Sedimentary record of the Late Cretaceous thrusting and collapse of the Salinia-Mojave magmatic arc

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ABSTRACT

Upper Cretaceous conglomerates in the Gualala basin, California, contain rhyolite and granite clasts that have been previously hypothesized to have disparate terranes of origin. New geochemical, age, and isotopic analyses of these conglomerate clasts suggest an igneous origin in the upper levels of the continental side of the Cretaceous Cordilleran magmatic arc. Sr-Nd isotope relations constrain a provenance in the pre-Neogene Salinia-Mojave arc segment. Given the tectonically reconstructed outboard depositional location for the Gualala basin, we interpret the initiation of rhyolite-granite conglomerate deposition in the Gualala basin to reflect the arrival of the westward-thrusted Salinian allochthon at the forearc, coincident with the collapse of the Salinia-Mojave segment of the magmatic arc. This interpretation constrains the age of batholithic collapse to be ca. 80 Ma and suggests that thrusting immediately followed or may have been contemporaneous with the youngest magmatic events in this part of the arc. The data do not support contributions from a northward-moving Baja British Columbia (Baja BC) terrane, or large-scale translation (~2000 km) of the basin.

INTRODUCTION

During mid-Cretaceous time, rocks currently exposed in the Sierra Nevada–Salinia/Mojave–Peninsular Ranges batholiths formed the roots of one of the longest continuous continental magmatic arcs on Earth. Modern pre-Neogene strike-slip palinspastic reconstructions invariably reveal a westward bulge of the batholith spanning the restored Salinia-Mojave portion of that arc (Fig. 1) (e.g., Ross, 1984; James, 1992; Powell, 1993). Within the area of this westward bulge, rocks of eastern (continental) batholithic affinities (granites and granodiorites that have $^{87}Sr/^{86}Sr_{initial} > 0.7060$) are present across the entire width of the batholith (Kistler and Peterman, 1978; Ross, 1984) and rocks of western (oceanic) batholithic affinity (gabbros and tonalites that have $^{87}Sr/^{86}Sr_{initial} < 0.7060$) are missing (Page, 1982). Westward thrusting of rocks of eastern batholithic affinities has been proposed as a response to shallowing of the subducting Farallon plate at the onset of the Laramide orogeny (Silver, 1982, 1983; Silver and Mattinson, 1986; May, 1989; Hall, 1991; James, 1992; Malin et al., 1995). We present a test of this model, using the forearc sedimentary record.

The Gualala basin is currently located at the northern end of the displaced Salinian block (Fig. 1, inset). Palinspastic removal of 465 km of Neogene right-lateral offset restores the Gualala basin to a depositional(?) location adjacent to and outboard of the northern edge of the Salinia-Mojave bulge (Fig. 1) (Ross, 1984; Hall, 1991; Powell, 1993). In such a position, the basin may have received sediments from the adjacent (now dissected) Sierra Nevada-Salinia-Mojave magmatic arc, or, alternatively, from colliding or passing exotic terranes. Maxson and Tikoff (1996) suggested that the Baja BC terrane may have shed detritus into the Gualala basin during the Late Cretaceous or earliest Paleogene as it translated northward. A third alternative, implied by paleomagnetic data from pre–Late Cretaceous basalt and Eocene sediments in the basin, is that the location of Late Cretaceous deposition was ~2000 km south of its current location (Kanter and Debiche, 1985), perhaps adjacent to the Peninsular Ranges segment of the magmatic arc at the latitude of Baja California.

SEDIMENTS OF THE GUALALA BASIN

Upper Cretaceous and Paleogene sedimentary rocks of the Gualala basin consist of conglomerates, sandstones, and mudstones interpreted to reflect inner, middle, and outer fan turbidite deposition at bathyal depths into a narrow, possibly fault-bounded basin (Wentworth, 1966; Loomis and Ingle, 1994). Paleocurrent indicators imply a dominantly northwestward sediment transport direction, parallel to the axis of the basin (Wentworth, 1966; B. Ritts, 1995, personal commun.). The depositional age of the Upper Cretaceous strata of the Gualala basin is constrained by microfossils and sparse macrofossils; initiation of deposition was during Campanian time (ca. 80 Ma) (Wentworth, 1966; Loomis and Ingle, 1994). The only exposed basement in the Gualala basin is a spilitic basalt of uncertain tectonic affinity that underlies the basal conglomerate of the basin; the contact is probably faulted, but the nature and magnitude of offset are unconstrained (Wentworth, 1966).

Wentworth (1966) assigned Upper Cretaceous rocks to the Gualala Formation, which is subdivided into the Stewarts Point and Anchor Bay members (Fig. 1, inset) on the basis of differences in conglomerate clast type and sandstone composition. The basal conglomerates of the Stewarts Point member are massive, clast-supported, inner fan deposits dominated by porphyritic rhyolitic and granitic lithologies, and contain individual boulders as much as 1 m in diameter (Wentworth, 1966; Loomis and Ingle, 1994). Upsection, the percentage of felsic volcanic clasts decreases, and gabbroic cobbles (absent in the basal section) increase in abundance (Wentworth, 1966; Bachman and Abbott, 1988). Conglomerate in the Anchor Bay member is dominated by gabbroic lithologies (Wentworth, 1966). This study focuses the porphyritic rhyolite and granite clasts of the basal Stewarts Point member.

GEOCHEMICAL, AGE, AND ISOTOPIC CHARACTER OF GUALALA FORMATION RHYOLITIC AND GRANITIC CLASTS

Granitic and rhyolitic clasts of the basal conglomerate of the Stewarts Point member have highly evolved compositions.[1] Most samples are

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[1] Data Repository item 9837, conglomerate clast descriptions and localities and chemical, isotope, and age data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

Data Repository item 9837 contains additional material related to this article.

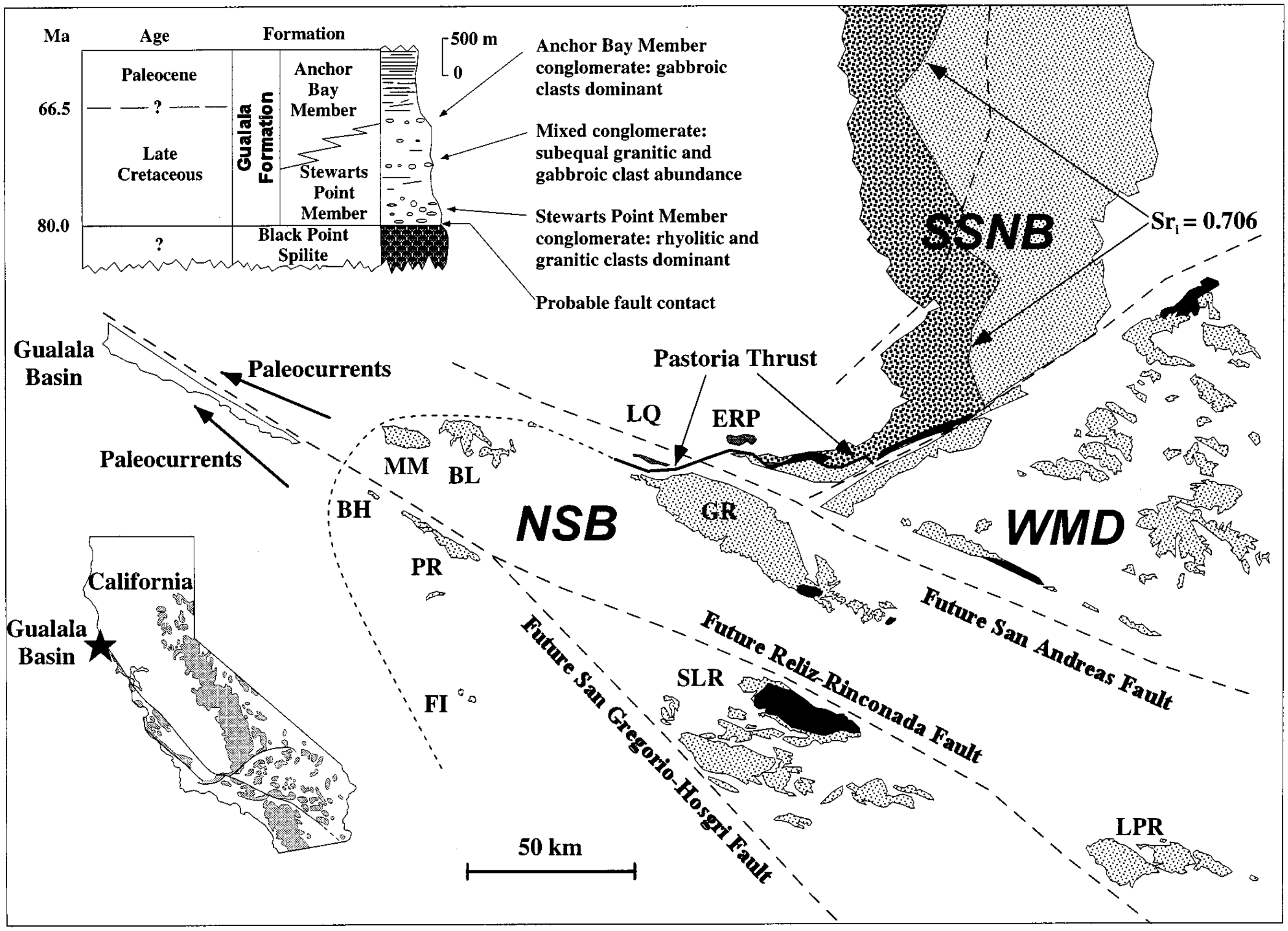

Figure 1. Palinspastic reconstruction of northern portion of Salinian bulge during Late Cretaceous (ca. 80 Ma) (modified from Powell, 1993). Cretaceous batholithic rocks are shaded light gray for continental and dark gray for oceanic. In southern Sierra Nevada batholith (SSNB) boundary is $^{87}Sr/^{86}Sr_{initial}$ = 0.7060 line (Kistler and Ross, 1990); in Sierran "tail" boundary is coincident with Pastoria thrust. Lower plate windows are shaded black within westward-thrusted northern Salinian block (NSB) and western Mojave Desert (WMD). Other localities: MM—Montara Mountain, BL—Ben Lomond, BH—Bodega Head, PR—Point Reyes, FI—Farallon Islands, LQ—Logan Quarry, ERP—Eagle Rest Peak, GR—Gabilan Range, SLR—Santa Lucia Range, and LPR—LaPanza Range. Current location of Gualala basin (star) and Mesozoic batholithic rocks (shaded) in California are shown in inset at lower left. Stratigraphic section for Upper Cretaceous Gualala Formation is shown in inset at upper left (modified from Loomis and Ingle, 1994).

highly leucocratic, and have only a trace of biotite; most have 0.5–3 wt% normative corundum and 77–79 wt% SiO_2. K_2O is generally in the range of 3.5–5 wt%, suggesting an origin on the continental side of the batholith (Bateman and Dodge, 1970). The abundance of rhyolite, the porphyritic texture, and the undeformed nature of the majority of samples suggest that they had an igneous origin in the upper levels of the magmatic arc.

Zircon U/Pb ages (this study) from individual cobbles yield mid-Cretaceous igneous crystallization ages. Many analyses are slightly normally discordant ($^{206}Pb/^{238}U$ age < $^{207}Pb/^{235}U$ age < $^{207}Pb/^{206}Pb$ age), and discordance patterns of multiple zircon fractions from the same sample indicate both inheritance and Pb loss. Interpreted crystallization ages range from 85 Ma to 120 Ma, although most samples are in the 90–105 Ma age range. The ages and discordance patterns observed in Gualala clasts are similar to those of the voluminous Cretaceous granitoids throughout California (Mattinson, 1978; Chen and Moore, 1982; Saleeby et al., 1987; James, 1992).

Clasts have $^{87}Sr/^{86}Sr_{initial}$ in the range of 0.7061 to 0.7090 and $\varepsilon_{Nd}(t)$ from +1.3 to –6.8, strongly supporting an origin on the continental side of the magmatic arc (Kistler and Peterman, 1973, 1978; DePaolo, 1981). When plotted on a Sr-Nd isotope diagram (Fig. 2), it is apparent that many of the Gualala clasts have elevated $^{87}Sr/^{86}Sr_{initial}$, at a given $\varepsilon_{Nd}(t)$, relative to the overall trend of the majority of Cretaceous Cordilleran granitoids, which can be remarkably well described by a single mixing line (Fig. 2). The contrasts in Sr-Nd variations are well illustrated by defining a parameter $\Delta\varepsilon Sr$, which is the difference in $^{87}Sr/^{86}Sr_{initial}$ (in ε_{Sr} notation) for the sample and that of the mixing curve, at a given $\varepsilon_{Nd}(t)$. More than 90% of the Cretaceous Cordilleran granitoids are within ±10 $\Delta\varepsilon Sr$ units of the best-fit mixing line, whereas two-thirds of the Gualala clasts have $\Delta\varepsilon Sr$ between +20 and +40. There is no evidence that $^{87}Sr/^{86}Sr_{initial}$ of the clasts is altered (see Data Repository Table 5). Some high-SiO_2 granites of the western Mojave Desert have a similarly high $\Delta\varepsilon Sr$ (Miller et al., 1996).

EVALUATING ALTERNATIVE SOURCE TERRANES

The Salinian block has been commonly inferred to be the most likely source for granitic detritus in the Gualala basin (Wentworth, 1966; Ross et al., 1973), largely on the basis of the proximity of the two terranes and the general similarity in composition. This link was questioned by James et al. (1993) on the basis of a single granodiorite clast that has a Jurassic age and oceanic Sr and Pb isotope compositions. Our data indicate that the vast majority of Stewarts Point member granitic and rhyolitic clasts have petrologic affinities to the interior, continental side of the Cretaceous magmatic arc. We suggest that the rela-

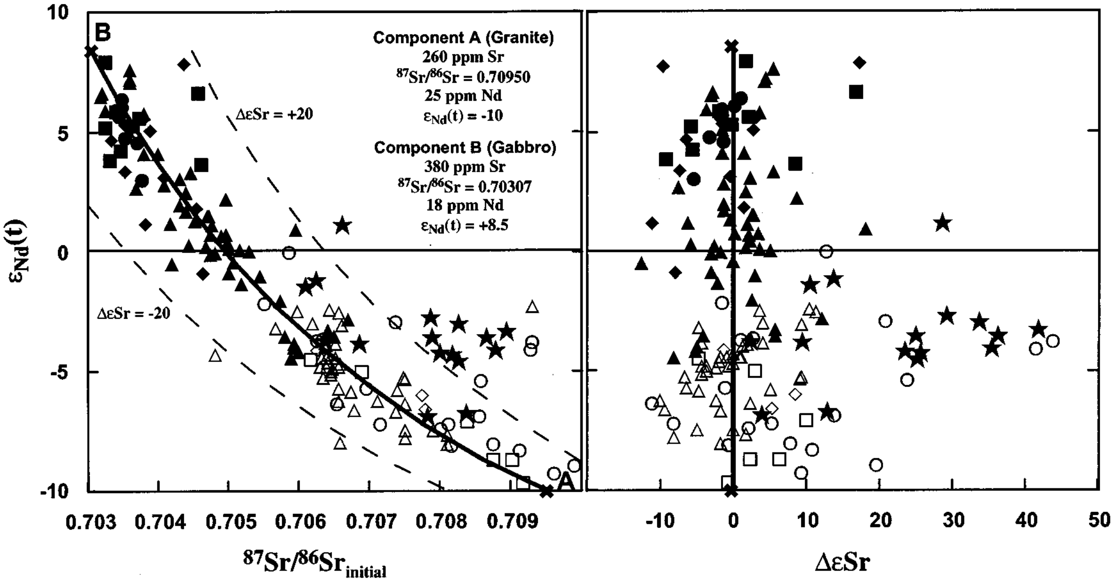

Figure 2. Sr-Nd isotope variations; stars are Gualala Formation rhyolite and granite conglomerate clasts (this study). Western (black symbols) and eastern (white symbols) Cretaceous Cordilleran batholiths (*n* = 136): white boxes—Salinian block (Mattinson, 1990), white circles—western Mojave Desert (DePaolo, 1981; Miller et al., 1996), white triangles—eastern Sierra Nevada (Kistler, 1993, and references therein), white diamonds—eastern Peninsular Ranges (DePaolo, 1981), black squares—Baja BC (Samson et al., 1989, 1990; Cui and Russell, 1995), black circles—Klamath Mountains (Barnes et al., 1992), black triangles—western Sierra Nevada (Kistler, 1993, and references therein; Pickett and Saleeby, 1994), black diamonds—western Peninsular Ranges (DePaolo, 1981).

tively sparse granodiorite clasts that have oceanic isotopic compositions (James et al., 1993; Schott and Johnson, 1996) more likely represent evolved members of the same oceanic terrane that was the source for the gabbroic clasts that dominate the Anchor Bay strata (Schott and Johnson, 1996), rather than an exotic terrane such as Baja BC, as suggested by Maxson and Tikoff (1996). Because Cretaceous igneous rocks throughout the Baja BC terrane have oceanic ^{87}Sr/^{86}Sr$_{\text{initial}}$ (< 0.7050; Armstrong, 1988), this exotic terrane is effectively precluded as a source for the highly evolved rhyolitic-granitic clasts (^{87}Sr/^{86}Sr$_{\text{initial}} > 0.7060$) that dominate the Stewarts Point member of the Gualala Formation.

The Salinia–western Mojave section of the arc is the most likely source for the Gualala Formation rhyolite and granite clasts because of their markedly higher ΔεSr, as compared to the rest of the Cretaceous Cordilleran arc (Fig. 2). Although eastern portions of the Peninsular Ranges and the central and northern Sierra Nevada batholiths have some age, geochemical, and isotopic similarities to Gualala clasts, there is no evidence to suggest that rocks from these regions were ever juxtaposed with the forearc. Thus, it is unlikely that either region could be the source for conglomeratic forearc sediment without significant evidence of sedimentary input from central and western portions of the batholiths. A provenance in the Peninsular Ranges batholith is further precluded by the lack of appropriate sources for Jurassic gabbroic clasts, which are interbedded with the rhyolites and granites upsection at Gualala (Schott and Johnson, 1996).

IMPLICATIONS FOR PALEOTECTONICS AND PALEOGEOGRAPHY

We suggest that initiation of rhyolite and granite conglomerate influx into the Gualala basin marks the arrival of batholithic rocks of continental affinities that had been thrust westward to a position adjacent to the forearc. This interpretation explicitly assumes an outboard depositional location for the Gualala basin, consistent with palinspastic reconstructions (e.g., Powell, 1993). Although some westward thrusting of the sedimentary section relative to the spilitic basement is possible, paleobathymetry requires bathyal depths at the time of deposition (Loomis and Ingle, 1994), thus ruling out a continental origin for the Gualala basin. This model is also consistent with paleocurrent evidence indicating dominantly northwestward transport directions for Gualala conglomerates (B. Ritts, 1995, personal commun.) (Fig. 1). By ca. 70 to 65 Ma, the granitic and rhyolitic source terrane had ceased to be an important sediment source for the Gualala basin (Schott and Johnson, 1996).

The tectonic event responsible for the westward displacement of the high-level eastern batholithic rocks (including the Salinian block and portions of the western Mojave Desert) was most likely to have been thrusting along low-angle detachments associated with the emplacement of the Pelona-Orocopia-Rand schists (Silver, 1982, 1983; Silver and Mattinson, 1986; Malin et al., 1995). The age of a westward-thrusting event for the Cordilleran arc was originally constrained in the Rand Mountains as Late Cretaceous (ca. 80 Ma) to mid-Miocene (ca. 25 to 18 Ma) (Silver, 1982, 1983; Silver and Nourse, 1986) and more recently as Late Cretaceous (ca. 87 to 79 Ma) (L. Silver and J. Nourse, 1995, personal commun.). Elsewhere it has been constrained as Late Cretaceous in the Transverse and northern Peninsular Ranges (May, 1989) and early Paleocene (ca. 65 to 62 Ma) to late Paleocene (ca. 57 to 55 Ma) in the Salinian block (Hall, 1991). Given the Campanian age of the basal conglomerate at Gualala (Loomis and Ingle, 1994), and recognizing the possibility that older strata of the basin may have been removed by faulting, our model requires a minimum age of ca. 80 Ma for the initiation of thrusting. This suggests that thrusting immediately followed or was contemporaneous with the youngest magmatism (ca. 85 to 80 Ma) in the Salinian block and western Mojave Desert (Mattinson, 1994; Miller et al., 1996; Kistler and Champion, 1997).

SUMMARY

Rhyolite and granite conglomerate clasts in the Late Cretaceous Gualala basin have an igneous origin in the upper levels of the continental side of the Cretaceous Cordilleran batholithic belt. Despite their outboard depositional position, the age, geochemical, and isotopic data fail to support paleomagnetic interpretations for either thousands of kilometers of northward transport (i.e., Kanter and Debiche, 1985), or provenance in the passing Baja BC terrane (i.e., Maxson and Tikoff, 1996). Instead, the geochemical and isotopic data presented here indicate provenance in the westward-thrusted Salinian-Mojave sections of the Cordilleran arc and constrain a minimum age of ca. 80 Ma for thrusting and arc collapse.

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