonic model wherein the western zone of the Peninsular Ranges batholith, as part of the larger Guerrero superterrane, originated as an east-facing island arc, exotic to North America. This proposal arises from supposition that the only proposed alternative models are one of a rifted-fringing arc (e.g., Busby et al., 1998), combined with the observation of east-directed thrusting along the eastern margin of the Guerrero superterrane in mainland México (Tardy et al., 1994). Dickinson and Lawton (2001) are also influenced by the tradition of poorly constrained age ranges for magmatism within the western zone of the batholith (i.e., that it was a Jurassic-Cretaceous arc).

As discussed in detail above, models supporting the accretion of the western zone of the Peninsular Ranges batholith (either as an east- or west-facing arc) do not conform with the relationships that exist between the Santiago Peak Volcanics and the continentally derived Bedford Canyon Complex. South of the ancestral Agua Blanca fault the Alisitos arc and adjacent central zone define a broad, west-vergent fold-and-thrust belt. Early Cretaceous east-vergent structures are known locally from the eastern zone in the southern Sierra San Pedro Mártir area (Schmidt, 2000) but have not been reported from most areas of the Peninsular Ranges. If the Alisitos arc had been an east-facing arc, and a contemporaneous west-facing continental arc existed in the present location of the central zone, then the accretionary prisms associated with both of these arcs have been removed. Given the lack of east-directed structures to support this interpretation, the additional tectonic complexity of having to remove an additional accretionary prism seems unnecessary. Finally, given the descriptions here of the dramatic differences in the tectonic evolution of the Peninsular Ranges across the ancestral Agua Blanca fault, there is no reason to think that similar transitions cannot exist between the Peninsular Ranges and its on-strike continuation in mainland México.

CONCLUSIONS

The Mesozoic tectonic evolution of the southwestern margin of North America has been one of the more poorly resolved aspects of Cordilleran geology. A variety of competing models have been proposed, most of which disagree on even the most fundamental aspects (e.g., origin of the western zone of the Peninsular Ranges). We suggest that, in part, the differences between these models are the result of tectonically significant variations in the along-strike character of the continental margin, and they are most pronounced across the Agua Blanca fault of northern Baja California, México. Variations across this fault can be observed in the geology of the central and western zones of the Peninsular Ranges strata as old as the Late Triassic. These variations include: (1) the presence or absence of Late Triassic through Jurassic continentally derived turbidite sequences (north) and/or

Early Cretaceous submarine sedimentary strata (south), (2) the environment of deposition of Early Cretaceous western zone volcanics, and contact relations between these volcanics and the continentally derived strata of the central zone (depositional, north; fault, south), (3) presence of xenocrystic Precambrian zircons in plutons and volcanic flows of the western zone (present, north; absent, south), (4) the frequency of lava types of western zone volcanics (abundant rhyolites, north; abundant basalts, south), (5) the general distribution and intensity of deformation within the western zone (minor to moderate, north; 20-km-wide fold-and-thrust belt, south), and (6) the character of deformation associated with the ancestral Agua Blanca fault (truncation, north; deflection into subparallelism, south).

We propose a model that specifically incorporates these along-strike variations. During Late Triassic through Jurassic, the central zone north of the ancestral Agua Blanca fault was the site of sedimentation of continentally derived turbidite sequences that were ultimately incorporated and deformed within an accretionary prism setting. We propose that all of the Late Triassic through Jurassic strata of similar lithology present within the central zone north of the Agua Blanca fault should be included within a single stratigraphic group, here termed the Bedford Canyon Complex. By the Early Cretaceous, the Bedford Canyon Complex was uplifted and exposed to subaerial erosion prior to the unconformable deposition of the Santiago Peak Volcanics. South of the ancestral Agua Blanca fault, the central zone was generally not submerged as it was to the north; thus, deposits of Late Triassic through Jurassic age are only preserved locally in this part of the batholith. The outboard trench and accretionary prism (i.e. Bedford Canyon Complex correlative strata) presumably existed west of the present-day central zone. During the latest Jurassic through Early Cretaceous, the central zone south of the ancestral Agua Blanca fault became submerged below sea level and filled with shallow to deep water sediments overlain by subaqueously deposited volcanics that grade upward into subaerial volcanics. Contemporaneous with Early Cretaceous basin sedimentation in the central zone, the Alisitos arc initiated on oceanic crust not previously associated with the continental margin. The Alisitos arc impinged upon the continental trench between 115 and 108 Ma and during accretion, forcing the subduction of the associated accretionary prism. While some uplift and exhumation of the central zone adjacent to the Alisitos arc may be attributed to the accretion of that arc, the majority of this central zone event was most likely caused by increased coupling between the continent and the subducting slab.

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