Segmentation of the Laramide Slab—evidence from the southern Sierra Nevada region

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ABSTRACT

During the latest Cretaceous-early Paleogene Laramide orogeny, the lithosphere beneath the southernmost Sierra Nevada batholith and the adjacent Mojave Desert region batholith was sheared off and displaced deeper into the mantle. The lithosphere beneath the greater Sierra Nevada batholith to the north was left intact until mid-Miocene time, when fragments of it were entrained as volcanic xenoliths. The Laramide slab was evidently segmented into a shallow flat segment to the south and a deeper segment to the north. Shearing off of the upper mantle to the south was followed by the tectonic underplating of schists derived from Franciscan subduction complex and possibly forearc basin protoliths. The overlying batholithic crust was deformed, deeply denuded, and tectonically breached westward across its forearc region while the schists were underplated. Westward breachment resulted from a combination of west-directed thrusting and extensional collapse. The westernmost breached rocks were tectonically removed by a combination of trench linked transform and subduction erosion processes. Subsequent tectonic erosion by the Neogene San Andreas transform has left the Salinia and the San Gabriel terranes as dispersed residual fragments of the westward breached arc segment.

The shallow slab segment appears to have been ~500 km in width, measured along the plate edge. To the south, the slab descent appears to have remained deep beneath the Peninsular Ranges batholith. Classic Laramide structures of the craton are concentrated in a corridor that corresponds to the shallow slab segment as defined by plate edge relations and the corresponding trajectory of Farallon–North American relative plate motions when viewed on a pre-Neogene palinspastic base. The plate interior is suggested to have been deformed first by end loading as the shallow slab segment initially descended beneath the plate edge, and then by greater basal traction components as the shallow segment progressed beneath the cratonic region. The subcontinental mantle lithosphere beneath the cratonic deformation zone remained intact through Laramide time.

Similar segmented slab topologies have been resolved beneath the modern Andean orogen where the shallow segments are correlated with the subduction of aseismic ridges. A number of researchers have suggested that the Laramide orogeny arose from the subduction of a counterpart of the Hess-Shatsky large igneous province of the northwest Pacific basin. Fragments of rock assemblages that are correlative to the Hess-Shatsky province that were accreted to the Franciscan complex in Laramide time support this view. Recognition of the resulting shallow slab segment and its trajectory beneath North America explains the geographic focusing of Laramide deformation, relative to the rest of the Cordilleran orogen, and the relationships between plate edge and plate interior deformational regimes.

Keywords: tectonics, subduction, delamination, Cordillera, Laramide.

INTRODUCTION

The Laramide orogeny is recognized as a regional compressional event that deformed the southwest North American craton in latest Cretaceous-early Paleogene time (Miller et al., 1992). A commonly cited plate tectonic mechanism for the orogeny is intensified traction and tectonic erosion of the subcontinental mantle lithosphere due to flattening of the subducted slab (Coney and Reynolds, 1977; Dickinson and Snyder, 1978; Bird, 1988). The response of the craton was deformation and uplift along a north-northeast–trending corridor extending from southwest Arizona through Wyoming (Fig. 1). This intracratonal deformation zone is for the most part inboard of the Cordilleran (Sevier) foreland fold-thrust belt, thereby calling for special circumstances relative to much of Cordilleran tectonic history. Slab flattening at Laramide time seemingly offers such a special circumstance, although the dynamics responsible for slab flattening are not well understood, nor is the reason for the geographic restriction of Laramide deformation relative to the much more regionally extensive Cordilleran active margin. Such a geographic focusing of Laramide deformation has been suggested to have resulted from the subduction of a counterpart of the Hess-Shatsky large igneous province of the northwest Pacific basin, which was embedded in the Farallon plate (Livaccari et al., 1981; Henderson et al., 1984; Barth and Schneiderman, 1996). The analysis offered here finds much merit in this view, although the main proposition presented here is not contingent on this view. This proposition asserts that the Laramide slab possessed a shallow slab segment and that the subduction of this shallow segment can be correlated with both plate edge and interior Laramide deformation.

Geologic events along the southwest Cordilleran plate edge that have been attributed to Laramide tectonics include: 1) the cessation of arc magmatism in the Sierra Nevada batholith and associated modification of the subbatholith geotherm by conductive cooling from below (Dumitru et al., 1991); 2) the low-angle

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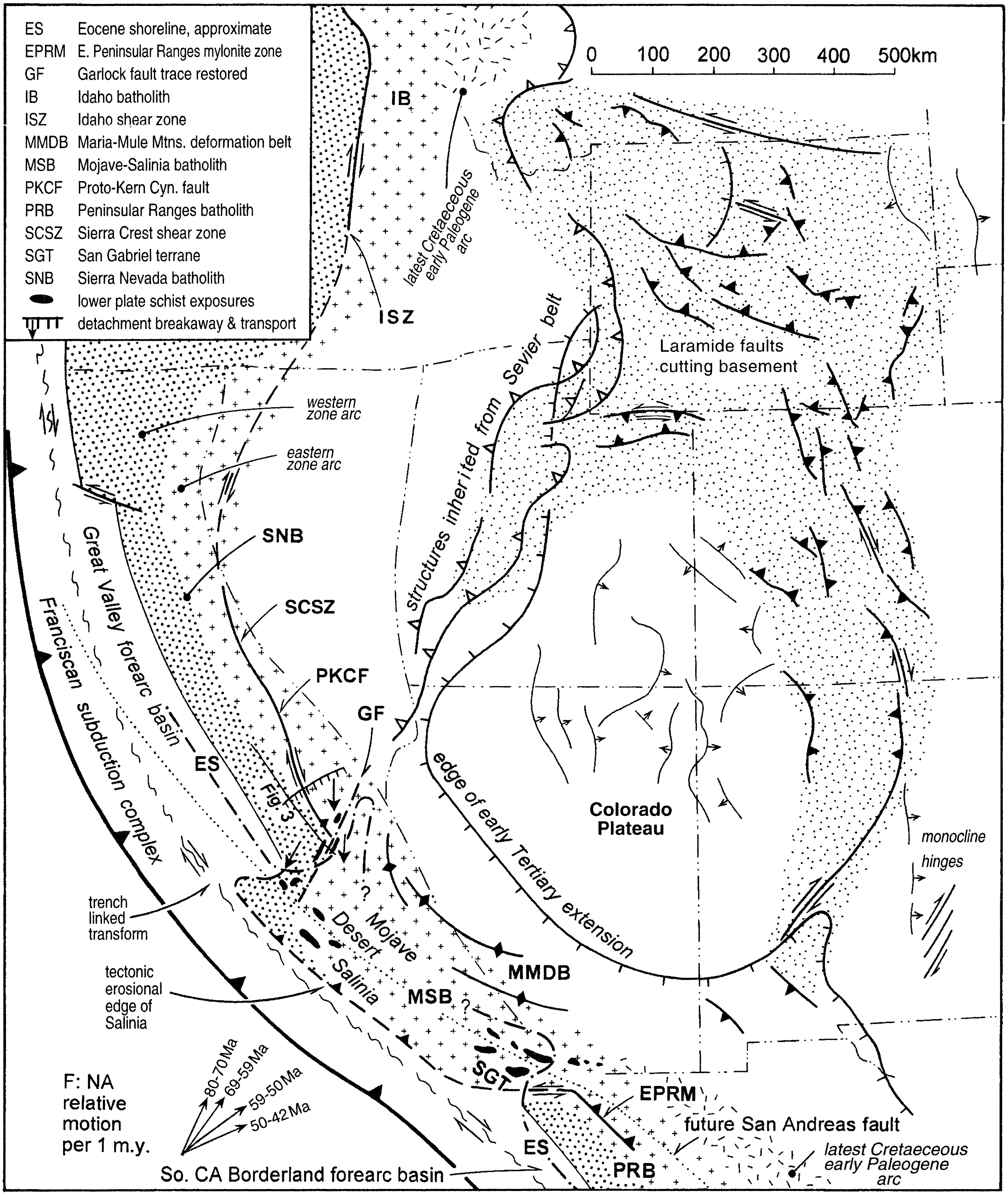
ES Eocene shoreline, approximate
EPRM E. Peninsular Ranges mylonite zone
GF Garlock fault trace restored
IB Idaho batholith
ISZ Idaho shear zone
MMDB Maria-Mule Mtns. deformation belt
MSB Mojave-Salinia batholith
PKCF Proto-Kern Cyn. fault
PRB Peninsular Ranges batholith
SCSZ Sierra Crest shear zone
SGT San Gabriel terrane
SNB Sierra Nevada batholith
lower plate schist exposures
detachment breakaway & transport
0 100 200 300 400 500km
IB
latest Cretaceous early Paleogene arc
ISZ
structures inherited from Sevier belt
Laramide faults cutting basement
western zone arc
eastern zone arc
SNB
SCSZ
PKCF
GF
Great Valley forearc basin
Franciscan subduction complex
ES
Fig 3
Colorado Plateau
edge of early Tertiary extension
monocline hinges
trench linked transform
tectonic erosional edge of Salinia
Mojave Desert
Salinia
MMDB
MSB
SGT
EPRM
future San Andreas fault
F: NA relative motion per 1 m.y.
80-70Ma
69-59Ma
59-50Ma
50-42Ma
So. CA Borderland forearc basin
ES
PRB
latest Cretaceous early Paleogene arc

thrust emplacement of Franciscan-affinity greywacke-basalt assemblages and their metamorphism in high-pressure greenschist–amphibolite facies (Rand-Pelona-Orocopia schists); and 3) the spatially related deformation, denudation, and westward breachment of an ~500-km-long segment of the Cordilleran batholith belt above the underplated schists (Silver, 1983; May, 1989; Jacobson et al., 1996; Malin et al., 1995; Barth and Schneiderman, 1996). The disrupted segment of the batholith belt corresponds to much of the Mojave Desert, Salinia and the San Gabriel terrane as restored to their pre-Neogene positions along the San Andreas fault, and the adjacent southern Colorado River Desert region. The northern end of the disrupted segment of the batholith belt coincides with a zone of deep denudation of the southernmost Sierra Nevada batholith that has rendered a structurally continuous oblique crustal section (Saleeby, 1990; Pickett and Saleeby, 1993). The southern end of the disrupted segment of the batholith belt corresponds to the northern Peninsular Ranges batholith. For discussions below, it is useful to symbolize these three segments of the batholith belt as: SNB = Sierra Nevada batholith; MSB = Mojave Desert–Salinia batholith, including the San Gabriel terrane and adjacent southern Colorado River Desert basement complexes; and PRB = Peninsular Ranges batholith.

Insights regarding the deep structure of the SNB in Laramide time are augmented by petrologic and geochemical data on lower-crust–upper-mantle xenoliths that were entrained in mid-Miocene volcanic rocks from the San Joaquin volcanic field, the location of which is shown in Figure 2 (Dodge et al., 1986, 1988; Ducea and Saleeby, 1996, 1998; Ducea, 2001; Lee et al., 2000; Saleeby et al., 2002). Constraints on the lower-crust–upper-mantle structure posed by the oblique crustal section, along with seismic and the xenolith data, together carry important implications regarding the topology and some of the effects of the Laramide slab. These implications and their relations to a spectrum of geologic features attributed to the Laramide orogeny are the subject of this paper.

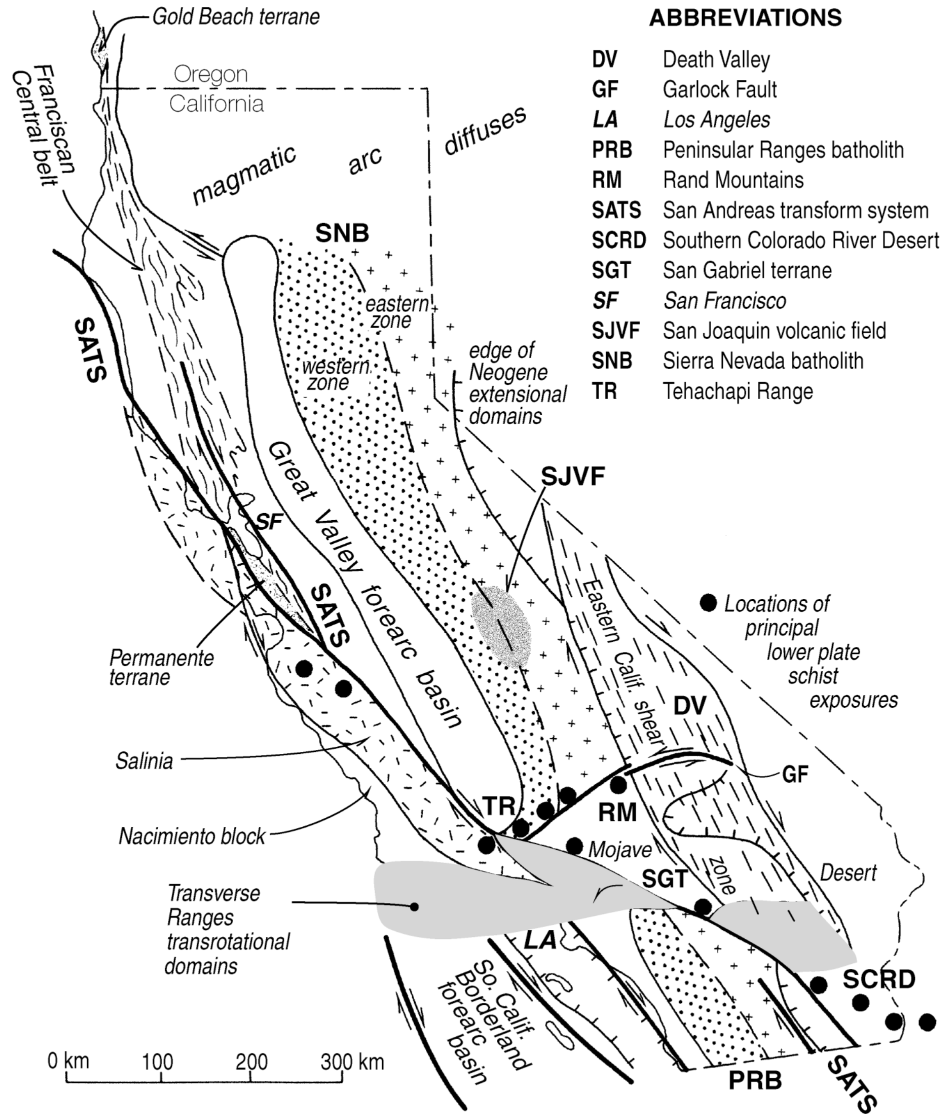

Figure 2. Map of California region showing in generalized form a number of key tectonic and geographic features that are referred to in text. The San Andreas transform system, Transverse Ranges transrotational deformation, Neogene extension, and the eastern California shear zone constitute main superposed deformations that were restored in the California region for the construction of the Figure 1 palinspastic base.

Much of the discussion will focus on Figure 1, which is a reconstruction of the principal tectonic elements of the southwest U.S. region at late Laramide time. Figure 2 shows some of these elements as they occur in their current geological setting in California, as well as the major Neogene tectonic systems that are restored on Figure 1. The key restorations are: 1) Salinia and the San Gabriel terrane along the San Andreas transform system (Ross,

Figure 1. Map showing selected tectonic and basement features of the southwest Cordillera at the close of the Laramide orogeny on a pre-Neogene palinspastic base. This map shows how the breached segment of the southwest Cordilleran batholithic belt, expressed primarily by Salinia and the San Gabriel terrane, lies in a north-northeast–trending deformation corridor that includes classic cratonal structures of the Laramide orogeny, and that this corridor is generally parallel to the Farallon–North American relative plate motions for Laramide time. The restored trace of the Garlock fault is used as a surface tracer for the position of the inflection in the slab. This tracer and its north-northwest projection bound the northwest margin of the deformation corridor that is consistent with the slab segmentation model for Laramide deformation. References given in text.

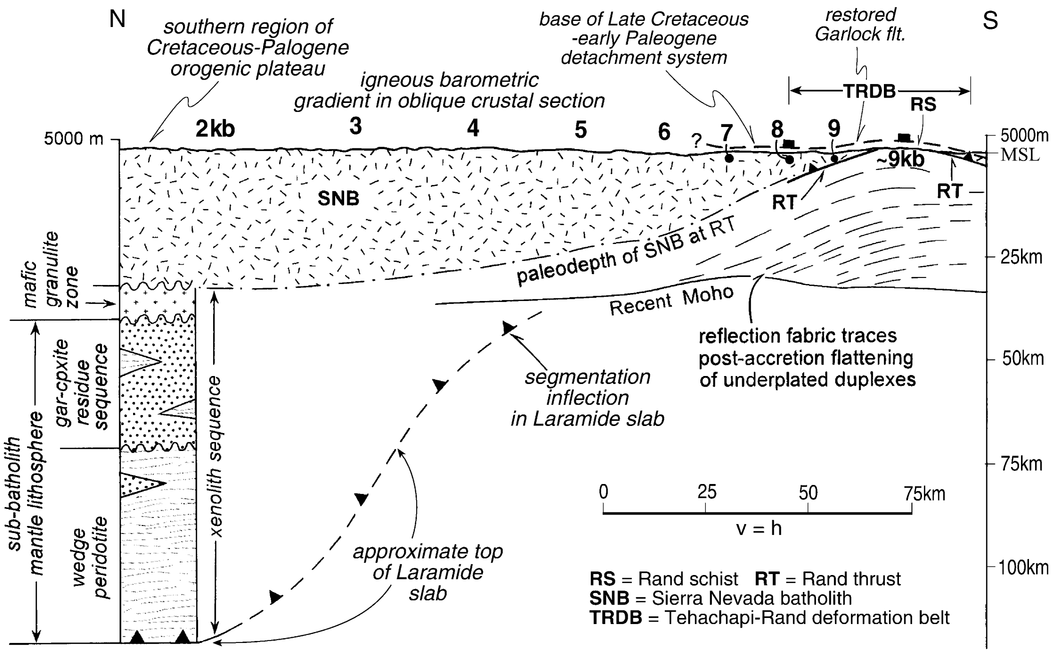

Figure 3. Generalized cross section from the central Sierra Nevada region southward along oblique crustal section and across Tehachapi-Rand deformation belt into the northernmost Mojave Desert with the Rand Mountains complex restored to its pre-Neogene position relative to the Sierra Nevada. General location of section line shown in Figure 1. This section shows contrasting deep-crust–upper-mantle structures for central and southernmost Sierra Nevada region following Laramide orogeny, revealing a segmentation in the subducted slab with the removal of the subbatholith mantle lithosphere and underplating of the Rand schist to the south. The subduction trajectory of the slab was roughly at right angles to and directed into the cross-section trend. References given in text.

1984; May, 1989; Hall, 1991; Silver and Mattinson, 1986); 2) transrotational deformation of the Transverse Ranges (Hornafius et al., 1986); 3) displacement along the Garlock fault (Malin et al., 1995); and 4) transtensional strain across the Death Valley region (Snow and Wernicke, 2000). The compatibility of these restorations with the structure of the Mojave Desert presents a problem, for which the answer is presumed to lie in the disputed kinematic patterns of Neogene extension and distributed dextral shear along the Mojave segment of the eastern California shear zone (cf. Dokka, 1986; Glazner et al., 1989, 1994; Dokka and Travis, 1990; Henry and Dokka, 1992). Furthermore, it is asserted here that Laramide tectonics left much of the Mojave Desert basement in a tectonically layered state, which in conjunction with only scattered basement exposures expressed today, greatly complicates the restoration of superposed Neogene deformation. The Figure 1 reconstruction also incorporates generalized pre-Cenozoic reconstructions of the greater Basin and Range province region (Coney and Harms, 1984). Major structures of the Laramide and Sevier deformation belts are shown after Allmendinger (1992), Christiansen and Yeats (1992), Miller et al. (1992), and Tickoff and Maxson (2001).

Figure 1 also shows the trace of a longitudinal cross section along the southernmost SNB as it extends southward across the Tehachapi Range and the restored Rand Mountains of the northernmost Mojave Desert (Fig. 3). This cross section displays the critical structural features of the Tehachapi-Rand deformation belt, a complex structural system that lies along the southern Sierra-Mojave Desert transition and that is directly related to the denudation of the southern SNB oblique crustal section.

CONTRASTING DEEP CRUST-UPPER MANTLE SECTIONS IN LATEST CRETACEOUS-PALEOGENE TIME

The southern ~100 km of the SNB exposes a southward-deepening oblique crustal section through Cretaceous batholith-generated crust from ~2 kb to ~9 kb conditions, or ~7 km to ~35 km depths (Ague and Brimhall, 1988; Saleeby, 1990; Pickett and Saleeby, 1993; Wood and Saleeby, 1998). The oblique crustal section, in conjunction with seismic data (Fliedner et al., 2000) and xenolith data from the San Joaquin volcanic field, offer an in depth picture of the primary lithospheric structure for the SNB (Ducea and Saleeby, 1996, 1998; Saleeby et al., 2003). The batholithic crust is predominately felsic to ~35 km deep. Below lies an ~10-km-thick transition zone containing batholithic rocks and mafic garnet granulite residues/cumulates that in turn grade into an ~35-km-thick section dominated by garnet clinopyroxenite residues that, like the granulites, were produced during batholith generation. The garnet pyroxenites are interlayered with progressively more spinel and deeper garnet peridotites that extend to an ~125 km depth. This lithospheric section remained intact in the central Sierra region at least until the mid-Miocene time of xenolith entrainment. It is shown diagrammatically at the northern end of the Figure 3 cross section. The garnet pyroxenite and peridotite levels of the section correspond to the subbatholith mantle lithosphere that represents the conductively cooled mantle wedge beneath the Cretaceous Sierran arc.

The subbatholith mantle lithosphere structure exhibited for the central SNB contrasts sharply from the deep structure observed along the Tehachapi-Rand deformation belt, shown at the southern end of the Figure 3 section. Late Neogene high-angle faults have been restored on Figure 3 (after Burchfiel and Davis, 1981; Malin et al., 1995) in order to elucidate the structural relations of the belt. The southernmost Sierra (Tehachapi) seismic structure correlates with the northern Mojave seismic structure of the Rand Mountains area. In both areas, field observations and geophysical data indicate that the base of the batholithic crust and its underlying mantle lithosphere have been tectonically removed and replaced by the Rand schist (Cheadle et al., 1986; Silver and Nourse, 1986; Malin et al., 1995; Wood and Saleeby, 1998). In the northern Mojave Desert region, the Rand thrust and lower plate schist exhibit modest structural relief and form the core of an antiformal window. To the north in the southernmost Sierra, the schist is exposed in small windows and larger fault-bounded slices along the Garlock fault (Sharry, 1981; Ross, 1989; Wood, 1997). Upper-plate rocks between the two areas correlate in age, lithology, and radiogenic isotopes (Silver and Nourse, 1986; Saleeby et al., 1987; Pickett and Saleeby, 1994; Wood and Saleeby, 1998). Thermobarometric constraints in both areas indicate that the level of detachment of the lower crust and the level of schist underplating were ~9 kb (Sharry, 1981; Pickett and Saleeby, 1993; Jacobson, 1995). The Rand thrust has been seismically imaged as dipping ~20° beneath the southernmost SNB as it extends northward from its surface expression along the small windows. Paleodepth (pressure) isopleth patterns within the upper plate SNB reflect a comparable dip to oblique crustal section. Thus, the level of detachment of the mantle lithosphere by the Rand thrust approximated the base of the felsic batholithic layer over a wide region.

The structural thickness of the Rand schist is unknown. Radiogenic isotopic data from Neogene volcanic rocks of the western Mojave Desert region indicate a lack of continental lithosphere mantle beneath the ~30-km-thick crust (Miller et al., 2000). Radiogenic and stable isotopic data of western Mojave Neogene volcanic rocks and of small intrusions of Late Cretaceous muscovite-garnet granites exhibit crustal components that match the Rand schist (Glazner and O'Neil, 1989; Miller et al., 1996). Crustal rocks that lie between the schist exposures and the current Moho were likely to have been constructed in large part from additional Franciscan-affinity rocks that were progressively accreted beneath the schist. The seismic structure of the western Mojave Desert crust reflects a layered assemblage that has characteristics that fall within the broad range of Franciscan protoliths and metamorphic derivatives (Cheadle et al., 1986; Li et al., 1992; Hauksson, 2000). The fan-like seismic reflection structure and its truncation by the Moho beneath the Tehachapi-Rand belt (Fig. 3) is interpreted as the mark of regional flattening of an underplated-duplex complex and the related smoothing out of the Moho subsequent to lower-crust tectonic accretion (Malin et al., 1995).

The batholithic plate above the Rand thrust was deformed during and shortly after schist underplating. This is evident on the cross section in Figure 3 by the regional tilting of the upper-plate batholithic crust and its denudation to nearly its primary Moho depths. Underplating of the schist and regional tilting were accompanied by westward oroclinal bending and penetrative plastic flow of the deep batholithic rocks, resulting in the distinctive westward protruding "tail" of the southernmost SNB (Fig. 2) (Burchfiel and Davis, 1981; Kanter and McWilliams, 1982; Wood and Saleeby, 1998). At mid- to upper-crust levels, the upper plate disaggregated into a series of detachment sheets that escaped southward into the southernmost Sierra–northern Mojave Desert region (Wood and Saleeby, 1998). The combination of the tectonic removal of the subbatholith mantle lithosphere, and the denudation of the overlying mid- to upper crust left the ~125-km-thick batholithic lithosphere tapered to a thin sheet or series of sheets in the southernmost Sierra–Northern Mojave Desert region. It appears that the Neogene Garlock fault preferentially localized itself along the tip of this tapered-off lithosphere section.

The contrast between the two subbatholithic sections shown at the opposite ends of the Figure 3 cross section calls for a fundamental deep-crust–upper-mantle structural break of Laramide age of which the manifestations in the overlying SNB were principally regional tilting and related crustal-scale denudation. An inflection in the underlying subducting slab that functioned like a large lateral ramp is implied. This further implies that the subducting slab was segmented into a shallow segment to the south and a deeper segment to the north.

BASEMENT TECTONICS ABOVE THE SHALLOW SLAB SEGMENT

The crustal response to the shallow slab segment is expressed by a number of geologic features that include (1) the distribution of the Rand and related lower plate schists, (2) the structure of the overlying MSB as well as the southernmost SNB, and (3) anomalous patterns in "forearc" sedimentation. The Rand schist belongs to a family of high-pressure greenschist-amphibolite facies rocks that were derived from protoliths encompassing Franciscan trench and Great Valley forearc basin-like assemblages and that tectonically underlie batholithic rocks at comparable structural levels throughout the southern California region (Jacobson et al., 1996). Age constraints on the thrust emplacement and cooling of the schists coincide with the latest Cretaceous, early Paleogene age of the Laramide orogeny (Silver and Nourse, 1986; Jacobson, 1990; Jacobson et al., 2000; R.W. Kistler, 1996, written commun.). The pre-Neogene distribution of all the principal exposures of these schists is shown on Figure 1, which corresponds to the north-south limits of the MSB and the adjacent southernmost SNB. This segment of the batholithic belt is unique in its degree of tectonic disruption and its related breachment westward across its forearc region (May, 1989; Hall, 1991; Malin et al., 1995; Barth and Schneiderman, 1996). To the north and to the south of the MSB, the Cretaceous forearc basin survived through Laramide time. The position of the forearc basin adjacent to the MSB was occupied by Salinia following Laramide time (Fig. 1). The northern to central areas of Salinia contain schist exposures and regional allochthonous relations that correlate with those of the western Mojave Desert region (Ross, 1976, 1984; Hall, 1991; Silver and Mattinson, 1986). Seismic reflection data across southern Salinia indicate that Salinia's batholithic rocks lie structurally above imbricated low-velocity material that most likely represents subducted sediments (Trehu and Wheeler, 1987). Thus, over a broad region that extends across the southernmost Sierra to the adjacent western Mojave Desert, including the pre-Neogene positions of Salinia and the San Gabriel terrane, and continuing southeastward into the southern Colorado River Desert region, the Cordilleran batholithic belt lies tectonically above Franciscan and Great Valley forearc affinity assemblages. This profound structural relation developed in Laramide time.

The forearc breachment of the MSB is also reflected by the westward oroclinal bend of the adjacent southernmost SNB and its upper-level detachment sheets (Burchfiel and Davis, 1981; Wood and Saleeby, 1998). Regional lithologic belts, which are internal to the SNB, and are defined by petrochemistry and wall-rock geology, exhibit the westward deflection, both in the plastically deformed mid- to deep-crustal exposures and in the overlying detachment sheets. This westward deflection pattern in the zonation of the batholithic belt continues into the MSB (Ehlig, 1981; Silver, 1983; Ross, 1984; Silver and Mattinson, 1986; May, 1989; James et al., 1993; Kistler and Champion, 2001), and then it ceases southward into the PRB where the batholith's longitudinal primary structure as well as its transition into its adjacent forearc basin remained intact (Silver et al., 1979; Crouch and Suppe, 1993).

The deformed MSB, its tectonically underlying schists, and the spatially related missing segment of the forearc basin are interpreted as the surface manifestation of the shallow segment of the Laramide slab along the plate edge (Malin et al., 1995). Batholithic magmatism ended with an abrupt regional cooling throughout Salinia during the early Laramide time of initial schist underplating (Naeser and Ross, 1976; Mattinson, 1978; Kistler and Champion, 2001). Magmatism waned at the same time in conjunction with regional cooling in the western Mojave Desert region (Miller and Morton, 1980). Such waning in magmatism was also marked by the emplacement of relatively small petrochemically distinct plutons carrying isotopic signatures of Rand schist in their source (Miller et al., 1996). These western Mojave Desert and Salinia events were accompanied in the eastern Mojave Desert region by regional crustal shortening, denudation, and the development of basement-derived clastic wedges along the Maria-Mule Mountains deformation belt (Fig. 1) (Carl et al., 1991; Foster et al., 1992; Miller et al., 1992; Karlstrom et al., 1993; Richard et al., 1994). A similar timing for the end of arc magmatism, denudation, and cooling is recorded in the San Gabriel terrane (Carter and Silver, 1971; Miller and Morton, 1980; Ehlig, 1981; Barth and Schneiderman, 1996). Thus, the subduction of the shallow slab segment is marked everywhere along the length of its strike by the termination of magmatism, deformation, and rapid denudation of the overlying segment of the magmatic arc.

BASEMENT TECTONICS ABOVE THE DEEP SLAB SEGMENT

The termination of arc magmatism throughout the greater SNB at the onset of Laramide time is well documented (Evernden and Kistler, 1970; Stern et al., 1981; Chen and Moore, 1982). It has been further suggested from the modeling of fission track data that the subbatholith mantle lithosphere was removed by Laramide flat slab subduction at a depth of between 35 and 50 km (Dumitru at al., 1991). This later assertion is clearly at odds with the xenolith data that indicate the survival of the subbatholith lithosphere throughout Laramide time (Fig. 3). The fission track data basis for this lithosphere removal model also needs reevaluation in the light of apatite (U-Th)/He dating conducted in the same region (House et al., 2001). Most notable are the effects of cooling related to Late Cretaceous-Paleogene high relief topography. The key element in the Dumitru et al. (1991) model is conductive cooling of the Sierran crust from beneath by the Laramide slab. In spite of the rejection of the conclusion that the Laramide slab removed the mantle lithosphere from beneath the greater SNB, the xenolith thermobarometric data record an apparent conductive cooling event, but for the entire mantle lithosphere (Lee et al., 2000; Saleeby et al., 2003).

The Cretaceous SNB developed by copious arc magmatism over a time interval of ~50 m.y. (Evernden and Kistler, 1970; Saleeby and Sharp, 1980; Stern et al., 1981; Chen and Moore, 1982; Saleeby et al., 1987). The abundance of mafic batholithic rocks along the west margin of the batholith, their ubiquitous occurrence throughout the batholith, and isotopic data on the large-volume felsic as well as mafic members of the batholith, all attest to the importance of the subbatholith mantle wedge in magma genesis (Saleeby et al., 2003). Maintaining a fertile mantle wedge over such a long period of magma genesis requires an influx of fertile peridotite into the wedge environment as subduction progresses. Geodynamic modeling of subduction in conjunction with global petrogenetic and geochemical data indicate the importance of asthenosphere cornerflow circulation and the influx of slab-derived hydrous fluids for mantle wedge magmatism (cf. Billen and Gurnis, 2001; Ulmer, 2001). Thermobarometric and petrogenetic data for the sub-SNB mantle xenoliths suggest a highly dynamic subarc mantle wedge that had a continuous material flux during magma genesis (Saleeby et al., 2003). This material flux included the circulation of asthenospheric mantle, an influx of slab-derived fluids, the rendering of hydrous basaltic magma, and the settling of garnet-pyroxene residue batches from upper level felsic magma production domains. This dynamic system was terminated abruptly at the onset of Laramide time. It is suggested that the single most important factor in this terminal event was the disruption of the asthenosphere cornerflow pattern by the interference of the shallow slab segment. Without the continued circulation of hot asthenosphere into the subarc mantle wedge, basalt magma production would have ceased, leading to the termination of voluminous higher level felsic magma production (Saleeby et al., 2003).

As shown in Figure 1, the shallow slab segment initially took a highly oblique trajectory beneath the southwest Cordilleran plate edge. The resulting damage to the subcontinental mantle lithosphere is considered to have been restricted, for the most part, to the southernmost SNB and MSB regions. It is hypothesized that a much broader region of the subcontinental asthenosphere and its subduction-related circulation pattern were affected by the shallow slab segment. The aggregate regional effect was the termination of arc magmatism along an ~1500 km segment of the plate edge stretching from the MSB northward to the Idaho batholith. The southern and northern ends of latest Cretaceous-early Paleocene batholithic belts that persisted through Laramide time along the more northerly and southerly reaches of the Cordilleran plate edge are shown near the opposite margins of Figure 1. Reestablishment of the (post-Laramide) regionally continuous magmatic arc followed an inward migration pattern from both ends of these syn-Laramide arc segments and ultimately coalesced in the central California region by the mid-Miocene (Burchfiel et al., 1992). This migration pattern appears to have respected the shallow slab segment corridor of the craton in that migration and coalesence were inward toward, and around the edges, of the Colorado Plateau. This is suggested to reflect the maximum damage zone of the asthenosphere by the shallow slab segment.

The initial oblique trajectory of the Laramide slab beneath the southwest Cordillera also resulted in the partitioning of dextral shear into a trench-linked transform system that affected the SNB and the Franciscan complex. In the SNB, a regional dextral shear zone developed along the belt of terminal batholithic plutons that were at solidus to hot subsolidus conditions during shearing (Busby-Spera and Saleeby, 1990; Tikoff and de Saint Blanquat, 1997; Wood and Saleeby, 1998). In the southern SNB, the proto–Kern Canyon fault of this system exhibits progressively greater west-directed reverse components of shear southward as it roots into upper plate tectonites of the Rand thrust system (Fig. 1). To the north, the proto–Kern Canyon fault is in continuity with the Sierra Crest shear zone. Other than this regional dextral shear zone, the greater SNB remained structurally intact and little deformed. Apatite (U-Th)/He thermochronometry from the central region of the batholith suggests that it existed as an orogenic plateau that had high relief fluvial topography during Laramide time (House et al., 2001). These data in conjunction with regional patterns in igneous barometry further suggest a coherent pattern of slow denudation during Laramide and most of Cenozoic time (Ague and Brimhall, 1988; Saleeby et al., 2003). This pattern breaks down in the southernmost SNB where tremendous uplift, oroclinal bending, and detachment faulting related to schist underplating have rendered the oblique crustal section.

SLAB SEGMENTATION

The Andean subduction-arc system is commonly cited as a modern analogue for Laramide tectonics of the southwest Cordillera. The Andean system is characterized by the segmentation of the down-going slab into normal, moderate, and shallow-dipping domains (Barazangi and Isacks, 1976; Gutscher et al., 2000). Seismic imaging of the Andean slab by Gutscher et al. (2000) reveals flat segments that are as shallow as ~50 km and as deep as ~120 km. A lateral ramp between two such slab segments would yield the type of lithosphere-scale structural patterns that are exhibited beneath the SNB-MSB transition (Fig. 3). Were it not for disruption by the San Andreas fault, this line of reasoning could be used to predict that a similar pattern could be found beneath the MSB-PRB transition. Gutscher et al. (2000) also show a close correlation of shallow flat slab segments with the subduction of oceanic plateaus or aseismic ridges. The abnormal subduction geometry of these shallow flat slab segments is thought to arise from the buoyancy effect of the greatly thickened crustal sections relative to that of the abyssal lithosphere. Most shallow slab segments associated with the subduction of single plateaus or ridges are on the order of 500 km in width measured along the respective plate edges, which is the approximate strike length of the disrupted segment of the batholithic belt in the southern California region (Fig. 1).

It has been suggested that a counterpart of the Hess-Shatsky large igneous province (Towisangna Ridge of Barth and Schneiderman, 1996) that was built on the Farallon plate was subducted in the southwest Cordilleran region in Laramide time, and that this led to the profound tectonic events of both the plate edge and interior (Livacarri et al., 1981; Henderson et al., 1984; Barth and Schneiderman, 1996). Blocks of intraplate basalt and pelagic limestone of the Permanente terrane in the central California Franciscan complex represent fragments of this igneous province that were accreted in Late Cretaceous-Paleogene time (Vallier et al., 1983; Blake et al., 1984; Sliter, 1984). It is suggested that these blocks are the remnants of a much larger massif that was subducted as part of the shallow slab segment in the southern California region, and that the derivative blocks were displaced northward by dextral faulting during and following subduction accretion (cf. McLaughlin et al., 1988). The current position of the Permanente terrane, and the Central mélange belt that dissipated much of the trench-linked transform motion, are shown in Figure 2. The origin and accretion history of the Permanente terrane adds considerable support for a causative link between ''Towisangna Ridge'' subduction and Laramide deformation.

A noteworthy difference between the Laramide flat slab segment envisaged here and those resolved beneath the Andes is, according to the Pacific Basin plate motion reconstructions for Laramide time (Engebretsen et al., 1985; Stock and Molnar, 1988), that at least the initial phases of shallow slab segment subduction were highly oblique to the southwest Cordilleran plate edge (Fig. 1). Such is not the case for the Andes. Some of the apparent consequences of this oblique subduction pattern for the Laramide are discussed below.

SLAB SEGMENTATION AND REGIONAL SOUTHWEST CORDILLERAN DEFORMATION

The effects of the oblique subduction of the Laramide shallow slab segment are manifest in a north-northeast–trending corridor that extends from the southwest Cordilleran plate edge into the adjacent craton. Figure 1 displays a close spatial correspondence between the cratonic deformation zone and the disrupted segment of the batholith belt, particularly if viewed in the context of the relative motion between the Farallon and North American plates. A critical tracer on Figure 1 is the restored trace of the Neogene Garlock fault (after Snow and Wernicke, 2000). This fault is most pronounced along the Tehachapi-Rand deformation belt where it coincides with the inflection in the Rand thrust as it descends beneath the ''pinched out'' terminous of the SNB oblique crustal section (Fig. 3). In this context, the restored Garlock fault is used as an approximate surface tracer of the segmentation inflection in the Laramide slab. Relative plate motion between the Farallon and North American plates for early Laramide time is parallel to the trend of this tracer (Engebretsen et al., 1985). By projecting this plate motion trajectory into the plate interior, one can see that virtually all of the first-order Laramide plate interior structures coincide with the shallow slab segment as defined above. The scale of the shallow slab segment and its overlying deformation corridor through the forearc, arc, and distal backarc (craton) are comparable to the spatial relations observed where the aseismic Juan Fernandez Ridge is descending beneath the Andes and the adjacent Sierras Pampeanas foreland thrust belt (Gutscher et al., 2000).

Considerable uncertainty exists for the relative motions between the Farallon and North American plates at Laramide time (Engebretsen et al., 1985; Stock and Molnar, 1988), but the derivative vectors that are shown on Figure 1 for 1 m.y. time increments of motion in the southern California region are taken at face value for this discussion. The cratonal zone of deformation may have resulted from a combination of end loading and basal traction from the shallow slab segment. Initial end loading accompanied the shearing off of the mantle lithosphere beneath the MSB. As discussed below, much of the mantle lithosphere beneath the cratonal deformation zone is considered to have been left intact above the shallow slab segment. Tracking the initial 10 m.y. subduction trajectory of the shallow slab segment (ca. 85–75 Ma) with the corresponding relative motion vector puts the leading edge of the shallow segment beneath the mid-Colorado Plateau region at ca. 75 Ma. The trajectory of the slab descent then began to change to a more easterly course between 74 and 69 Ma. This change in trajectory corresponds in time to an eastward migration and/or intensification of cratonal deformation (Brown, 1988). Arches and uplifts that lie buried in the midcontinent region and that formed between 75 and 50 Ma (Tikoff and Maxson, 2001) may also reflect this change in the subduction trajectory for the shallow slab segment.

The topology and subduction trajectory of the Laramide slab as envisaged above helps explain controversies concerning the preservation of the subcontinental mantle lithosphere beneath most of the southwest Cordillera. Isotopic data of Cenozoic volcanic rocks and mantle xenoliths (Livaccari and Perry,1993; Farmer et al., 1989; Miller et al., 2000; Lee et al., 2001) suggest regional post-Laramide preservation of the mantle lithosphere in the backarc to cratonal region. These findings are at odds with models of whole scale removal of the mantle lithosphere in the region by a regionally extensive flat slab (cf. Bird, 1988; Dumitru et al., 1991). The topologic and kinematic model presented above predicts that the only region where Laramide-age removal of the mantle lithosphere is required is beneath the MSB region (Fig. 1). A deeper flat slab geometry, as imaged in parts of the Andes by Gutscher et al. (2000) and as envisaged here for the greater SNB, would leave the lithosphere intact in the SNB back-arc region. In contrast, isotopic data for Miocene volcanic rocks of the western Mojave Desert reflect no such continental lithosphere component (Glazner and O'Neil, 1989; Miller et al., 2000). Miller et al. (2000) also show that Miocene volcanic rocks that erupted in the eastern Mojave Desert region, east of the termination of the Garlock fault, do carry the isotopic fingerprints of the subcontinental lithosphere mantle. These data appear to trace the approximate downdip limit of the whole-scale shearing off of the mantle lithosphere by the shallow slab segment. The fact that it in general spatially corresponds to the eastern termination of the Garlock fault is in accord with the interpretation of the Garlock fault as a shallow-level tracer of the slab segmentation inflection.

Discussion will now focus again on the plate edge environment. Based on the surface distribution of the lower plate schists and on the westward breaching patterns of the MSB, Malin et al. (1995) suggested an ~500 km width for the shallow slab segment. The possible southward continuation of intra-arc tectonic features that may be associated with the shallow segment extends ~100 km southward into the otherwise intact PRB (May, 1989; Goodwin and Renne, 1991; George and Dokka, 1994). Most notable is the development of high-strain fabrics and denudation along the eastern Peninsular Ranges mylonite zone (Fig. 1). The restriction of this early Laramide age structural zone to the northernmost PRB, and the survival of the corresponding segment of the forearc basin, are taken as the mark of the southern bounds on the shallow slab segment. The sinistral transfer structure shown in Figure 1 between the eastern Peninsular Ranges mylonite zone and the basement rooted thrusts of the San Gabriel terrane is after May (1989). The contrast between the crustal deformation expressions of the slab segmentation inflections between the SNB-MSB in the north and MSB-PRB in the south are interpreted to reflect the dextral obliquity in early Laramide plate convergence, the time when these deformation systems formed.

Early Laramide ductile deformations along the eastern Peninsular Ranges mylonite zone, Maria-Mule Mountains deformation belt, proto–Kern Canyon fault, and Sierra Crest shear zone appear to have been localized by the thermal weakening of active, or recently active, arc magmatism. This pattern may continue northward along poorly exposed batholithic rocks of the northwest Nevada region (Wyld and Wright, 2001) and ultimately into the western Idaho shear zone (Tikoff et al., 2001). Evidence for broadly distributed dextral shear also affecting the Laramide cratonal deformation zone, including east-west–oriented antithetic sinistral shears, has been reviewed by Tikoff and Maxson (2001). This broad pattern of upper plate dextral shear for Laramide time is also manifest in the Franciscan subduction complex (McLaughlin et al., 1988; Jayko and Blake, 1993).

One of the outstanding problems for resolving the history of Salinia is the fate of its western zone, which consists of Early Cretaceous batholithic and pre-Cretaceous metamorphic framework rocks. Petrologic and geochemical signatures at its northern end exposures (Silver and Mattinson, 1986; Kistler and Champion, 2001), as well as clasts in adjacent Eocene conglomerates (Schott and Johnson, 2001), bear witness to the past existence of such rocks. The view adopted here is that a combination of extreme crustal attenuation resulting from late- to post-Laramide crustal collapse and subduction erosion, in conjunction with trench-linked transform faulting, can account for the absence of such rocks (Figs. 1 and 4). Several relationships within the Franciscan complex bear on this issue. As noted above, northward translation of the Permanente terrane along the Central mélange belt can account for the displacement of fragments of the Towisangna Ridge from its presumed locus of impact along the MSB segment of the plate edge. Franciscan rocks of the Gold Beach terrane in southwest Oregon (Fig. 2) consist of Early Cretaceous western zone-like arc rocks that are suggested to have been displaced northward from the western PRB region in latest Cretaceous–early Cenozoic time (Jayko and Blake, 1993). Considering that the northern PRB forearc is intact, excluding Neogene disruption, it seems more likely that the Gold Beach terrane may have originated as part of the MSB western zone. Franciscan rocks that bound the western margin of Salinia consist of the Nacimiento block. These rocks are suggested to have originated along the Peninsular Ranges offshore trench region, and to have been displaced and accreted against Salinia by dextral transpression in latest Cretaceous–early Paleogene time. (Jayko and Blake, 1993). These rocks lie in a position that was apparently vacated by the missing western zone rocks of Salinia. Finally, as discussed below, the MSB underwent a vigorous phase of orogenic collapse in conjunction with its disruption and forearc breachment. Fragments of the western zone of Salinia, as well as its forearc, may have been tectonically eroded by subduction as well as dextral shear in conjunction with orogenic collapse.

The relationships outlined above for the Franciscan complex and Salinia at Laramide time suggest that the westward breachment pattern of the MSB delivered attenuated crustal fragments of the respective arc to a trench-linked transform system that resulted from dextral oblique convergence. Serial events in tectonic erosion by strike-slip displacement and possibly subduction erosion, and subsequent accretion of more southerly derived subduction complex packages, left Salinia in a much reduced state and in a position liable for further disruption and dispersal along the Neogene San Andreas transform system.

CRUSTAL COLLAPSE ABOVE THE SHALLOW SLAB SEGMENT

The tectonic collapse of orogenically thickened crust resulting from the mid- to Late Cretaceous Sevier and the latest Cretaceous–early Paleogene Laramide orogenies has been discussed by a number of researchers and linked to mid-Tertiary extensional tectonics of the Basin and Range province (Coney and Harms, 1984; Sonder et al., 1987; Wernicke et al., 1987). Hodges and Walker (1992) have discussed evidence for the initiation of such orogenic collapse in the southwest Cordillera, at least locally, as early as latest Cretaceous time (70–75 Ma). Malin et al. (1995) suggested that the forearc breachment of MSB as well as regional horizontal ductile flattening in the underlying schists likewise reflect Laramide-age crustal collapse. This view is developed further below, and it is further suggested that the profound tectonic events that led to the replacement of the mantle lithosphere beneath the MSB by largely wet sediment in conjunction with the late- to post-Laramide steepening of the subducting slab promoted orogenic collapse and forearc breachment of the MSB.

The extreme crustal attenuation exhibited along the Tehachapi-Rand deformation belt (Fig. 3), and for much of the MSB is suggested to have in part been facilitated by rheological conditions resulting from schist underplating. Uranium/lead age data on detrital zircon from metaclastic units of the lower plate schists show significant Late Cretaceous batholithic as well as Proterozoic crystalline basement source components that match those of the MSB and its eastern cratonal basement

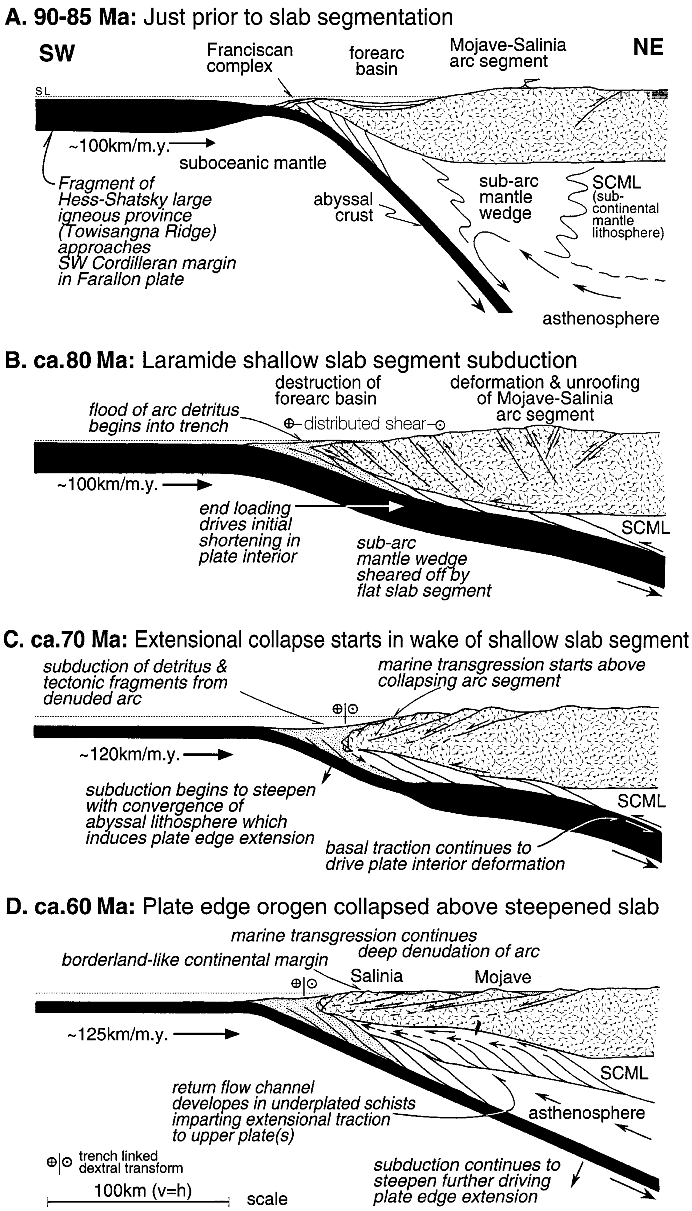

Figure 4. Series of generalized cross section models of the southwest Cordilleran plate edge in the region of the Mojave-Salinia segment of batholithic belt (MSB) showing how the Laramide shallow slab segment deformed the forearc-arc region as subduction flattened; then as subduction steepened, regional extension promoted orogenic collapse and forearc breachment of the disrupted arc segment. Superpositioning of structures is not shown in continental plate for reasons of simplicity.

wallrocks (Jacobson et al., 2000). These data suggest rapid uplift and erosion of the MSB sediment source, as well as rapid tectonic transport of the corresponding clastic wedge(s) into the metamorphic environment. Seismic data from beneath the Tehachapi-Rand deformation belt, as well as from Salinia and the western Mojave Desert, suggest underplating of perhaps up to an ~30-km-thick wedge of schist-affinity material (Cheadle et al., 1986; Trehu and Wheeler, 1987; Li et al., 1992; Malin et al., 1995; Hauksson, 2000). Exposures of the schists are dominated by metaclastic rocks but also contain significant hydrous metabasalts and lesser serpentinites. The tectonic replacement of the subbatholith mantle lithosphere by such an assemblage effectively replaces a dry pyroxene + garnet + olivine rheology with a wet mica + feldspar + quartz rheology, resulting in a tremendous reduction in material strength (Tullis and Yund, 1980; Blanpied et al., 1995; Kohlstedt et al., 1995; Wintsch et al., 1995; Tullis et al., 1996). Stable isotope and petrologic studies of the Franciscan Catalina schist indicate very high water fluxes during progressive subduction and metamorphism from 5 to 11 kb conditions (Bebout and Barton, 1989). The Catalina schist is very similar to the schists that are underplated beneath the MSB. An analogous high-water flux migrating from the underplated schist protoliths into the overlying quartzofeldspathic batholithic crust, as evidenced by widespread retrograding in the upper plate rocks, would promote substantial weakening of the upper plate as well. It is suggested that these extreme tectonic and rheological conditions resulted in the production of a highly weakened orogenic crustal section along the plate edge that was highly susceptible to gravitational collapse. Malin et al. (1995) point this out and imply that this alone can account for the collapse and forearc breachment of the MSB. It is further suggested below that the passing of the shallow slab segment and the resulting steepening of the slab dip promoted regional extension along the plate edge and, in conjunction with the extreme rheological conditions noted above, a prolonged episode of vigorous orogenic collapse characterized medial to late Laramide time for the MSB.

Figure 4 is a model that shows the sequence of events that led to the uplift and collapse of the MSB. This model is intended to be generic for the MSB region and reflects the sequence of events affecting the northern-MSB–southern-SNB transition perhaps up to ~10 m.y. earlier than for the southern MSB region. The model is based on the concept of the shallow slab segment resulting from the subduction of the Towisangna Ridge (Livaccari et al., 1981; Hendersen et al., 1984; Barth and Schneiderman, 1996). The Figure 4 model also incorporates the work of McNulty and Farber (2002), which documents the early phases of crustal collapse of the Peruvian Andes above its corresponding shallow slab segment. This work suggests that the initiation of orogenic collapse there is linked in time with the passing of the trailing flank of the subducted Nazca Ridge beneath the forearc region. The corollary added here is that the subduction of less buoyant abyssal lithosphere, in the wake of the subducted Nazca Ridge, induces a steepening in the slab that further induces extensional tectonics in the overlying orogenically thickened crust.

Figure 4A shows in highly generalized fashion the principal plate edge elements in the MSB region prior to arrival of the Towisangna Ridge. In Figure 4B, the Ridge has subducted several hundred kilometers beneath the plate edge. The greater buoyancy of the Ridge-hosting lithosphere, relative to abyssal lithosphere, results in a flattening in the subduction trajectory. The subarc mantle wedge and part of the adjacent subcontinental mantle lithosphere are sheared off and displaced downdip into the mantle with the shallow slab segment. Mantle wedge-driven arc magmatism is terminated. This phase of shallow slab subduction was highly oblique to the plate edge (Fig. 1) and, as discussed above, the asthensophere counterflow ''engine'' for mantle wedge-driven magmatism was disrupted behind the greater SNB resulting in its termination as well.

The onset of flat slab subduction resulted in the imbrication and destruction of the overlying forearc basin. Fragments of the outer forearc basin as well as its bounding accretionary prism may have been displaced down the shallow subduction zone and tectonically underplated as the subarc mantle wedge was sheared off. High-strain deformation of the overlying arc is shown concentrated along its western edge, as seen in the western Tehachapi Range, and along its active thermally weakened eastern edge, as seen in the Maria-Mule Mountains deformation belt. The entire MSB arc segment underwent rapid uplift and erosional denudation resulting in a flood of arc detritus into the adjacent trench. The dextral shear component of oblique subduction is shown distributed across the western edge of the arc and out to the trench as shown by the oroclinal bending of the southern SNB and such structural trends continuing into northern Salinia. To the north, dextral shear was partitioned into the proto–Kern Canyon fault–Sierra Crest shear system and the Franciscan Central belt mélange. Such dextral shearing in the Franciscan complex is presumed to have extended along the MSB and PRB segments of the plate edge as well.

The events depicted in Figure 4B correspond to early Laramide time with respect to the plate interior events. Early Laramide deformation of the interior is suggested to have resulted from the endloading of the continental lithosphere as the subarc mantle wedge was sheared off. Basal traction between the shallow slab segment and the overlying continental lithosphere is suggested to have become a progressively greater driving force for plate interior deformation as the shallow slab segment propagated beneath the plate interior region.

Figure 4C and D depicts the passing of the trailing flank of the Towisangna Ridge down beyond the plate edge, and the ensuing steepening of the slab dip with the subduction of normal abyssal lithosphere. Given the relative plate motions shown in Figure 1, a ridge that has a down-slab dimension of ~1000 km would yield the time-space relations that are depicted. There are no definitive constraints on the other dimensions of the Ridge, other than it is unlikely that it exceeded ~500 km based on the width of the deformation corridor left by the shallow slab segment. Nor are there any constraints on the angle that the Ridge impinged on the plate edge, other than the ~500-km-wide deformation corridor and the relative motion vectors. Such length scales are similar to the major segments of the Hess-Shatsky large igneous province in the northwest Pacific basin (Iwabuchi, 1984). Such length scales for the Towisangna Ridge viewed in the context of the plate kinematics depicted in Figures 1, 4C, and 4D, places the trailing flank of the Ridge beneath the central Colorado Plateau region at ca. 60 Ma. Thus, the shallow slab segment still possessed the capability of imparting a basal traction along the subcontinental lithosphere beneath the principal cratonic deformation zone.

The passing of the Towisangna Ridge's trailing flank beneath the plate edge and the attendant steepening of the slab are suggested to have induced a suction along the slab upper plate interface that induced regional extension and subsidence along the plate edge. Regional extension commenced (at least locally) by ca. 70 Ma along the thickened and thermally softened eastern zone of the arc, and it is suggested to have been distributed above the entire MSB arc segment in conjunction with schist underplating. Underplating is suggested to have incorporated progressively more denuded arc detritus with time, and possibly tectonically eroded fragments of the forearc and western zones of the arc. Such subduction erosion has been shown to have been an important process in attenuating the forearc crust during shallow slab subduction beneath the Peruvian Andes (von Huene et al., 1996). Regional extension, subduction erosion, and trench-linked transform fault erosion along western Salinia have destroyed virtually the western half of the MSB as well as its forearc. This model predicts the possible existence of thrust-wedges and/or transposed layers of MSB as well as its forearc rocks at depth within the underplated schists; a possibility implied by seismic data (Hauksson, 2000).

The initial phases of schist underplating are thought to have contributed to crustal thickening, isostatic uplift, and gravitational instability of the orogen. As the slab steepened, schist underplating is suggested to have accelerated. Dehydration reactions and attendant fluid fluxes progressively weakened the entire crustal column, and a ''runaway'' extensional collapse episode commenced. As the slab continued to steepen, the upper levels of the underplated wedge found a trenchward trajectory as its path of easiest escape. A return flow channel developed in the upper wedge, similar to that modeled for accretionary wedges by Cloos (1982) and Emerman and Turcotte (1983). The return flow channel exerted a traction along the base of the weakened upper plate that further promoted its gravitational collapse and breachment toward the forearc. In some localities, this coupled upper- and lower-plate collapse process went to such an extreme as to cut out the deep crustal upper plate rocks along the ''thrust'' system and replace them with shallow-level detachment sheets juxtaposed immediately above the schists (Wood and Saleeby, 1998). The transport pattern in the return flow channel and its traction along the base of the upper plates resulted in the commonly observed kinematic patterns along the ''thrust'' exposures that are contrary to the subduction transport pattern of initial schist emplacement (Ehlig, 1981; Simpson, 1990; Yin, 2002).

The steepening of the slab and the implicit suction at depth along the plate edge imply the inflow of asthenosphere ± subcontinental lithosphere beneath the eastern Mojave Desert region. Late Cenozoic volcanic-hosted lower-crust–upper-mantle xenolith suites suggest the existence of such a complex upper-mantle structure, as well as the presence of latest Cretaceous–early Paleogene basaltic intrusions produced by decompression partial melting of ascended asthenosphere (Leventhal et al., 1995).

MARINE TRANSGRESSION ACROSS CRUSTAL COLLAPSE ZONE

The extreme crustal attenuation envisaged for the crustal collapse process discussed above is reflected in the latest Cretaceous to mid-Eocene transgression of marine strata across the deeply denuded MSB (Fig. 4). This is extraordinary considering that the greater SNB to the north persisted as an orogenic plateau that had perhaps 3 km or more regional elevation through Laramide time (House et al., 2001). One would expect from the Figure 3 cross-section relations that the initial tectonism and isostatic response to schist underplating would have elevated the southernmost SNB and adjacent MSB to higher than ambient elevations. In the case of the southernmost Sierra region, the adjacent Cretaceous forearc basin sequence is missing (Goodman and Malin, 1992), probably as a result of uplift and oroclinal bending during schist underplating. Paleocene-Eocene strata lie unconformably on the deeply denuded and westward-deflected SNB of the southernmost Great Valley and extend eastward along the trend of the Tehachapi-Rand deformation belt. These more easterly, locally derived, coarse clastic strata have depositional features and structural relations suggesting deposition in supradetachment basins (Wood and Saleeby, 1998). By Eocene time, the eastern known limits of this complex basinal system were under marine conditions (Cox, 1987). A similar pattern of Eocene-age, coarse, locally derived marine clastic sedimentation characterizes the deeply denuded upper-plate basement rocks of the southern Colorado River Desert region as well as correlative rocks of the western San Gabriel terrane and of adjacent southernmost Salinia (Howell, 1975). The easternmost known extent of the Eocene transgression above the collapsed segment of the batholithic belt is depicted by the approximate trace of the Eocene shoreline in Figure 1. This shoreline trace conforms to the regional facies patterns of the pre-Laramide forearc basin system both to the north and to the south of the collapsed MSB.

Latest Cretaceous to Eocene depositional patterns across the collapsed MSB suggest the existence of a complex borderland environment that underwent general regional-scale transgression through time. Western and central Salinia record Maastrichtian to Paleocene marine deposition of coarse, locally derived, clastic strata in a rugged normal fault controlled basinal setting (Grove, 1993). Such depositional patterns are also recorded for Paleocene strata of the central San Gabriel terrane (Sage, 1975). At the time of the maximum Eocene transgression, thick sequences of marine clastic strata were shed laterally across the northern end of Salinia and extended northward along the adjacent southern Great Valley forearc basin. Similar strata were shed laterally across the southern end of Salinia and extended southward along the northern reaches of the adjacent southern California borderland forearc basin (Nilsen and McKee, 1979). These sediment dispersal patterns mimic and accentuate the tectonic dispersal patterns of the collapsed segment of the batholithic belt. Possible western facies of this depositional system, as well as the western zone of the batholithic belt in Salinia, are missing and are presumed to have been displaced by trench-linked transform faulting and subduction erosion. Eocene marine strata of northernmost Salinia carry distinctive conglomerate clasts that attest to the past existence of rock types that typify the extreme western zone of the southwest Cordilleran batholithic belt (Schott and Johnson, 2001).

The latest Cretaceous–early Paleogene transgressive marine sequences that were deposited across the collapsed segment of the batholithic belt should not be misconstrued as forearc basin strata. Throughout Salinia, in the southern Sierra–northern Mojave Desert region and in the San Gabriel terrane, these strata lie depositionally on westward-breached, Late Cretaceous, eastern zone batholithic rocks. To the north and south of the collapsed segment of the batholithic belt, these strata have sedimentary facies relations with strata deposited in the adjacent surviving segments of the forearc basin system (Nilsen, 1984; Nilsen and McKee, 1979; Kanter, 1988), but where these strata rest on the westward breached MSB, they are unique in their tectonic significance.

CONCLUSIONS

The deep-crust–upper-mantle structure inherited in the southern Sierra Nevada region from Mesozoic subduction and arc magmatism contains a fundamental tectonic boundary that cuts across the regional trend of the batholith belt. To the north, the subbatholith mantle lithosphere remained intact to a depth of ~125 km at least until mid-Miocene time. In the southernmost Sierra and adjacent western Mojave-Salinia segment of the regional batholithic belt, the mantle lithosphere was sheared off by a shallow segment of the Farallon slab and displaced deeper into the mantle. The shallow slab segment was probably carrying a fragment of an aseismic ridge that was the counterpart of the Hess-Shatsky large igneous province of the northwest Pacific basin. Its thickened mafic crustal section relative to abyssal lithosphere is presumed to have rendered a greater buoyancy leading to slab segmentation into the respective shallow domain. The sheared off segment of the subbatholith mantle lithosphere was replaced by a tectonically underplated greywacke-basalt protolith assemblage derived from the Franciscan subduction complex as well as possible forearc basin material that was displaced downdip into the shallow subduction zone. The overriding segment of the batholith belt was deformed, deeply denuded, and breached westward into the corresponding forearc region. This plate edge tectonic regime commenced at ca. 85 Ma and persisted until ca. 60 Ma, encompassing much of the classic Laramide orogeny time.

Viewing the regional structures produced along the southwest Cordilleran plate edge during this tectonic regime on a pre-Neogene palinspastic base, and considering the relative motions between the Farallon and North American plates at Laramide time, leads to the following conclusion. The Laramide slab possessed a shallow flat segment along an ~500-km-long stretch of the plate edge in the southern California region. Classic Laramide structures of the deformed craton lie in a corridor that corresponds to the shallow flat slab segment with respect to the trajectory of Farallon–North American relative plate motions. A direct causative link between plate edge and plate interior Laramide deformation is implied. It is suggested that end loading during the initial shearing off of the subbatholith mantle lithosphere, joined by basal traction along the base of the subcratonic mantle lithosphere (as the shallow slab segment was subducted), led to the pattern of basement deformation observed in the craton. A modern analogue in terms of scaling of the shallow slab segment and the plate edge to plate interior deformation corridor is exhibited where the Juan Fernandez Rise is currently subducting beneath the southern Andes and adjacent Sierra Pampeanas foreland thrust belt. It is further suggested that extensional collapse of the deformed crust above shallow slab segments may arise from the passing of the shallow slab segment and the ensuing steepening of the slab. This process is in its inception in the Peruvian Andes and was taken to completion along the southwest Cordillera with the regional collapse and forearc breachment of the corresponding arc segment.

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