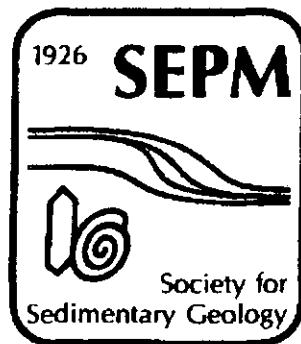


# **GEOLOGY AND TECTONICS OF THE GUALALA BLOCK, NORTHERN CALIFORNIA**

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**WILLIAM P. ELDER**

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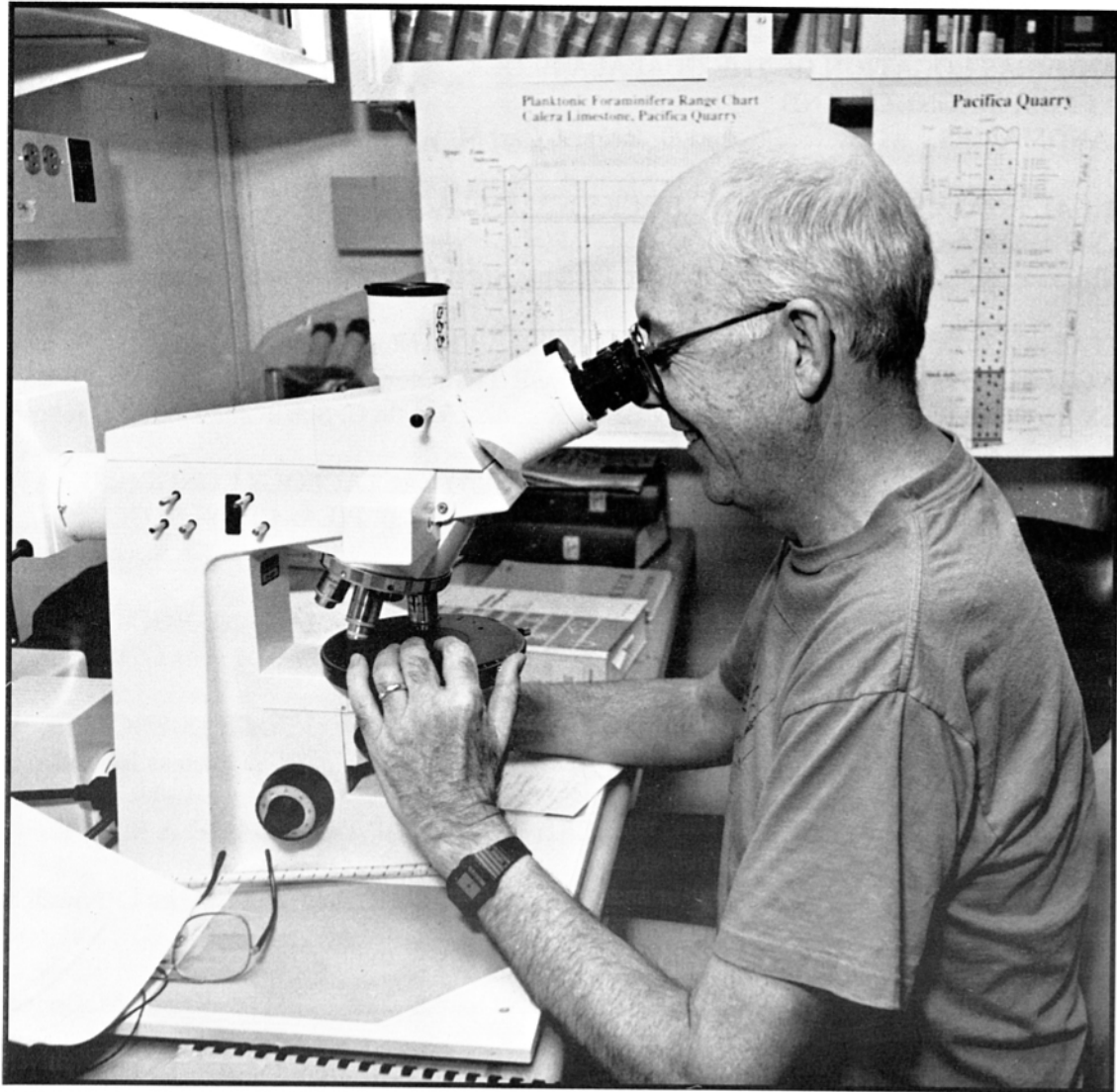
## DEDICATION

This volume is dedicated to the life and scientific contributions of William V. Sliter, micropaleontologist and stratigrapher with the U.S. Geological Survey. Seen here at his microscope, Bill Sliter was working with colleagues at the U.S. Geological Survey on complex stratigraphic problems in the Cretaceous and early Tertiary rocks of the Gualala block at the time of his unexpected death in October, 1997.

Bill's work in the Gualala area was only one of a larger group of foraminiferal studies that he conducted from the 1970's until his death. His work focused on Cretaceous and early Tertiary foraminifers of the mid-Pacific Ocean (DSDP and ODP programs) and eastern Pacific continental margin (Alaska, western Washington, and the Oregon and California coast ranges), the Mediterranean (Italy), and the Caribbean (Mexico and Venezuela). Bill's involvement with the DSDP and ODP programs provided him with a world-wide perspective of the plate tectonic evolution of ocean basins. He applied this unique perspective to his numerous collaborations with paleomagnetists, structural geologists, stratigraphers and other paleontologists. Out of these collaborations came models of the timing and rates of migration of oceanic seamounts and plateaus, from the deep ocean to their accretion and translation along continental margins of the Pacific rim. Together with

his colleague Isabella Primoli-Silva, Bill developed a detailed foraminiferal zonation for the Cretaceous based on worldwide correlations of pelagic limestone sections and became one of a very few experts in identifying foraminifers in thin section, not only for the Cretaceous, but the Tertiary as well.

Bill's work in the California coast ranges, on foraminifers in Mesozoic and Tertiary limestones from oceanic and terrigenous rocks of the Central and Coastal belts of the Franciscan Complex was particularly significant. Bill's dating and comparison of the foraminiferal assemblages to known latitudinal variations in foraminiferal morphology, provided independent validity to controversial paleomagnetic studies suggesting large-scale northward translations of some of the Franciscan Complex. More recently, Bill had become interested in the affinities of some early Tertiary larger foraminifers that occur as part of a distinctive stratigraphic sequence in some parts of the coast ranges. His work in the Gualala area was at an early stage but was focused on a better understanding of the Cretaceous and early Tertiary stratigraphy, which hopefully would lead to tighter constraints on the pre-San Andreas fault translation history of the Gualala block. His numerous colleagues and friends remember Bill as fun loving, tireless, and ever fascinated and involved with geology and people.



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**LATE CRETACEOUS TO EOCENE GUALALA BASIN PROVENANCE CONSTRAINTS FROM  
CONGLOMERATE CLASTS: IMPLICATIONS FOR THE ORIGIN AND EARLY EVOLUTION OF THE  
SALINIAN BLOCK**

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**ABSTRACT**

Coordinated study of the petrographic, geochemical, geochronologic, and isotopic characteristics of Gualala basin conglomerate clasts offers new insight into the changing provenance of the basin between the Late Cretaceous and middle Eocene. Conglomerate clasts are subdivided into four lithologically and isotopically distinct groups. Group I clasts, abundant in the lower portion of the Upper Cretaceous Gualala Formation (Stewarts Point Member), include rhyolitic and granitic lithologies that have mid-Cretaceous crystallization ages, and that reflect an origin at high levels on the inboard side of a continental magmatic arc. In contrast, Group II clasts, which dominate the higher levels of the Gualala Formation (Anchor Bay Member), are mostly gabbros and quartz diorites that were derived from a Jurassic oceanic arc. Group III and IV clasts occur together in the middle Eocene section of the German Rancho Formation and have textural characteristics indicative of a markedly proximal source. Group III clasts are mid-Cretaceous tonalites and granodiorites that are typical of the axial portions of the Cretaceous batholiths of California. In contrast, Group IV clasts, although volumetrically minor, are distinctive garnet-bearing trondhjemitic and tonalitic lithologies that have unusual early Cretaceous crystallization ages, and isotope compositions which are most characteristic of the outboard edge of the Cretaceous batholiths of California. Because the strata containing Group I and II conglomerate clasts are interlayered, an important constraint on the Late Cretaceous source area is the implied juxtaposition of two markedly contrasting magmatic terranes adjacent to the forearc depositional basin. The northern margin of the westward thrust Salinia-western Mojave

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allochthon (SWMA) best satisfies Late Cretaceous provenance constraints. Clasts of the middle Eocene German Rancho Formation require a provenance distinct from those of earlier Gualala basin sediments and also from conglomerates of similar age elsewhere in the Salinian block. We propose a tectonic model for the origin and early evolution of the Salinian block which integrates the Gualala basin conglomerate provenance constraints and yields testable hypotheses. Late Cretaceous conglomerate sedimentation at Gualala is proposed to be a direct response to the emplacement of the SWMA at a forearc proximal location. A local basement block, probably a tectonically displaced fragment of the outboard portion of the SWMA (the "missing" western portion of the Salinian block?), is inferred to be the source of middle Eocene German Rancho Formation conglomerate clasts.

**INTRODUCTION**

The location and origin of sedimentary rocks of the Gualala basin continues to spark controversy some three decades after the question of their provenance was first addressed. Currently located in coastal California at the northern end of the displaced Salinian block (Figure 1), the Gualala basin palinspastically restores to an outboard position at the northwestern (current coordinates) edge of the westward displaced Salinia-western Mojave allochthon (SWMA) (Figure 2) after removal of Neogene dextral strike slip on the San Andreas and related faults (Kistler et al., 1973; Ross, 1984; Hall, 1991; Powell, 1993). The remarkably complete record of Upper Cretaceous through Eocene clastic sedimentation that is preserved in the basin offers potentially unparalleled insight into the poorly documented collapse of the Salinia-Mojave segment of the

Cretaceous magmatic arc, the origin and early evolution of the Salinian block, and the earliest stages of the transition from subduction to transform tectonics at the western margin of North America.

The pioneering sedimentological study of the basin by Wentworth (1966) was among the first to recognize the significance of the basin's provenance for reconstruction of the San Andreas fault system. Wentworth's (1966) recognition of

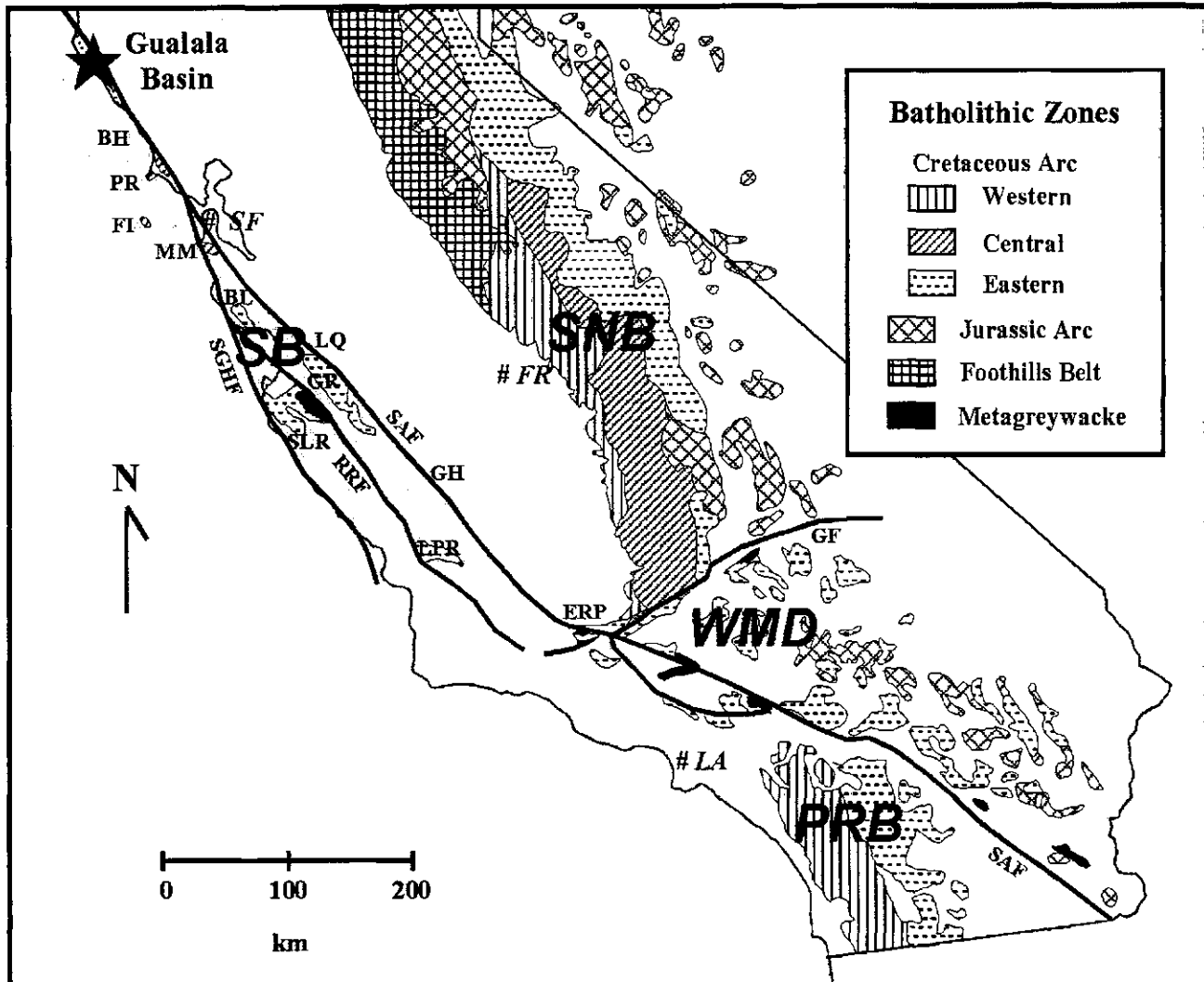


Figure 1. Index map of central and southern California. The Late Cretaceous-Early Tertiary conglomerates of the Gualala basin (star) are the focus of this study. Mesozoic Cordilleran volcano-plutonic arc rocks are patterned. Displaced Salinian block shaded light grey. Jurassic gabbroic basement: ERP = Eagle Rest Peak, GH = Gold Hill, LQ = Logan Quarry. Mesozoic granitic basement in the Salinian block: BH = Bodega Head, PR = Point Reyes, FI = Farallon Islands, MM = Montara Mountain, BL = Ben Lomond, GR = Gabilan Range, SLR = Santa Lucia Range, LPR = La Panza Range. Neogene strike-slip faults: SAF = San Andreas fault, SGHF = San Gregorio-Hosgri fault, RRF = Reliz-Rinconada fault, GF = Garlock fault. Regional basement domains: SB = Salinian block, SNB = Sierra Nevada batholith, WMD = western Mojave Desert, PRB = Peninsular Ranges batholith. Cities: # SF = San Francisco, # FR = Fresno, # LA = Los Angeles.



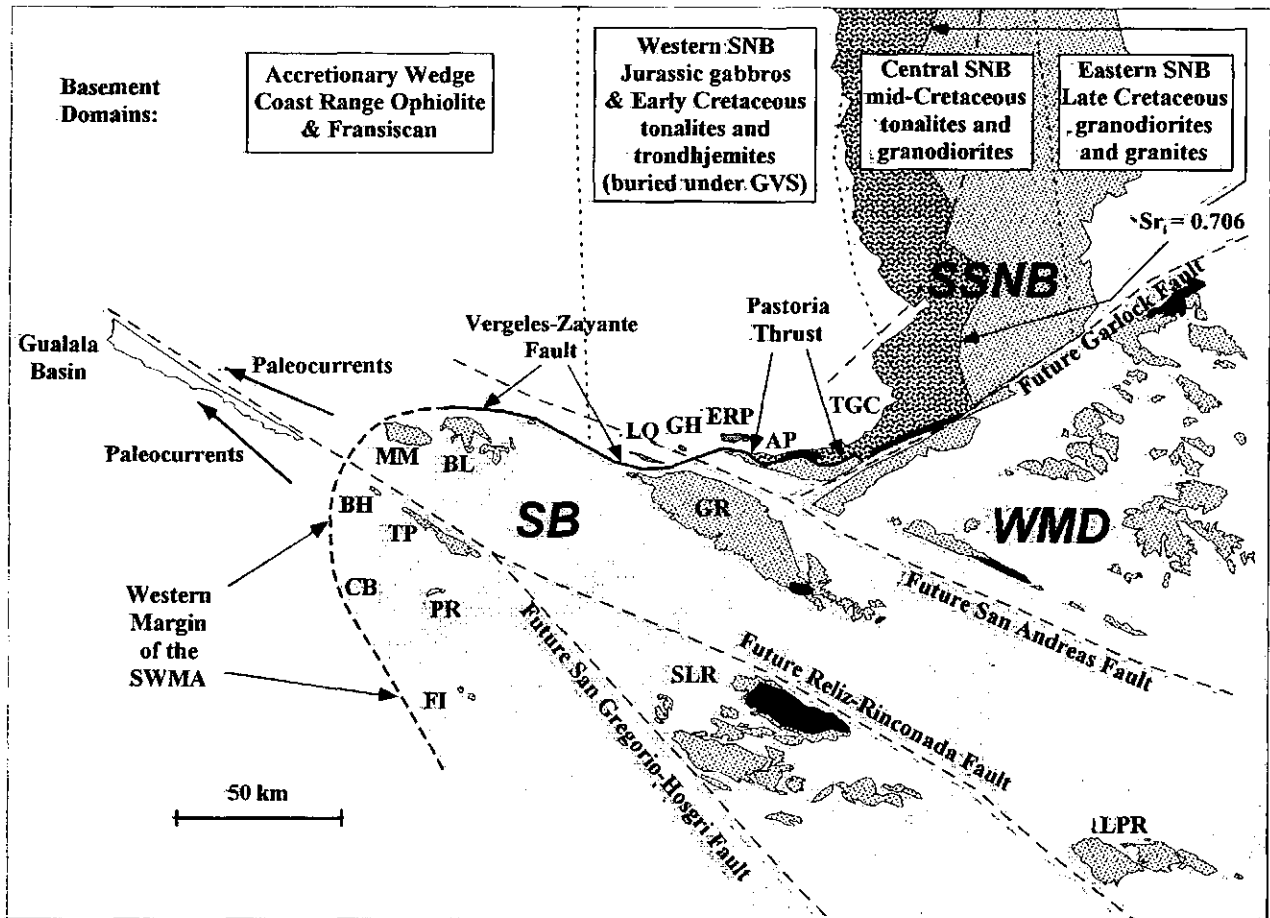


Figure 2. Pre-Neogene palinspastic reconstruction detail of the northern end of the Salinia-western Mojave allochthon (SWMA) (modified from Powell, 1993). Basement terranes of the SWMA (shaded grey) include areas underlain by granitic basement in the western Mojave Desert (WMD), onshore and offshore Salinian block (SB), and southernmost Sierra Nevada batholith (SSNB) south of the Pastoria thrust. Cretaceous batholithic rocks are stippled light grey for continental and dark grey for oceanic. In the southern Sierra Nevada batholith this boundary is  $^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}} = 0.7060$  line (Kistler and Ross, 1990); in the Sierran "tail" this boundary is coincident with Pastoria thrust; in northern Salinian block (NSB) this boundary is the Vergeles-Zayante fault. Lower plate windows (metagreywacke) within SWMA are shaded black. Other localities: MM = Montara Mountain, BL = Ben Lomond, BH = Bodega Head, TP = Tomales Point, CB = Cordell Bank, PR = Point Reyes, FI = Farallon Islands, GR = Gabilan Range, SLR = Santa Lucia Range, and LPR = LaPanza Range, LQ = Logan Quarry, GH = Gold Hill, ERP = Eagle Rest Peak, AP = Antimony Peak, TGC = Tehachapi Gneiss Complex.

the absence of Franciscan detritus in the Upper Cretaceous and Paleogene section remains one of the most significant constraints on the original depositional location of the basin. Subsequent investigations of the petrologic and isotopic characteristics of a unique group of gabbroic clasts in the Upper Cretaceous section at Gualala led Ross

(1970), Kistler et al. (1973), and Ross et al. (1973) to propose that similar rocks near Eagle Rest Peak in the southern Sierra Nevada "tail", and in correlative fault slivers at Logan Quarry and Gold Hill (Figures 1 and 2), might represent the remnants of a viable source terrane. The source for most Upper Cretaceous and Paleogene granitic detritus

was ascribed by these workers to the subadjacent Salinian block (Wentworth, 1966; Ross et al., 1973). For over a decade these correlations, which imply up to 600 km of right lateral offset on the San Andreas and related faults since the Late Cretaceous, stood unchallenged. However, paleomagnetic studies of Gualala basin sediments yielded anomalously low inclinations, suggesting ~2000 km of post-depositional northward translation of the basin (Kanter and Debiche, 1985). Moreover, James (1986) and James et al. (1993) have questioned the specific correlation of Gualala gabbro clasts with an Eagle Rest Peak-Logan Quarry-Gold Hill source, and further, have cast doubt upon the Salinian block as a source terrane for at least some of the granitic detritus in the basin. Finally, it has recently been suggested that some of the basin's sediment may have originated from passing or colliding exotic terranes (Maxson and Tikoff, 1996).

In order to address more definitively the unresolved questions posed above, we have undertaken a detailed provenance study of the Upper Cretaceous and Paleogene rocks of the basin. Provenance studies of the sedimentary rocks of the Gualala basin have special relevance to paleogeographic and paleotectonic studies in western North America because they provide a unique record of clastic sedimentation in space and time. This paper reports the results of petrographic, geochemical, isotopic, and geochronologic investigation of conglomerate clasts from the Gualala basin and their bearing on paleogeographic and paleotectonic reconstructions. We have examined dozens of conglomerate clasts of diverse lithologies from localities throughout the Upper Cretaceous and Eocene sections at Gualala. Our broad aim has been to characterize the range of rock types exposed in the source area(s) throughout the Late Cretaceous and Paleogene depositional history of the basin. Through examination of multiple aspects of the petrology and geochemistry of a wide variety of samples, we can place exceptional constraints on potential source terranes and the variation of provenance through time, which in turn offers insight into the tectonic evolution of the Salinian block.

## GEOLOGIC SETTING

Upper Cretaceous through Eocene sedimentary rocks of the Gualala basin include conglomerates, sandstones, and mudstones which are interpreted to be inner-, middle-, and outer-fan turbidity current deposits that were shed into a narrow, possibly fault-bounded basin (Wentworth, 1966; Loomis and Ingle, 1994) (Figures 3 and 4). Paleocurrent evidence suggests dominantly northwestward transport occurred along the axis of the basin (Wentworth, 1966; B. Ritts, personal communication, 1994). Conglomerate clast lithologies and sandstone compositions were used to subdivide the Upper Cretaceous strata into the Stewarts Point and Anchor Bay Members of the Gualala Formation of Wentworth (1966); Paleocene and Eocene rocks were assigned to the German Rancho Formation of Wentworth (1966). Cobble and boulder conglomerates, which are the focus of this paper, are abundant only in the basal

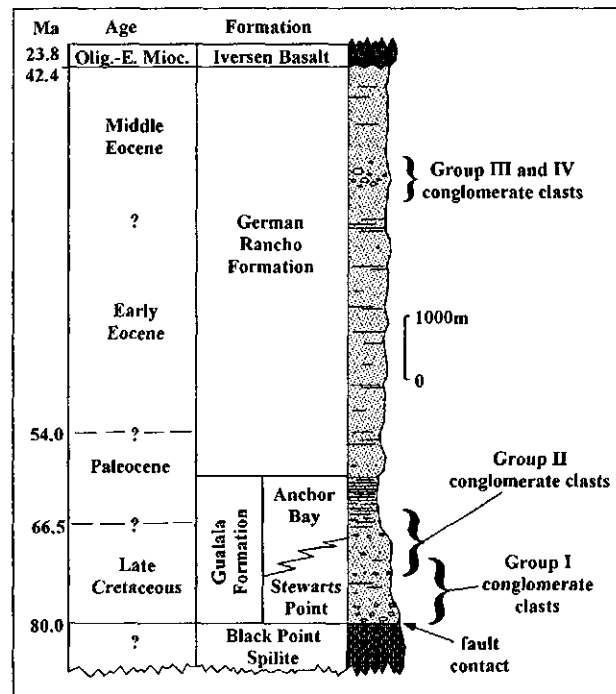


Figure 3. Stratigraphic section for Gualala basin (modified from Loomis and Ingle, 1994) showing the stratigraphic occurrence of the four clast groups discussed in the text.

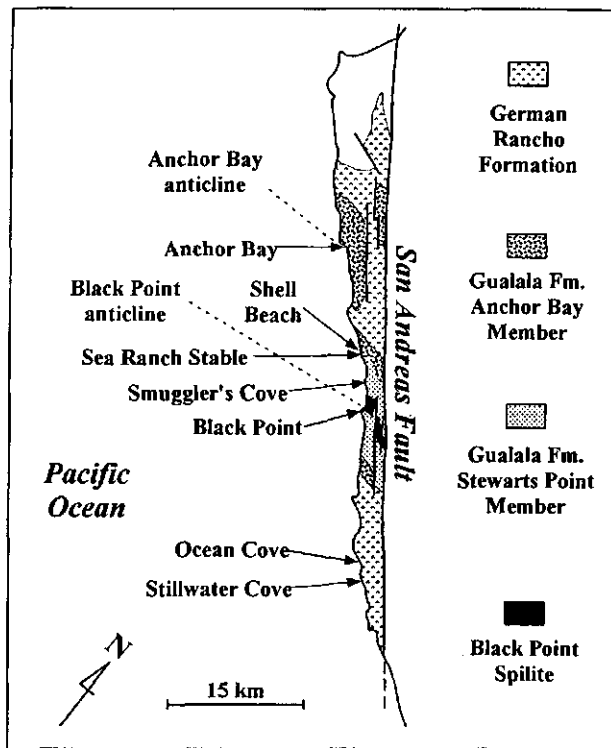


Figure 4. Geologic map of the Gualala basin (modified from Ross et al., 1973) showing conglomerate sample localities. All sampled clasts were collected from sea cliff outcrops.

Upper Cretaceous section and again in the middle Eocene section, but sandstones appear to have been deposited nearly continuously throughout this time span (Wentworth, 1966; Loomis and Ingle, 1994). The paleontologically determined age for the basal conglomeratic strata of the Stewarts Point Member which structurally overlie the Black Point spilite is Campanian (~80 Ma) (Loomis and Ingle, 1994).

Conglomerate clasts throughout the Upper Cretaceous Gualala Formation are generally well rounded and often range up to 30 cm in diameter. Lithologically, the Upper Cretaceous conglomerates are distinguished from contemporaneous deposits in the Salinian block and Great Valley Sequence by the high relative abundance of gabbroic cobbles and a total absence of Franciscan detritus (Wentworth, 1966; Grove, 1989; Seiders and Cox, 1992). Upper Cretaceous conglomerate clasts of the Gualala Formation reflect a bimodal distribution of compositions. The

basal strata of the Stewarts Point Member contain abundant porphyritic granitic and rhyolitic clasts, and are notably lacking in more mafic lithologies. Upsection, near the mapped contact between the Stewarts Point and Anchor Bay Members, granitic and gabbroic clasts are interbedded (Figures 3 and 4). Gabbroic clasts are most abundant higher in the Anchor Bay Member, constituting 30% to 60% of all clasts in this unit (Wentworth, 1966; Grove, 1989).

Wentworth (1966) noted that the bulk of the Eocene conglomerate is "totally different in composition," as compared to the Upper Cretaceous conglomerates, despite similarities in appearance and inferred depositional environment. The middle Eocene strata of the German Rancho Formation contain conglomerates with abundant cobbles and boulders of plutonic rocks. Tonalitic lithologies predominate, and some of the most distinctive clasts are a group of leucocratic garnet-bearing tonalites and trondhjemites. Boulders range up to three meters in diameter and are generally less well rounded than clasts in the Upper Cretaceous Gualala Formation. This is in stark contrast to other Eocene conglomerates in California, which generally contain much smaller, well rounded (far-travelled) porphyritic volcanic clasts (Bachman and Abbott, 1988; Grove, 1989).

## METHODS

We focused our study on cobbles and boulders that were large enough to assure representative chemical and isotopic compositions, and sufficient material for U/Pb zircon age determinations; the clasts studied are generally larger than 10 cm in diameter. Efforts were made to sample a wide variety of representative clast types at each locality in order to reveal as wide a range of source rocks as possible. Analyzed samples therefore reflect a range of representative clast compositions, although they do not necessarily reflect a statistically proportionate sampling. Acquiring U/Pb crystallization ages for the clasts is important not only as a direct tool for provenance analysis, but also to accurately interpret initial  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  isotope compositions for the individual clasts. Although the preferential sampling of large clasts may have introduced a bias

toward more resistant lithologies and more proximal source areas, this is probably not a major difficulty since the Gualala clast assemblage is dominated by immature, monocyclic detritus.

Conglomerate clasts were collected at a number of localities from different stratigraphic levels of the Upper Cretaceous section (Figures 3 and 4). Granitic and rhyolitic clasts from the Stewarts Point Member were collected from massive, unbedded basal conglomerate at Black Point on the south limb of the Black Point anticline, as well as from bedded conglomerates at Smugglers Cove on the north limb of the Black Point anticline. Hybrid conglomerates containing mixtures of granitic and gabbroic clasts were sampled at Sea Ranch Stable near the mapped contact between the Stewarts Point and Anchor Bay Members and at Shell Beach, where hybrid conglomerate is found within the lower portion of the Anchor Bay Member (Wentworth, 1966). Gabbroic conglomerate clasts were also collected from the Anchor Bay Member in the Anchor Bay anticline. Middle Eocene German Rancho Formation conglomerate clasts were collected from a single(?) submarine fan complex which is repeated by faulting and exposed in the Stillwater Cove - Ocean Cove area (Wentworth, 1966).

Multiple analyses were performed on most clasts. Whole rock powders were analyzed for major and trace elements by x-ray fluorescence (XRF). U/Pb ages were determined for single or multiple populations of zircon from individual clasts. Many analyses were slightly normally discordant ( $^{206}\text{Pb}/^{238}\text{U}$  age  $<$   $^{207}\text{Pb}/^{235}\text{U}$  age  $<$   $^{207}\text{Pb}/^{206}\text{Pb}$  age), indicating either lead loss or minor inheritance. Interpreted ages reflect either concordant U/Pb analyses or projected ages based on the discordance behavior of multiple zircon populations from a single clast. Isotope ratios of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  were determined from whole-rock powders by thermal ionization mass spectrometry (TIMS), and initial values were calculated based on the U/Pb zircon crystallization age for each sample. Where zircon yield was insufficient for analysis, or U/Pb results were strongly discordant, assumed ages (based on clasts of similar composition and stratigraphic position) were used to calculate initial Sr and Nd isotope

ratios. Lead isotope ratios were determined on feldspar separates, and oxygen isotope ratios were determined on quartz separates.

## CONGLOMERATE TYPES

Conglomerate clasts from the Gualala basin are subdivided into four distinct groups based primarily on lithology, geochemistry, isotope compositions, crystallization ages, and to a subordinate degree, on stratigraphic position. Clasts of each of the four petrologically distinctive groups generally occur within a restricted stratigraphic interval, although some overlap and intermingling exists. Group I and II clasts are interbedded near the mapped contacts of the Stewarts Point and Anchor Bay Members of the Gualala Formation. Clast Group I occurs exclusively in the Upper Cretaceous portion of the Gualala Formation, and groups III and IV occur exclusively within the middle Eocene strata of the German Rancho Formation. Group II clasts are most abundant in the Anchor Bay Member of the Gualala Formation, but also occur (sparsely) in the German Rancho Formation. Because there is a limited degree of age and compositional overlap between clasts of Groups I and III, the distinction between these two clast groups is based primarily on lithologic and stratigraphic grounds. The four clast groups are summarized in Table 1 and Figures 5 and 6, and are discussed below.

### Group I: High-Level Continental Granite and Rhyolite Clasts

The majority of felsic clasts in the Upper Cretaceous section, including all of the analyzed clasts from the basal Stewarts Point section, are broadly classified as continental granite and rhyolite. Porphyritic rhyolite and leucocratic granite are the two most abundant clast lithologies in Group I. Most of these felsic clasts have highly evolved major-element compositions (75-79 wt.%  $\text{SiO}_2$ ; 3.5-5.0 wt.%  $\text{K}_2\text{O}$ ) that are indicative of an origin at high levels of a continental magmatic arc. The majority of clasts of this group have mid-Cretaceous U/Pb zircon crystallization ages (95-105 Ma), contemporaneous with a major magmatic pulse seen throughout the Sierra Nevada, Salinian-Mojave, and Peninsular Ranges batholiths (Silver et

**Table 1: Gualala Basin Conglomerate Clasts**

	<u>Group I</u>	<u>Group II</u>	<u>Group III</u>	<u>Group IV</u>
<b>Formation</b>	Gualala Stewarts Point Mem.	Gualala Anchor Bay Mem.	German Rancho	German Rancho
<b>Depositional Age</b>	Late Cretaceous	Late Cretaceous	Middle Eocene	Middle Eocene
<b>Clast Composition</b>	Granodiorite to Granite & Rhyolite	Gabbros & Quartz Diorites	Tonalite to Granodiorite	Garnet-bearing Tonalites & Trondhjemites
<b>Clast Ages (U/Pb Zircon)</b>	85-106 Ma, 120 Ma (n = 7)	144-165 Ma (n = 9)	95-103 Ma, 112 Ma (n = 8)	108-140 Ma (n = 8)
<b><math>^{87}\text{Sr}/^{86}\text{Sr}</math> initial</b>	0.7061 to 0.7090 (n = 16)	0.7030 to 0.7052 (n = 17)	0.7056 to 0.7064 (n = 12)	0.7034 to 0.7044 (n = 12)
<b>Epsilon Nd (t)</b>	-6.8 to -1.0, +1.3 (n = 18)	+5.5 to +8.6 (n = 15)	-3.2 to +0.9 (n = 11)	+0.9 to +7.2 (n = 9)
<b><math>^{206}\text{Pb}/^{204}\text{Pb}</math></b>	18.91 to 19.76	18.19 to 18.54	18.77 to 19.17	18.58 to 18.72
<b><math>^{207}\text{Pb}/^{204}\text{Pb}</math></b>	15.65 to 15.80	15.38 to 15.62	15.60 to 15.70	15.55 to 15.71
<b><math>^{208}\text{Pb}/^{204}\text{Pb}</math></b>	38.69 to 39.41 (n = 16)	37.29 to 38.83 (n = 9)	38.49 to 38.84 (n = 9)	38.15 to 38.59 (n = 9)
<b><math>\delta^{18}\text{O}</math></b>	+8.2 to +11.2 (n = 15)	+6.3 to +9.0 (n = 9)	+9.1 to +10.9 (n = 11)	+6.2 to +7.4 (n = 10)

al., 1979; Stern et al., 1981; Chen and Moore, 1982; Mattinson, 1978, 1994; James, 1992; Miller et al., 1996). Individual clasts within this group have discordant U/Pb ages which are interpreted to be as old as 120 Ma and as young as 85 Ma. Strontium, Nd, and Pb isotope compositions are all consistent with an origin in the central and eastern portions of the Cretaceous Cordilleran magmatic arc in California (Kistler and Peterman, 1973, 1978; Silver et al., 1979; DePaolo, 1981; Silver and Chappell, 1988; Mattinson, 1990; Chen and Tilton, 1991; Kistler, 1993) (Figures 5 and 6). This is best illustrated by initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (Figures 5d and 6b-e), which are uniformly greater than 0.706, and range up to almost 0.709, unequivocally characteristic of rocks originating on the inboard, continentally-contaminated side of the Cretaceous

Californian arc (Kistler and Peterman, 1973, 1978; Silver et al., 1979; Chen and Tilton, 1991).

The granitoids of the western Mojave Desert and central Salinian block have chemical and isotopic compositions that are a good match for the provenance characteristics which are required by Group I conglomerate clasts. High initial  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.706 to 0.709) and high silica (>74 wt. %  $\text{SiO}_2$ ) granites are more common in this segment of the arc (as currently exposed) than in either the Sierra Nevada or Peninsular Ranges batholiths (Kistler and Peterman, 1973, 1978; Kistler and Ross, 1990; Bateman et al., 1984; Ross, 1972, 1984, 1989; Miller et al., 1996; Baird and Miesch, 1984). Furthermore, some Mojave granites have anomalously elevated initial  $^{87}\text{Sr}/^{86}\text{Sr}$ , at a given

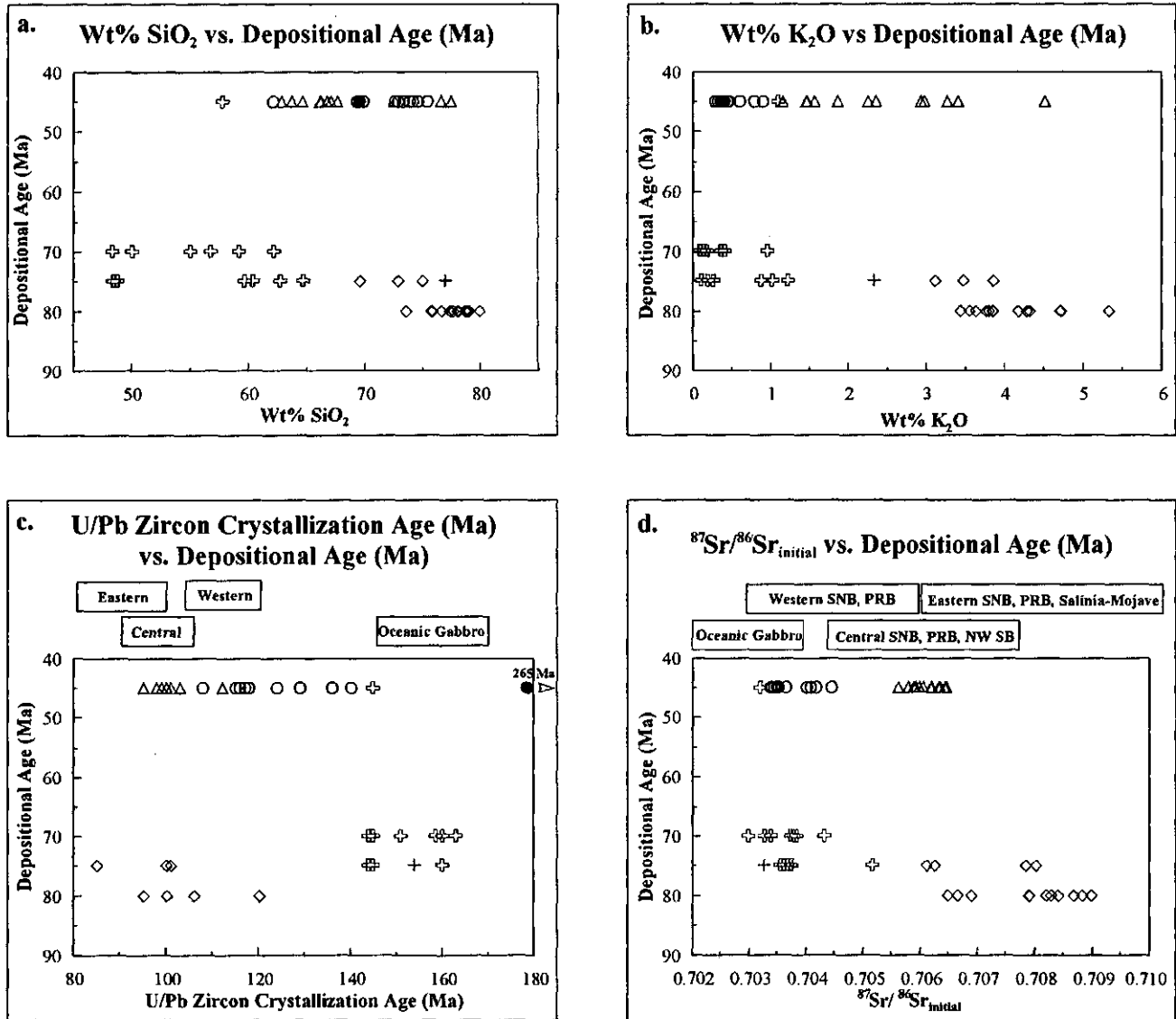


Figure 5. Plots showing the variation in clast composition and U/Pb crystallization age as a function of depositional age: a) wt.% SiO<sub>2</sub>, b) wt.% K<sub>2</sub>O, c) U/Pb zircon crystallization age, d) initial <sup>87</sup>Sr/<sup>86</sup>Sr. Group I clasts = diamonds, Group II clasts = crosses (open crosses = gabbroic, closed crosses = granitoid), Group III = open circles, Group IV = triangles, unassigned clasts = closed circles. Bars above graphs in c) and d) indicate the range of values for the majority of samples in each region of the California batholiths.

$\epsilon_{Nd}(t)$ , indicating that the high initial <sup>87</sup>Sr/<sup>86</sup>Sr Stewart Point felsic clasts were most likely derived from the Mojave region (Schott and Johnson, 1998) (Figure 6c). Initial <sup>87</sup>Sr/<sup>86</sup>Sr vs.  $\delta^{18}O$  and initial <sup>87</sup>Sr/<sup>86</sup>Sr vs. <sup>206</sup>Pb/<sup>204</sup>Pb variation diagrams (Figure 6d and 6e) clearly illustrate that Gualala Formation felsic clasts have a greater isotopic similarity to Salinia-Mojave granitoids than similar rock types from the eastern half of the

central and northern portions of the Sierra Nevada batholith (Masi et al., 1981; Mattinson, 1990; Chen and Tilton, 1991; Miller et al., 1996).

### Group II: Oceanic Gabbros and Granitoids

The vast majority of clasts assigned to this group occur within the distinctive Upper Cretaceous Anchor Bay Member of the Gualala

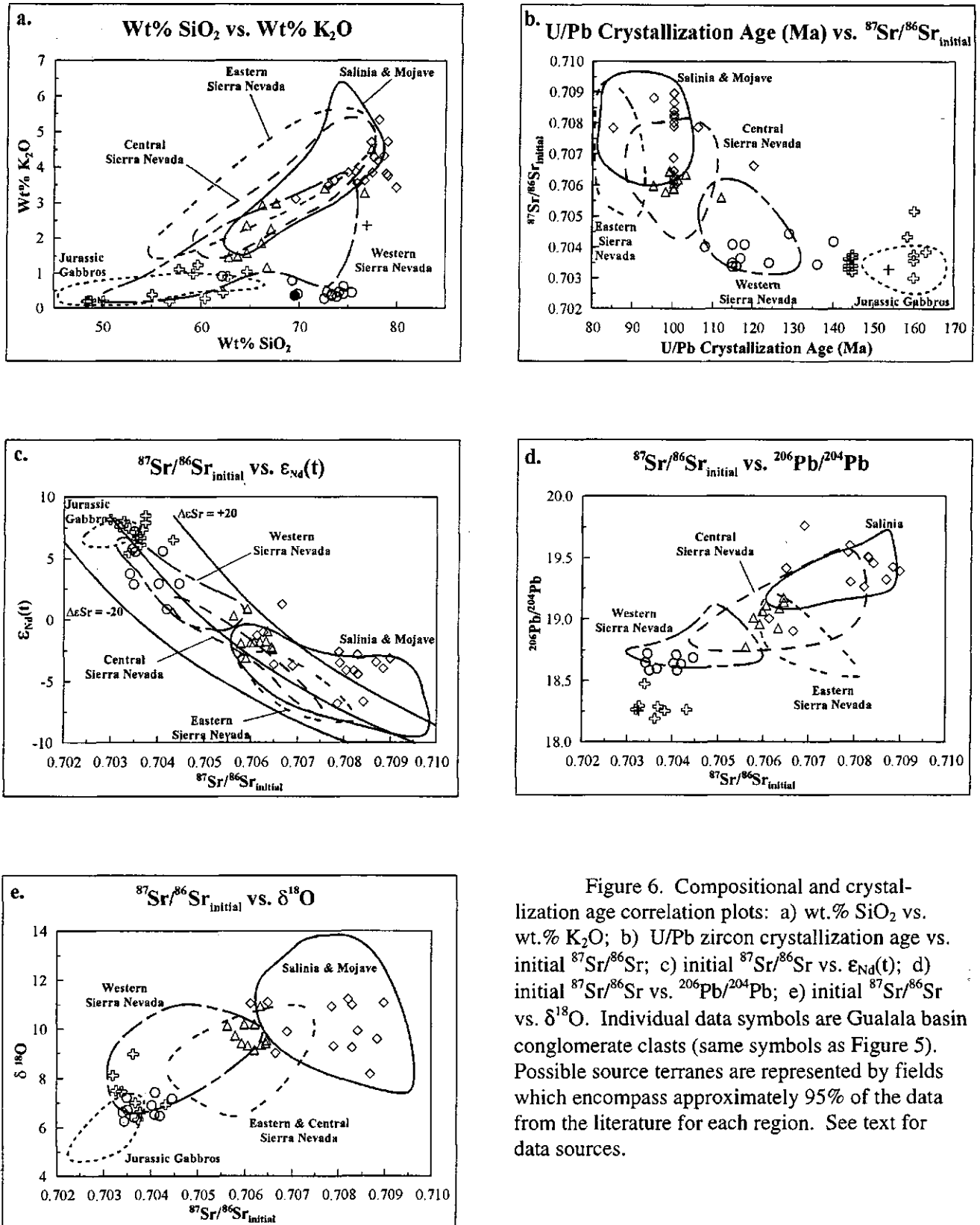


Figure 6. Compositional and crystallization age correlation plots: a) wt.% SiO<sub>2</sub> vs. wt.% K<sub>2</sub>O; b) U/Pb zircon crystallization age vs. initial <sup>87</sup>Sr/<sup>86</sup>Sr; c) initial <sup>87</sup>Sr/<sup>86</sup>Sr vs. ε<sub>Nd</sub>(t); d) initial <sup>87</sup>Sr/<sup>86</sup>Sr vs. <sup>206</sup>Pb/<sup>204</sup>Pb; e) initial <sup>87</sup>Sr/<sup>86</sup>Sr vs. δ<sup>18</sup>O. Individual data symbols are Gualala basin conglomerate clasts (same symbols as Figure 5). Possible source terranes are represented by fields which encompass approximately 95% of the data from the literature for each region. See text for data sources.

Formation, although at least one clast belonging to this group was identified in the middle Eocene German Rancho Formation. The clasts of this group have drawn the most attention from previous workers (e.g., Ross, 1970; Kistler et al., 1973; Ross et al., 1973; James et al., 1993), primarily due to the abundance of unusual mafic compositions. As noted by these previous workers, compositions range from diabase to "anorthositic" gabbro to quartz gabbro. Clasts of this group yield U/Pb zircon crystallization ages which are commonly concordant to just slightly normally discordant and range in age from 144 Ma to ~165 Ma (James et al., 1993; Schott and Johnson, 1996).

Strontium, Nd, and Pb isotope ratios are all indicative of an origin in an oceanic setting (Figures 5 and 6). Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios fall into the restricted range of 0.7030 to 0.7038 for all but two of the clasts assigned to this group;  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of these two clasts may be elevated due to hydrothermal alteration with seawater (Johnson and O'Neil, 1988). Two clasts from the mixed conglomerate facies (lowermost Anchor Bay strata) are provisionally assigned to this group based on "oceanic" isotopic compositions, despite the fact that these clasts have more evolved chemical compositions; the first clast is a 154 Ma granodiorite clast that has an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.7033 (James et al., 1993), and the other clast is an undated granodiorite clast that has  $\epsilon_{\text{Nd}}(t)$  of +8.3 at an assumed age of 150 Ma (this study).

#### **Group III: Mid-Batholithic Tonalite and Granodiorite**

Clasts assigned to this group make up the bulk of the middle Eocene German Rancho Formation conglomerate assemblage. Although Group III clasts are generally distinct from the Group I continental granite and rhyolite clasts, there is a small degree of lithologic, geochemical, and isotopic overlap, as well as nearly complete overlap of crystallization ages, and therefore the distinction between these groups is not entirely independent of stratigraphic position. In terms of chemical and isotopic compositions and age range, Group III clasts are characteristic of the voluminous plutonic rocks that occupy axial portions of the

Sierra Nevada and Peninsular Ranges batholiths (Kistler and Peterman, 1973, 1978; Silver et al., 1979; DePaolo, 1981; Baird and Miesch, 1984; Bateman et al., 1984; Silver and Chappell, 1988; Ross, 1988, 1989; Kistler and Ross, 1990; Chen and Tilton, 1991; Kistler, 1993; Pickett and Saleeby, 1994) (Figures 5 and 6). Lithologically, these clasts are medium- to coarse-grained, generally equigranular tonalites and granodiorites that contain biotite and hornblende. U/Pb zircon crystallization ages are tightly clustered at 95-103 Ma. Rocks of this group have moderately well clustered Sr and Nd isotope compositions of initial  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7056$  to  $0.7064$ , and  $\epsilon_{\text{Nd}}(t) = +0.9$  to  $-3.2$ , respectively (Figure 6c). A single clast that has a gneissic texture and granitic bulk composition yielded a 112 Ma U/Pb zircon age, but is isotopically indistinguishable from the remainder of Group III clasts, and this sample is tentatively assigned to this group.

#### **Group IV: Garnet-Bearing Tonalite and Trondhjemite**

Although garnet-bearing rocks make up only about five percent of the Middle Eocene conglomerate clast population, their unusual and distinctive composition places important constraints on source terranes. In the field these rocks are distinguished not only by the presence of garnet, but also by their bleached-white weathering color, which reflects a sparsity of mafic minerals. Petrographic textural evidence suggests the garnet is of igneous origin. The majority of the garnet-bearing clasts are trondhjemites because of their low color index and remarkably low  $\text{K}_2\text{O}$  contents at moderate to high silica contents (Barker, 1979) (Figure 6a). Garnet-bearing clasts fall into narrowly defined ranges for initial  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7035 to 0.7045) and  $^{206}\text{Pb}/^{204}\text{Pb}$  (18.58 to 18.72), but paradoxically they yield a wide range of (mostly concordant) U/Pb zircon crystallization ages (108 to 140 Ma) and  $\epsilon_{\text{Nd}}(t)$  (+0.9 to +7.2) (Figures 5 and 6). These isotope ratios generally reflect an igneous origin on the western (oceanic) side of the Cordilleran batholiths (Kistler and Peterman, 1973, 1978; Silver et al., 1979; DePaolo, 1981; Silver and Chappell, 1988; Chen and Tilton, 1991). The Early Cretaceous crystallization ages overlap both a



pronounced magmatic lull in California (~145 to ~125 Ma) and the initiation of voluminous Cretaceous magmatism in the western portions of the California batholiths (~125 to ~105 Ma).

A single garnet-free clast that has trondhjemitic geochemical affinities yielded a near-concordant U/Pb crystallization age of ~265 Ma, and thus defies classification within the four groups listed above. This clast has isotopic compositions that are most similar to the Group III clasts.

### DISCUSSION: LATE CRETACEOUS PROVENANCE CONSTRAINTS

The abundance of Group I conglomerate clasts, which were derived from high levels of the continental side of a magmatic arc, is surprising, given the bathyal depths and interpreted forearc depositional location of the Gualala basin (Loomis and Ingle, 1994). Forearc sediments in California generally overlie oceanic basement (Dickinson, 1981), and are generally widely separated from eastern arc rocks that have continental isotopic compositions (i.e., initial  $^{87}\text{Sr}/^{86}\text{Sr} > 0.706$ ) (Kistler and Peterman, 1973, 1978). The abundance of large (up to 30 cm) Group I clasts in the lower part of the Gualala Formation (and absence of clasts characteristic of the western arc) appears to require juxtaposition of eastern arc crust with the forearc; such juxtaposition is interpreted to reflect westward-directed collapse of the Cretaceous arc (Schott and Johnson, 1998). The Group I clasts cannot be derived from a passing exotic terrane, such as that proposed for the Baja-BC correlation (Maxson and Tikoff, 1996), because such a terrane would not have the continental isotopic compositions of the Group I clasts (Schott and Johnson, 1998). It is also unlikely that the Gualala basin itself is a far-travelled exotic terrane (Kanter and Debiche, 1985) because such terranes would be expected to have oceanic isotopic compositions.

Although Cretaceous granitoids currently exposed in the east-central Salinian block and western Mojave Desert are geochemically and isotopically similar to Group I clasts, they probably represent significantly deeper levels of the crust. The majority of Group I clasts appear to have crystallized at shallow levels in the crust, whereas

granitoids in Salinia and the western Mojave Desert represent mid-crustal levels, as indicated by the common occurrence of sillimanite in pendants and wall rocks (John, 1981; Ross, 1989). The difference in batholithic levels probably reflects significant post-Late Cretaceous erosion of the source terranes.

Uplift and erosion of the Group I source terrane was rapid, as indicated by the presence of a Group I granodiorite clast that has an ~85 Ma crystallization age in Stewarts Point strata. Assuming a depositional age between 80 Ma and 75 Ma (Loomis and Ingle, 1994), crystallization, uplift and westward tectonic transport, erosion, and deposition in the forearc must have occurred in less than 10 m.y. Based on these depositional ages westward transport may have immediately followed or been contemporaneous with the youngest magmatism in the SWMA (Schott and Johnson, 1998), although clasts younger than 85 Ma have not yet been found in the Gualala basin.

There are a number of potential source terranes for Jurassic oceanic gabbros of clast Group II, although no currently exposed terrane is a perfect match. The concordant U/Pb zircon ages at ~145 Ma for a number of Group II clasts precludes correlation of gabbros with known oceanic origin in the Coast Range Ophiolite and the western Foothills belt of the Sierra Nevada batholith, including the Eagle Rest Peak-Logan Quarry-Gold Hill gabbroic complex, because all of these terranes have ages of 150 to 165 Ma (Saleeby and Sharp, 1980; Hopson et al., 1981; James et al., 1993). It is impossible to fully evaluate the significance of this age discrepancy due to the fact that significant portions of the Jurassic gabbroic belt are currently buried beneath Tertiary sediments in the San Joaquin Valley (Ross, 1989), and we suggest that it is likely that the buried gabbroic belt contains ages that are younger than 150 Ma.

Several potential source terranes for Group II clasts can be eliminated. The lack of chert and serpentine in the Gualala sediments effectively precludes a source within the Franciscan terrane (Wentworth, 1966), and would also appear to rule out much of the Coast Range Ophiolite. Jurassic mafic rocks in the western Mojave Desert yield appropriate ages, but have clearly continental

isotope compositions (Miller and Glazner, 1995), and therefore cannot be the source of the Group II clasts. Jurassic gabbros are not present in any abundance in either the Peninsular Ranges (Silver et al., 1979) or the majority of the Salinian block (Ross, 1984).

When considered in their stratigraphic context, the bimodal compositional range of Group I and Group II clasts provides a unique provenance constraint for Upper Cretaceous rocks at Gualala. Group I clasts dominate the basal Stewarts Point strata of the Upper Cretaceous section, whereas Group II clasts are more prevalent upsection in the Anchor Bay Member. Because clasts from both groups are mixed and interbedded near the mapped contacts of the Stewarts Point and Anchor Bay Members, it is inferred that their source terranes were adjacent during the Late Cretaceous. Wentworth (1966) inferred that these contrasting clast types originated from two distinct terranes located on opposite sides of the basin, and suggested that the tectonic juxtaposition of these terranes by pre-Late Cretaceous strike-slip faulting might also be responsible for the origin of the basin. Alternate mechanisms for juxtaposing these terranes might include low angle detachment or thrust faulting (Schott and Johnson, 1998), or strike-slip juxtaposition on the same side of the basin (Schott, 1993).

The most suitable Late Cretaceous depositional location for the Gualala basin is adjacent to the northern margin of the westward transported Salinian-western Mojave allochthon (SWMA) (Figure 2). The northern edge of the SWMA is marked in the southernmost Sierra Nevada batholith (San Emigdio and western Tehachapi Mts.) by the Pastoria thrust, which has been recognized as a major tectonic break (Ross, 1989), and provides an explanation for the juxtaposition of markedly different source terranes, as indicated by the Group I and Group II clasts. Rocks located in the upper plate of the thrust, exposed to the south of the fault trace, are mid- to high-level Cretaceous granites and granodiorites that have isotopic compositions that are characteristic of the eastern portions of the Cordilleran batholithic belt (i.e.,  $^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}} > 0.707$ ) (Kistler and Ross, 1990) (Figure 2). These

rocks are offset across the Neogene San Andreas and Garlock faults from correlative granitic rocks of eastern batholithic character that currently crop out in the Gabilan Range and western Mojave Desert respectively (Ross, 1984; Ross, 1989; James, 1992; Powell, 1993) (Figure 1). Rocks of the lower plate, exposed north of the Pastoria thrust, are mafic in composition and have oceanic isotope compositions (i.e.,  $^{87}\text{Sr}/^{86}\text{Sr}_{\text{initial}} < 0.705$ ) (Ross, 1989; Kistler and Ross, 1990; Pickett and Saleeby, 1994). The westernmost exposure in the lower plate is the Late Jurassic (~160 Ma) mafic plutonic complex of Eagle Rest Peak (Reitz, 1986) (Figure 2). Just southeast of the Eagle Rest Peak body in the lower plate is the heterogeneous quartz diorite to tonalite of Antimony Peak (Ross, 1989). This body is variably deformed and has yielded a U/Pb crystallization age of ~131 Ma (E. James, 1997, electronic communication). Further to the east, lower plate rocks are strongly deformed ~115 Ma mafic gneisses of the Tehachapi gneiss complex (Saleeby et al., 1987; Pickett and Saleeby, 1994). Geophysical and well data suggest that the Jurassic gabbros currently exposed at Eagle Rest Peak and Logan may be part of a more extensive Upper Jurassic (and lowermost Cretaceous?) oceanic basement terrane that is currently buried beneath Paleogene and Neogene sediments in the San Joaquin Valley and Butano basin (Ross, 1984; Ross, 1989). The Pastoria thrust may be correlative with the Vergeles-Zayante fault in the Salinian block (Ross, 1984; Ross, 1989) (Figure 2); the latter fault also separates mid-Cretaceous continental affinity granitoids from Jurassic oceanic gabbros, although evidence suggests that the Vergeles-Zayante fault is not currently a low-angle fault (Ross, 1984).

In summary, the provenance constraints for Upper Cretaceous conglomerates at Gualala can be well explained by regional source terranes and Late Cretaceous tectonic events within the California segment of the Cordilleran arc, and do not require the involvement of exotic terranes.

#### DISCUSSION: MIDDLE EOCENE PROVENANCE CONSTRAINTS

Conglomerate clast Group III constitutes the majority of the middle Eocene clast population.

One of the more unusual aspects of this clast group is the relatively high ratio of plutonic to volcanic lithologies as compared to the Upper Cretaceous conglomerates at Gualala and other Eocene conglomerates throughout California (Bachman and Abbott, 1988; Grove, 1989). Because many other Eocene sediments in California reflect a strong chemical weathering environment (Bartow, 1987), the presence of abundant, large plutonic cobbles in the Eocene section at Gualala is strong evidence for a very proximal source at the time of deposition. The large size (up to three meters in diameter) and less well-rounded nature of clasts in this group also strongly suggest a localized source.

Group III clasts are broadly similar to many of the voluminous mid-Cretaceous plutonic rocks in the axial regions of California's batholiths, although their proximal nature effectively precludes derivation from most of these terranes. Group III clasts are isotopically similar to some of the tonalites and granodiorites that are exposed at the northern and western margins of the Salinian block, specifically those at Bodega Head, Tomales Point, Montara Mountain, Ben Lomond, and offshore at Cordell Bank and the Farallon Islands (Mattinson, 1990; Kistler and Champion, 1991) (Figures 1 and 2). The proximal nature of the Group III clasts suggests that the scattered exposures of the northern and western Salinian block may reflect a much more significant offshore area that has greater similarities to the axial portions of the Cordilleran batholiths than the better exposed onshore sections in the central Salinian block. The substantial age overlap and minimal isotopic and geochemical overlap between Group I and Group III clasts (Figures 5 and 6) is consistent with the interpretation that these clast groups are derived from different parts of the same westward transported portion of the Cordilleran batholithic belt (the SWMA). A single analyzed gabbroic clast from the middle Eocene section that has source characteristics which are indistinguishable from Group II clasts may indicate that either the source terrane for Upper Cretaceous Group II clasts was still exposed near the basin, or that similar rocks occur as a minor part of the Group III source terrane.

Garnet-bearing tonalites and trondhjemites which fit the source terrane characteristics that are required by Group IV clasts are extremely rare in the Mesozoic Cordilleran batholiths. Their low  $K_2O$  contents (at high  $SiO_2$ ), low initial  $^{87}Sr/^{86}Sr$  ratios, moderate to high  $\epsilon Nd(t)$  and Early Cretaceous ages are all strongly indicative of a western batholithic (oceanic) source (Bateman and Dodge, 1970; DePaolo, 1981; Stern et al., 1981). The only garnet-bearing tonalites and trondhjemites described in the Sierra Nevada are found in the Fine Gold Intrusive Suite in the Foothills belt just north of Fresno, and in drill core into the buried western portion of the batholith in that region (Calk and Dodge, 1986; Saleeby et al., 1989; Liggett, 1990; Truschel, 1996). Lower Cretaceous trondhjemites occur in a similar tectonic setting in the Klamath Mountains (Barnes et al., 1996) and the Peninsular Ranges batholith (Silver and Chappell, 1988), although garnet is sparse or absent in these rocks. No source rock for this lithology is currently exposed in the Salinian block, the southern Sierra Nevada, or western Mojave Desert (Ross, 1972, 1973, 1989). It seems likely, however, that a more extensive belt of Lower Cretaceous garnet-bearing tonalites and trondhjemites may exist at the extreme western margin of the arc, obscured today by Neogene sedimentary cover. If such a belt continued south to the Salinia-Mojave segment of the batholithic belt, it may have been displaced westward with the SWMA, thus currently occupying a region offshore. We infer, therefore, that the "missing" western margin of the Salinian arc (Page, 1982) was composed of Lower Cretaceous tonalite and trondhjemite and was present near the location of the Gualala basin at least as recently as the middle Eocene. Because the garnet-bearing clasts of Group IV are so unusual relative to the majority of middle Eocene Group III conglomerates, yet both clast types had a proximal source, it is likely that Group IV clasts were derived from a subsidiary tectonic block or sliver that was juxtaposed with the larger Group III clast source terrane.

The absence of the distinctive high-level interior batholith rocks that are characteristic of Group I clasts in the German Rancho Formation, and the sparsity of clasts which are characteristic of Group II, suggests that the Late Cretaceous source

area no longer occupied a position that was proximal to the basin in the middle Eocene and/or that it had been significantly reduced in topographic stature. The change in source terranes from the Late Cretaceous to middle Eocene suggests that tectonic shuffling of the source terranes and basins occurred, probably accompanied by localized uplift.

### TECTONIC MODEL, ALTERNATIVES, AND IMPLICATIONS

The provenance constraints presented above provide a framework for developing an integrated model for the origin and early evolution of the Salinian block that is not possible using exposed granitic bodies alone. We hypothesize an originally continuous, transversely-zoned continental magmatic arc that stretched from northern Alta California to southern Baja California (Figure 7a). This arc was generated by subduction of the Farallon Plate beneath the western margin of North America with significant growth of the Cretaceous batholithic belt until about 85 Ma (Page and Engebretson, 1984).

Figure 7b illustrates the configuration of terranes at about 80 Ma, immediately following westward transport of the SWMA in response to the shallowing of the subducting slab in this part of the arc (Silver, 1982, 1983; Silver and Mattinson, 1986; Silver and Nourse, 1986; May, 1989; Hall, 1991; James, 1992; Malin et al., 1995). We propose that the basal Upper Cretaceous Group I conglomerate marks the arrival of the SWMA at a forearc proximal location (Schott and Johnson, 1998). This interpretation suggests that the minimum age for westward transport on the northern edge of the SWMA is older than ~80 Ma (Schott and Johnson, 1998). The upsection appearance of Group II conglomerate clasts is inferred to reflect erosion through the upper plate of the SWMA into Jurassic oceanic gabbros of the lower plate of the detachment. An alternative explanation for the upsection increase in gabbroic conglomerate may involve translation of the basin northward or westward away from the advancing allochthon. Such a translation could be accommodated along the low angle detachment fault which separates the structurally lowest

conglomerate from underlying spilitic basalt (Wentworth, 1966). In either case, it appears that the Campanian source terrane had either been worn down by erosion or tectonically separated from the basin by the end of the Cretaceous period, as indicated by the paucity of Group I clasts in the Anchor Bay Member conglomerate of the Gualala Formation.

The abrupt reappearance of coarse conglomerate in the middle Eocene appears to reflect a localized basement uplift, although a sudden drop in sea level may provide a plausible alternative (May and Warne, 1987). Because the Late Cretaceous and middle Eocene source terranes show little lithologic or isotopic overlap, it seems likely that the basin was tectonically shifted away from its Late Cretaceous source area and/or a new source terrane was tectonically juxtaposed with the basin in the middle Eocene. We propose minor (cumulatively tens of kilometers) dextral strike-slip dismemberment, slivering, and elongation of the outboard portions of the SWMA (i.e., Jayko and Blake, 1993) (Figure 7c), as a response to strain partitioning in a transpressional plate convergence setting (Page and Engebretson, 1984) at the leading edge of the North American plate. As such, the faulted and dismembered fragments of the SWMA which now underlie offshore portions of the Salinian block represent the primary source for Group III and IV clasts, and are the final remnants of the "missing" western portion of the Salinian arc (Page, 1982) (queried area on Figure 7c). The proposed Paleocene or early Eocene dismemberment and elongation of the western margin of the SWMA, in conjunction with oroclinal bending of the southernmost Sierran batholith (Kanter and McWilliams, 1982; McWilliams and Li, 1985), would also largely account for the asymmetric protrusion of the northern end of the SWMA in many pre-Neogene palinspastic reconstructions of the region (Figure 2) (Ross, 1984; Hall, 1991; James, 1992; Powell, 1993). Such a scenario obviates the need for a proto-San Andreas fault (Suppe, 1970; Nilsen, 1978).

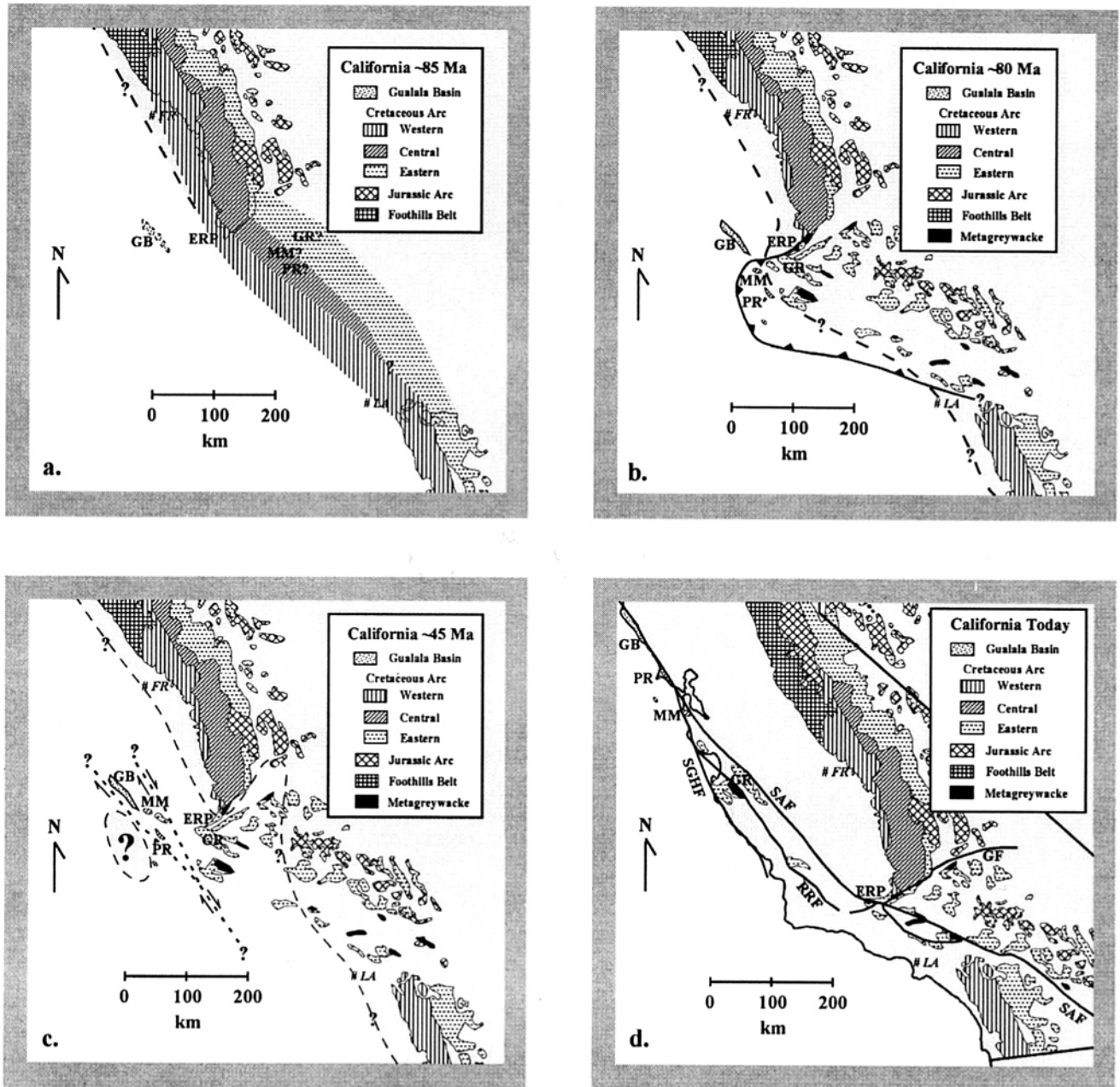


Figure 7. Cartoon paleotectonic/paleogeographic reconstructions of California: a) 85 Ma b) 80 Ma c) 45 Ma d) today. Gualala basin = GB. Other abbreviations are the same as in Figures 1 and 2. Grey shading indicates areas above sea level. Queried island south of Gualala basin in c) is the hypothesized source for proximally derived German Rancho Formation clasts and may represent the “missing” western portion of the Salinian block (Page, 1982). See discussion in text.

## CONCLUSIONS

Detailed provenance analysis based on U/Pb zircon crystallization ages, geochemistry, and isotope compositions of a variety of conglomerate

clast lithologies can be used to constrain both the location of origin and the subsequent tectonic evolution of a suspect terrane. In the case of the Gualala basin, the interfingered occurrence of two contrasting clast types, one derived from high

levels of the interior (continental) side of the mid-Cretaceous Salinian-Mojave magmatic arc, and the other derived from an oceanic Jurassic gabbro terrane, constrains a Late Cretaceous depositional location adjacent to the northern end of the westward transported Salinia-western Mojave allochthon. The Campanian age (~80 Ma) of basal Gualala Formation conglomerates provides a minimum age for the juxtaposition of these terranes (Schott and Johnson, 1998). Provenance constraints from Upper Cretaceous conglomerates do not support large-scale transport of the basin from low latitudes, or derivation of sediment from passing or colliding outboard terranes, such as the proposed Baja BC terrane (Schott and Johnson, 1998). Subsequent middle Eocene conglomerate sedimentation at Gualala records different source terranes than either the Upper Cretaceous conglomerates or other Eocene conglomerates elsewhere in California. An isolated basement fragment that has chemical and isotopic characteristics of the axial and outboard portions of the Cretaceous batholiths is inferred to have been slivered off the outboard edge of the SWMA and emplaced adjacent to the Gualala basin by the middle Eocene. When these Paleogene tectonic events are viewed in the context of the early evolution of the Salinian block, they suggest an alternative to the proposed proto-San Andreas fault and provide a possible solution to the puzzle of the "missing" western portion of the Salinian arc.

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