

Chapter 13

Petrogenesis and evolution of the Salinian magmatic arc

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ABSTRACT

Granitic rocks ranging in age from Early Cretaceous (about 100 to 110 Ma, and perhaps as old as 120 Ma) to Late Cretaceous (76 Ma) make up the "Salinian magmatic arc" of California. These granitoids, along with a variety of metamorphic country rocks, constitute the pre-Cenozoic basement of the Salinian block or Salinian composite terrane (SCT), an important, but somewhat enigmatic element in the Mesozoic tectonic evolution of the California Cordillera. The ages of magmatic emplacement, based on interpretation of zircon data, reveal a systematic younging to the east across the axis of the arc. The locus of active intrusion migrated eastward at an average rate of about 3 to 4 mm per year, presumably in response to an evolving continental-margin subduction system. Initial Pb, Sr, and Nd isotopic ratios also vary systematically across the arc. The oldest and westernmost intrusions are the most "primitive" in their isotopic characteristics; however, with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7055 to 0.7070, ϵ_{Nd} values of -4.4, and fairly radiogenic Pb isotopic ratios, their sources are much more highly evolved or "continental" than the sources of, for example, western Sierra Nevada plutons. Younger SCT plutons, emplaced farther east (and, presumably, farther "inboard"), have even more "continental" signatures, with higher Sr ratios, more negative ϵ_{Nd} values, more "crustal" Pb signatures, and clear evidence for inheritance of Precambrian zircons from their sources. Overall, most of the SCT initial isotopic data appear to define a main mixing trend between more primitive or "oceanic" end members (never observed in the SCT) and a continental crustal end member. The latter may be of metasedimentary origin, perhaps similar to the schist of the Sierra de Salinas, into which some of the plutons intrude. The youngest and easternmost plutons show mixing between the main trend and a distinctive end member with high $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, a low $^{206}\text{Pb}/^{204}\text{Pb}$ ratio, and a low ϵ_{Nd} value. This end member may be the Barrett Ridge gneiss, or similar rocks at depth with a Precambrian history of high-grade metamorphism. Evidently the Salinian magmatic arc straddled the margin of the craton, and the plutons were derived, in part, by anatexis and hybridization of the preexisting basement rocks.

INTRODUCTION

The Salinian block or "Salinian composite terrane" (SCT) of western California (Vedder and others, 1983) is a large, allochthonous terrane underlain by a basement complex comprising Cretaceous granitic rocks and a variety of high-grade metamorphic rocks. The SCT is an elongate tectonic slice,

bounded on both sides by major fault systems; the San Andreas system on the northeast, and the Sur-Nacimiento system on the southwest (Fig. 1). These faults "sandwich" the granitic and high-grade metamorphic rocks of the SCT between two essentially identical belts of "oceanic" Franciscan-assemblage rocks. Apart from well-documented Neogene San Andreas fault offsets of about 305 km, the details of the tectonic transport and emplace-

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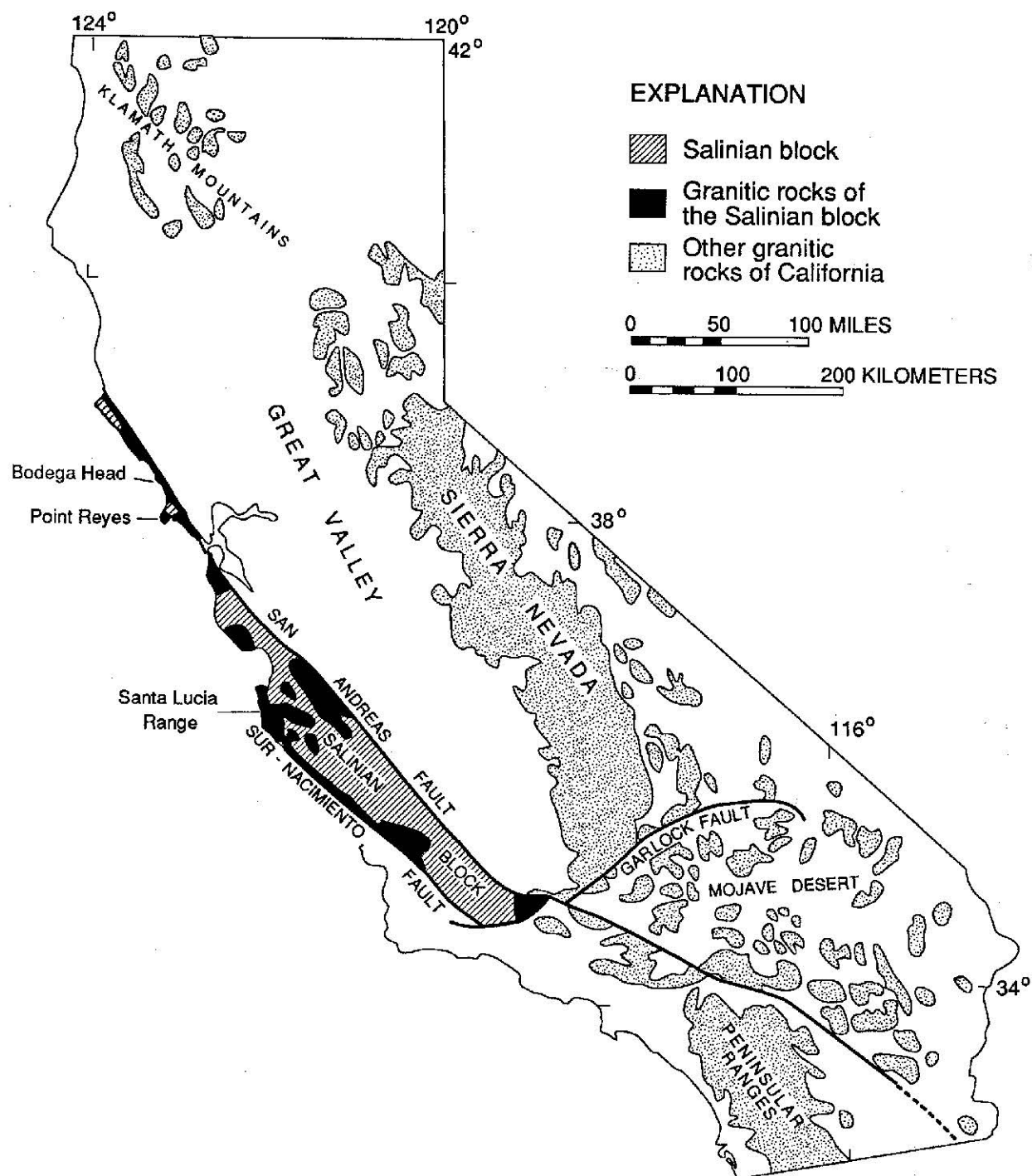


Figure 1. Simplified geologic map of California, showing the tectonic setting of the Salinian composite terrane.

ment history of the SCT have been the subject of considerable controversy, as discussed in more detail later.

This chapter focuses on the petrogenesis of the Cretaceous granitic rocks of the SCT. The granitic rocks, and the metamorphic rocks they intrude, are well suited for a variety of geochronologic and isotope tracer studies, including U-Pb geochronology of zircon, sphene (titanite), and apatite, and the initial isotopic compositions of Pb, Sr, and Nd. These studies yield important clues about the origins of the granitic magmas, and the evolution of the "Salinian magmatic arc" in space and time. As detailed in this chapter, the Salinian magmatic arc is a typical Cordilleran magmatic system. Granitoid magmas were emplaced during a span of about 30 to 40 m.y. in the Cretaceous, with the locus of magmatic activity migrating eastward during this time. The granitoids show systematic variations in various isotopic parameters with age and location suggesting that magmatic migration straddled the cratonal margin. The isotopic characteristics of the youngest and most inboard granitoids are dominated by Precambrian crustal signatures, indicating that melting of such ancient crust, or melting of metasedimentary rocks, derived in part from such ancient crust, contributed a large proportion of the magma from which the SCT granitoids crystallized.

BACKGROUND

Tectonic setting

As noted above, the details of the pre-Neogene tectonic history of the SCT are highly controversial. Inasmuch as the tectonic history bears directly on the ancestry of the SCT—that is, the original setting for Salinian magmatism and metamorphism—it is essential to briefly examine current interpretations (a more detailed discussion can be found in Mattinson and James, 1985).

There are currently two major schools of thought regarding the pre-Neocene tectonics of the SCT. One school, relying almost exclusively on recent paleomagnetic evidence, holds that the SCT has been displaced northward a total of 2,100 to 5,600 km since Late Cretaceous time. The second school, relying on a variety of geologic and isotopic evidence, rejects the paleomagnetic data and holds that the SCT is allochthonous "only" to the extent of several hundred kilometers.

Clearly, the well-documented Neogene movement history of the San Andreas fault system is only the latest manifestation of the extensive translations associated with Pacific (Pacific-Kula-Farallon) plate–North American plate interactions throughout the Mesozoic and Cenozoic eras. This is made apparent by the mounting paleomagnetic, paleontologic, and geologic evidence for northward translations of thousands of kilometers for the "Wrangellia" terranes (e.g., Jones and others, 1977) and some parts of the Franciscan complex (Blake and Jones, 1978; Alvarez and others, 1980), and for the assembly of much of the western margin of the North American continent by wholesale accretion of such far-traveled allochthonous terranes. It remains to be determined whether the SCT has participated in these extensive

pre-Neogene northward translations, or is only a much more recent (late Neogene) Pacific plate passenger. Perhaps more subtly, within the context of accretionary tectonics, what is the significance of the present-day San Andreas fault, if any, beyond the fact that it has been the Pacific–North American plate boundary for the past few millions of years? Must we look much farther inboard (east) to find autochthonous North American basement with which to compare the basement rocks of the SCT?

It has long been clear that well-demonstrated Neogene offsets of only about 305 km along the San Andreas fault zone do not explain fully the apparent offsets of at least 500 to 600 km of parts of the SCT, relative to the Sierran batholithic belt. The "extra" offset has been explained in various ways by a number of workers. Some have proposed pre-Neogene movement along a proto- or ancestral San Andreas fault (e.g., Suppe, 1970; Silver and others, 1971; Gastil and others, 1972; Garfunkel, 1973; Armstrong and Suppe, 1973). Others have documented slivering and extension of the SCT by internal faults (Johnson and Normark, 1974; Ross and Brabb, 1973; Howell, 1975; Dibblee, 1976); for example, the Rinconada fault with 40 to 60 km of right slip (Dibblee, 1976; Graham, 1978), and the San Gregorio–Hosgri fault with 80 to 115 km of right slip (Silver, 1974; Hall, 1975; Graham and Dickinson, 1978). Figure 2 shows the major areas of crystalline basement exposure in the SCT with the Rinconada and San Gregorio–Hosgri slip restored. The west-to-east cross section in this figure is used later for projection of age and isotopic parameters. Silver (1982, 1983) has suggested major west-directed thrusting of an SCT "flake" prior to San Andreas movement.

Most of the above hypotheses are based on the premise that the SCT, at least during the Cretaceous, was a part of the Sierran–Peninsular ranges Cordilleran system, and that it could be restored to its "rightful place" by unslipping Neogene San Andreas movement plus a modest amount of pre-Neogene movement, as discussed above. Recent geological and isotopic support for this premise has been presented by Ross (1984) and Silver and Mattinson (1986). Ross suggests some possible strong correlations between granitic rocks of the Gabilan Range and those of the Sierran tail, and also a possible correlation between the schist of Sierra de Salinas in the SCT, and the schist of Portal–Ritter Ridge (a possible correlative of the Pelona–Orocopia–Rand suite) east of the Sierran tail, on the northeast side of the San Andreas fault. Silver and Mattinson (1986) noted that, with removal of 305 km of right slip on the San Andreas fault system, Pb isotope patterns in Cretaceous plutonic rocks appear to continue unbroken across the SCT, the Sierran tail, and the Mojave.

An entirely different hypothesis is suggested by paleomagnetic work over the past several years in the SCT and adjacent terranes. This work reveals that some sedimentary rocks and granitic rocks of the SCT exhibit low apparent paleomagnetic inclinations, suggesting that they have acquired their magnetic signatures at low latitudes, and raising the possibility of pre-Neogene translations of thousands of kilometers. Kanter and Debiche (1985) provided a summary of recent studies; a few salient

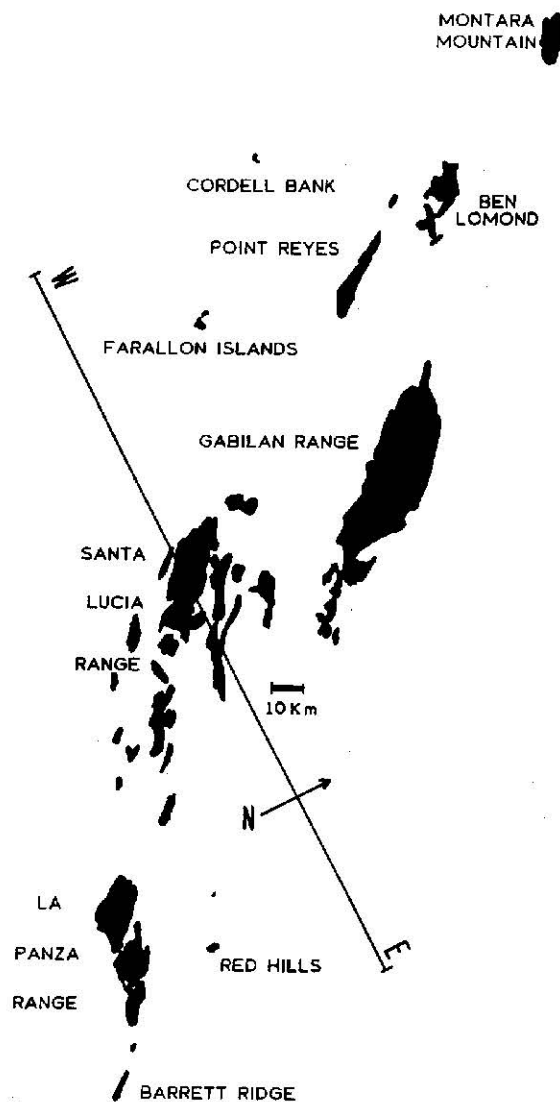


Figure 2. Tectonic reconstruction of Salinian basement outcrops. Right slip of 110 km removed from the San Gregorio-Hosgri fault trend, and 60 km removed from the Rinconada fault (after Mattinson and James, 1985). West to east line of section 100 km long is used for projection of age and isotopic data in several of the following figures.

results are noted here. Studies of the Late Cretaceous sedimentary rocks at Pigeon Point (Champion and others, 1980; Wilson and others, *in* Page, 1982) suggest 2,500 to 5,600 km of post-Late Cretaceous northward translation. Studies of the Paleocene sedimentary rocks at San Pedro Point (Champion and others, 1984, and *in* McWilliams and Howell, 1982) suggest about 2,100 km of northward translation since the Paleocene. Some caution is in order, however, because these interpretations involve major structural corrections, and many of the original data points were discarded due to severe overprinting by secondary magnetization. Moreover, the tectonic relation of the Pigeon Point area to the

SCT is not entirely clear. Nevertheless, additional supporting evidence for large translations comes from preliminary paleomagnetic work on Salinian plutonic rocks (Kanter and others, 1982), paleomagnetic work on the Stanley Mountain terrane, which lies outboard of the SCT and may have been amalgamated with it as early as the Late Cretaceous (McWilliams and Howell, 1982), and preliminary results from the spilites of the Gualala basin (Kanter and Engebretson, 1982; Kanter and others, 1982).

To summarize, the most recent phase of tectonic emplacement of the SCT is related to opening of the Gulf of California in the past few million years, and the accompanying few hundreds of kilometers of right-lateral offset along the San Andreas fault zone. There is considerable controversy regarding the timing, extent, and nature of earlier phases of emplacement of the SCT, however. Current (and conflicting) tectonic models for the emplacement of the SCT in its present position invoke additional north-northwestward translations of a few hundred to a few thousand kilometers, or major westward-directed thrusting (e.g., compare Dickinson, 1983; Page 1982; and Silver, 1982, 1983). Further evaluation of these opposing tectonic schemes is beyond the scope of this brief tour of SCT tectonic setting. The controversy is likely to persist until much more paleomagnetic, geologic, and isotopic work is completed and critically evaluated.

Summary of basement geology

Metamorphic country rocks. The older country rocks into which the Cretaceous granitoids were emplaced comprise three distinct metamorphic suites (Ross, 1977): (1) "Sur-Series" type metamorphic rocks of the central, western, and northern SCT (subdivisions of the SCT follow Ross, 1978); (2) high-grade gneisses, migmatites, and schists of the southeastern SCT (including the Barrett Ridge slice); and (3) the schist of the Sierra de Salinas in the central SCT. The significance of these country rocks is twofold. First, they provide clues to the pre-intrusive tectonic history of the SCT, with the potential for correlation with similar units elsewhere in southern California (e.g., see the earlier discussion of the possible Sierra de Salinas Schist correlation with the Pelona-Orocopia-Rand suite). Second, and of particular interest to this study, the metamorphic host rocks exposed at the surface may have equivalents at greater depth. Thus, they may provide a glimpse of the type of material through which the granitic magmas have ascended (with the possibility for contamination), or of materials at still greater depth where, by anatexis and mixing, they have contributed directly to granitic genesis. Each suite is discussed briefly below.

The "Sur Series" rocks of the Santa Lucia Range (Trask, 1926) and their presumed equivalents elsewhere in the SCT, are chiefly quartzo-feldspathic granofels and gneiss, biotite-feldspar quartzite, aluminous and graphitic schists, marble, para(?) amphibolite, and calc-silicate rocks. These metasedimentary rocks evidently were derived from a shallow, platformal sequence of continental-margin origin. Limited Sr and U-Pb isotopic evidence suggests a Paleozoic depositional age and indicates deriva-

tion, in part, from a Precambrian cratonic source (James and Mattinson, 1988). Metamorphism of the suite is essentially syn-plutonic (Compton, 1966; Weibe, 1970) and thus is about mid-Cretaceous in age (Mattinson, 1978).

Metamorphic rocks from the southeastern SCT are predominantly high-grade gneisses, migmatites, and schists, with local thin-bedded amphibolite, marble, calc-hornfels, and quartzite. The metamorphic rocks crop out in a large block in the Mt. Pinos-Mt. Abel area, the southeasternmost basement in the Salinian block, and in two very small areas at Barrett Ridge and Red Hills. Mattinson (1983) reported a U-Pb zircon concordia intercept age of about 1.7×10^9 yr for the Barrett Ridge gneiss. Ross (1977) suggested that the high-grade rocks of the Barrett Ridge slice correlate with the high-grade rocks of the San Gabriel Mountains.

The schist of the Sierra de Salinas in the central SCT is a homogeneous biotite quartzo-feldspathic rock with minor quartzite, marble, and amphibolite. On the basis of chemistry, Ross (1976) suggested that the schist was derived from a thick, uniform pile of graywacke. The schist crops out on both sides of the Salinas Valley, and has been penetrated by wells as far south as the San Ardo oil field (Ross, 1976). The Sierra de Salinas schist is unlike any other metamorphic rock in the SCT. Its closest relatives may be the Pelona and Orocopia schists in the Mojave Desert, especially the Pelona schist of Portal and Ritter Ridge and Quartz Hill (Ross, 1976). The Sierra de Salinas schist is intruded by unmetamorphosed 80- to 85-Ma plutons (Mattinson, 1982a). Thus the metamorphism of the schist is mid- to Late Cretaceous or older. The schist contains abundant Precambrian zircon grains, indicating derivation from an ancient cratonic source; however, direct evidence for the age of deposition is sparse. On the basis of limited Rb/Sr data, James and Mattinson (1988) suggested that the protolith of the schist was deposited in the Mesozoic.

Plutonic rocks. Plutonic rocks are exposed throughout the SCT, but are concentrated in the central part, which includes the Gabilan Range, the Ben Lomond area, the La Panza Range, and the eastern part of the Santa Lucia Range. Granitoids of the SCT are, for the most part, typical of the Cordilleran batholith belt in a general way. They are calc-alkalic to calcic; variation diagram trends are in the range of those for the Sierra Nevada and the Peninsular Ranges. A few bear garnet as an accessory mineral (Ross, 1972). Most appear to have been emplaced at mesozonal depths. The SCT plutons contrast with those from the western parts of the Sierra Nevada and Peninsular Ranges batholiths in that diorite and true trondhjemite are rare to absent, as are plutons with "oceanic" initial Sr, Nd, and Pb isotopic signatures (discussed in more detail later). Thus, by contrast with the "intact" parts of the California cordilleran magmatic belt (Sierra Nevada and Peninsular Ranges batholithic belt), the western part of the "Salinian magmatic arc" appears to be missing (see Page, 1982, for discussion).

Two suites of rocks in the SCT are anomalous. Anorthositic and quartz gabbros of possible ophiolitic affinities crop out at Logan as a fault sliver at the eastern margin of the SCT, and

"charnockitic" plutonic rocks crop out in the western SCT south of Monterey. The rocks at Logan have been correlated with gabbro at Eagle Rest Peak in the San Emigdio Mountains by Ross (1970). They are Jurassic in age (James and others, 1986, and in prep.) and are unrelated to the granitoids of the SCT. The suite of deep-seated granitoids from the western SCT includes synmetamorphic charnockitic tonalite and cumulate ultramafites that are associated with granulite-grade wall rocks (Compton, 1960; Wiebe, 1970). These rocks are distinctive in terms of their metamorphic history and their thermal history (Mattinson, 1978) compared with other SCT granitoids. These differences appear to relate primarily to the present level of exposure, because the crystallization ages and the isotopic signatures of the charnockitic rocks are essentially identical to those for mesozonal plutons to the north (see Mattinson, 1978, and discussions below).

METHODS AND RESULTS

Granitic rocks and selected metamorphic rocks have been collected from throughout the SCT, from onland outcrops, the Farallon Islands, and sub-sea outcrops from Cordell Bank over a number of years. Minerals for U-Pb, Rb-Sr, and Sm-Nd isotopic analyses have been separated and purified by conventional techniques. Emphasis in earlier phases of this study has been primarily on U-Pb geochronology (Mattinson, 1978, 1982a, 1983, 1986; Mattinson and James, 1985, 1986; James, 1984, 1986). In this chapter, the geochronologic data are summarized graphically (Figs. 3, 4, 5) and discussed briefly.

This study concentrates on the results of isotope tracer work, using initial Pb, Sr, and Nd data. The detailed analytical results are too bulky to present here, so the data are summarized in a series of figures and one table of selected samples (Table 1). The

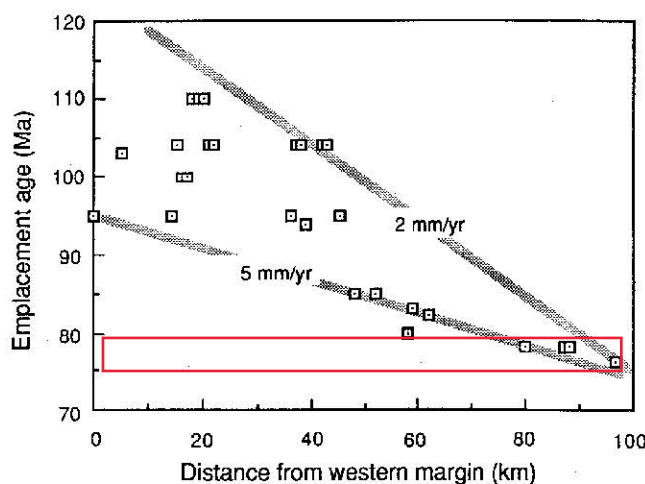


Figure 3. Emplacement ages based on interpretation of zircon data from SCT granitic rocks plotted along west to east cross section from Figure 2. Trend of ages indicates a west to east migration for the locus of magmatic activity. Heavy stippled lines bracket migration rate at 2 and 5 mm per year; average rate is about 3 to 4 mm per year.

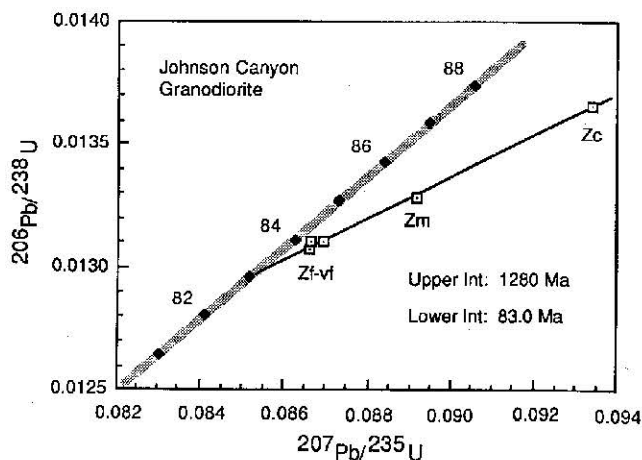


Figure 4. Concordia diagram showing a pattern of "micro-discordance" from the Johnson Canyon granodiorite, southern Gabilan Range. Five fractions of zircon define an emplacement age (lower intercept on concordia) of 83 Ma. The three lowest points represent fine- to very fine-grained zircon fractions that contain a very small inherited component, but are dominated by newly crystallized igneous zircon. Medium- and coarse-grained zircon fractions contain progressively more important inherited components, probably in the form of cores with igneous overgrowths. The upper intercept of about 1,300 Ma reflects inheritance of Precambrian zircons of about this age, older zircons that were already discordant prior to incorporation in the Cretaceous granodiorite, or a mixture of older and younger zircons (Mattinson, 1982a, and in preparation).

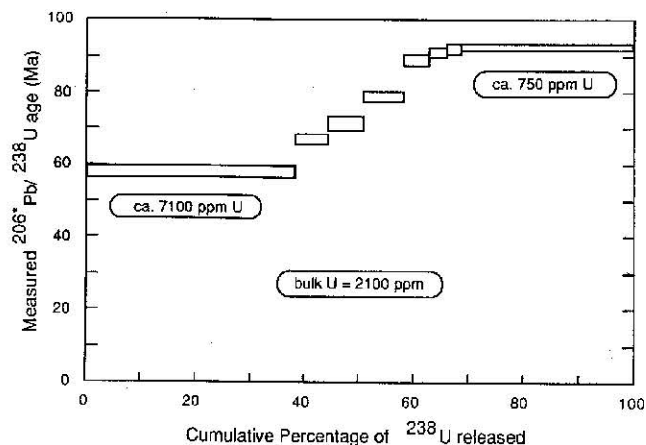


Figure 5. Results of a stepwise dissolution experiment (Mattinson, 1984, and in prep.) on a high-uranium zircon fraction from granodiorite of Gloria Road, southern Gabilan Range. These high-U zircons commonly show the effects of recent Pb loss superimposed on the "primary" patterns due to inheritance and magmatic crystallization. This "incremental U release" diagram is analogous to $^{39}\text{Ar}/^{40}\text{Ar}$ incremental release patterns. High-U, radiation damaged, and readily soluble zircon is dissolved in the early steps (left side of the diagram). The U-Pb system associated with these steps is highly discordant, as indicated by the low apparent $^{206}\text{Pb}/^{238}\text{U}$ ages. Much more refractory zircon, digested in later, much longer dissolution steps, and finally, in a total dissolution step (identical to conventional zircon analysis, right side of diagram), is an order of magnitude lower in U concentration. The U-Pb system associated with these steps is either concordant, or plots on "primary" discordia trajectories so that the magmatic crystallization age of the granitoid can be obtained.

isotopic composition of initial Pb for the granitoids has been determined directly by analyzing feldspar separates. Feldspars in the granitoids have very low U/Pb ratios, and corrections for in situ decay of U are not necessary. Initial Pb is plotted in Figures 6, 7, 8, and 9.

Initial Sr isotopic ratios have been approximated closely by analyzing Sr from apatite separates. The apatites have very low Rb/Sr ratios; therefore, as in the case of the feldspar Pb, no in situ decay corrections are necessary. U/Pb systematics of apatite from a wide range of SCT samples reveal that while most of the apatites became isotopically closed systems shortly after magmatic crystallization, some have remained open with respect to Pb migration (and, thus, possibly Sr migration) for as much as 20 m.y. after initial crystallization (i.e., the apatites record cooling ages rather than primary crystallization ages; Mattinson, 1978, 1982b). In such cases, the apatites yield upper limits on the initial Sr ratios. Nevertheless, whole-rock Rb/Sr ratios for most samples tend to be fairly low (see Evernden and Kistler, 1970; Ross, 1972; Kistler and Peterman, 1973), and only very small errors are introduced by measuring the initial ratios in this way. In fact, the errors are possibly smaller than those that would be introduced by correcting present-day whole-rock data using measured Rb/Sr ratios from the all too commonly deeply weathered SCT grani-

toids. Initial Sr ratios for selected samples are plotted in Figure 10, and the correlation between initial Sr and initial $^{208}\text{Pb}/^{204}\text{Pb}$ in Figure 11.

Initial Nd ratios have been determined by analyzing Nd and Sm from apatite separates, and correcting the Nd ratio for in situ decay of Sm over the age of the rock. The apatites concentrate the rare earth elements strongly relative to whole-rock samples. As in the case of Sr, any evolution of the Nd ratio between the time of primary crystallization and the time of closure of apatite as indicated by the U/Pb cooling ages would be negligible. Nd data for selected samples are plotted in Figure 12, and the correlation between Nd and Sr is plotted in Figure 13.

Analytical methods for all the isotopic systems are fairly conventional, and are discussed only briefly. Zircons were digested, and U and Pb isolated by methods modified after Krogh (1973). Smaller dissolution vessels were used, and a double digestion procedure followed (Mattinson, 1987). Some high-uranium zircons were subjected to a stepwise dissolution procedure (Mattinson, 1984, and in prep.) in order to "see through" the effects of recent Pb losses. U and Pb separation followed Krogh (1973), except for miniaturization (150 μl resin volume columns). Sr and Nd were isolated using procedures similar to those described in Kwon (1986).

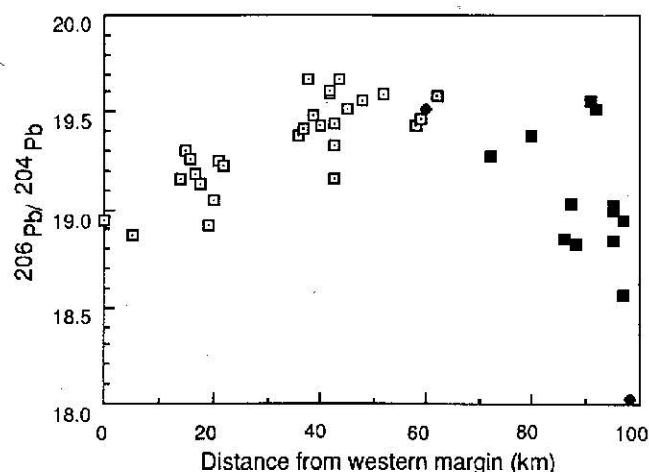


Figure 6. $^{206}\text{Pb}/^{204}\text{Pb}$ for SCT granites projected onto the west to east line of section from Figure 2. Granitic rocks from Cordell Bank, Montara Mtn., the Farallon Islands, Point Reyes, Bodega Head, Ben Lomond, the Gabilan Range, and the Santa Lucia Range are plotted as open squares. Granitic rocks from Adelaida, the La Panza Range, Red Hills, and Barrett Ridge are plotted as filled squares. The schist of Sierra de Salinas (at 60 km) and the Barrett Ridge gneiss (near the eastern end of the section) are plotted as filled diamonds.

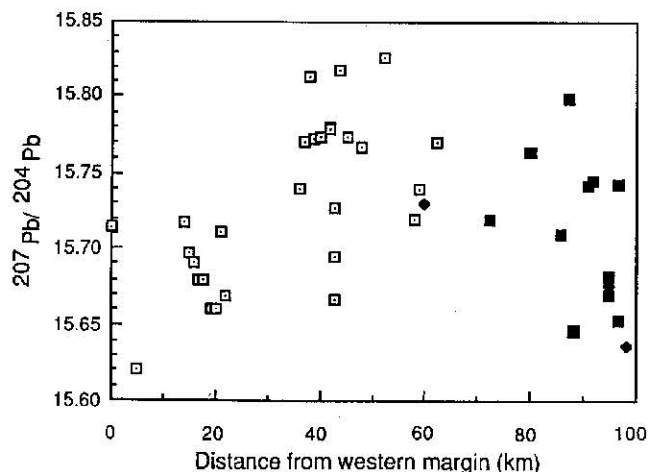


Figure 7. $^{207}\text{Pb}/^{204}\text{Pb}$ for SCT granites projected onto the west to east line of section from Figure 2. Symbols as described in caption for Figure 6.

TABLE 1. SELECTED ISOTOPIC DATA FROM SCT GRANITOIDS AND METAMORPHIC ROCKS

Specimen*	Location†	Dist.‡	Pb isotopes**			Sr‡	Nd‡	Ref.§§
			206/204	207/204	208/204	87/86	Epsil.	
1G	Cordell Bank	0	18.94	15.71	38.86			3
2G	Montara Mtn.	5	18.86	15.62	38.50	0.70565		2
3G	Farallon Is.	14	19.16	15.72	38.90	0.70616	-4.4	3
4G	Bodega Head	15	19.30	15.70	38.87	0.70683		1
5G	Point Reyes	22	19.22	15.67	38.79	0.70705		1
6G	N. Gabilan	36	19.37	15.74	39.06	0.70690	-4.9	3
7G	Santa Lucias	44	19.67	15.82	39.49	0.70864		3
8G	S. Gabilan	58	19.43	15.72	39.18	0.70875	-8.6	3
9G	S. Gabilan	59	19.47	15.74	39.21	0.70839	-7.0	3
10SdS	S. Gabilan	60	19.52	15.73	39.30	0.71033	-7.6	3
11G	Red Hills	88	19.03	15.80	39.69	0.70917	-9.6	3
12G	La Panza	91	19.55	15.74	39.19	0.70903	-8.6	3
13G	Barrett Ridge	95	19.00	15.68	40.88	0.75094		3
14BRG	Barrett Ridge	95	18.84	15.68	41.54	0.76072	-20.6	3
15G	Barrett Ridge	97	18.95	15.74	39.66	0.71533	-11.4	3
16BRG	Barrett Ridge	98	18.02	15.64	40.05	0.74864	-20.0	3

*G = granitoid; SdS = Sierra de Salinas Schist; BRG = Barrett Ridge Gneiss.

†Detailed specimen locations available from the author on request.

‡Approximate distances from western edge of section shown on Figure 2.

**Pb isotopic compositions corrected for mass fractionation based on replicate analyses of NBS Pb standards.

‡For granitoids, these are initial ratios; for metamorphic rocks, these are ratios at the time of granitoid emplacement.

§§1 = Mattinson (1978); 2 = James (1986); 3 = Mattinson (unpublished data)

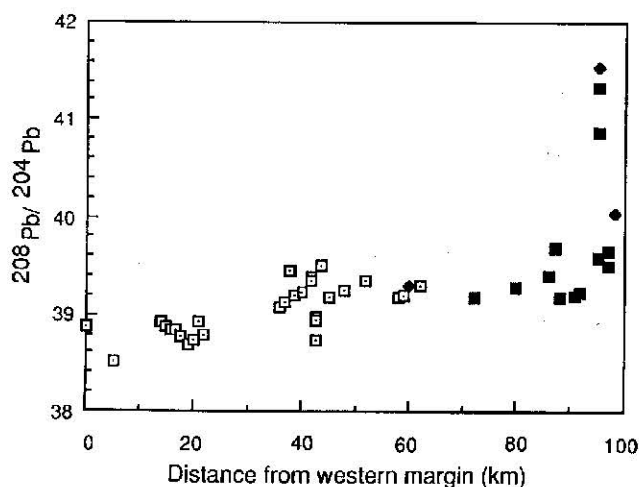


Figure 8. $^{208}\text{Pb}/^{204}\text{Pb}$ for SCT granites projected onto the west to east line of section from Figure 2. Symbols as described in caption for Figure 6.

Early U and Pb determinations were run on the University of California, Santa Barbara (UCSB) Avco single collector instrument, running Pb by the conventional silica gel-phosphoric acid method, and U by using graphite and phosphoric acid on a single rhenium filament. More recent U and Pb determinations and all Sr and Sm-Nd determinations were run on the UCSB Finnigan-MAT 261 multicollector instrument. Pb was run by the silica gel-phosphoric acid method, U in part by using graphite and phosphoric acid or graphite and nitric acid, and in part by using silica gel and phosphoric acid. Sr was run using tantalum oxide powder and phosphoric acid on a single rhenium filament. Sm and Nd were run as metal by double filament techniques.

DISCUSSION

Zircon geochronology

Magmatic crystallization ages of SCT granitoids as inferred from zircon data are summarized in Figure 3. Before discussing these ages and their tectonic and petrogenetic significance, it is important to note that most individual ages are based on interpretation of several fractions of zircon. Depending on the complexity of the isotopic history of the individual sample, this interpretation can range from straightforward and well constrained to only weakly constrained. Although detailed analytical results of SCT samples will be presented elsewhere, it is useful to examine a few examples.

The isotopic systematics of zircon populations from most SCT granitoids can be described with a single word: discordant. Discordance in these zircon populations stems primarily from inheritance of older zircons of a variety of ages. In "well-behaved" discordant populations, the patterns of discordance or

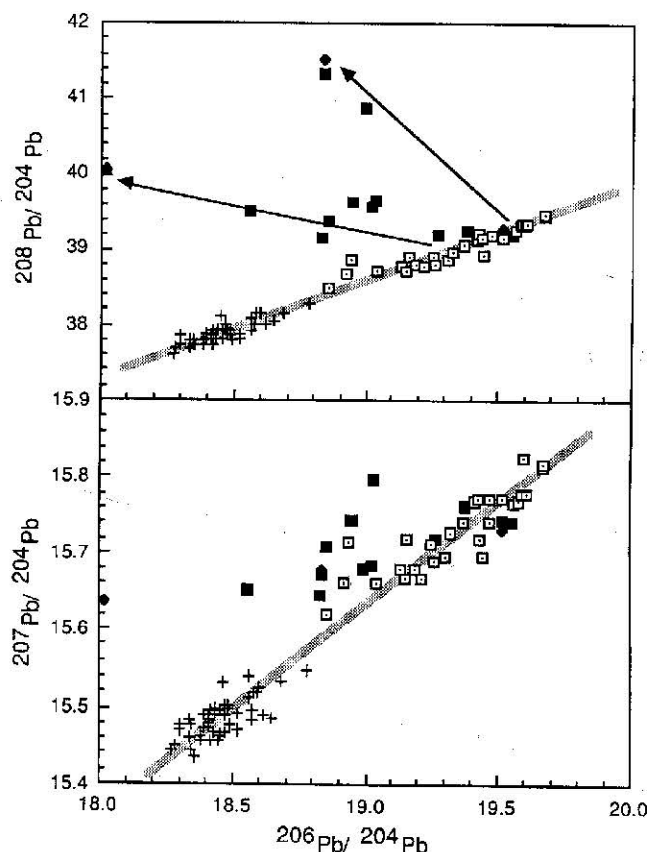


Figure 9. $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ evolution diagram for SCT granitoids and metamorphic rocks. Symbols as described in caption for Figure 6, except that the crosses represent the field of MORB from the Gorda-Juan de Fuca Ridge (Church and Tatsu-moto, 1975) and from the East Pacific Rise at 21°N (Vidal and Clauer, 1981). The heavy stippled line represents a possible mixing trend between primitive, MORB-like sources and evolved, crustal sources to generate a "main trend" on which most of the northwestern and central granitoids lie. Southeastern granitoids appear to be pulled off this trend by mixing with a third source, possibly the Barrett Ridge Gneiss. This is shown most clearly in the $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram, where the secondary mixing trends are suggested by the solid arrows.

"micro-discordance" can be interpreted with some confidence to yield the primary crystallization age of the granitoid; and to give some idea about the age range of the inherited component, see, for example, Figure 4. If the inherited zircons include a range of ages, scatter in the observed data may preclude a precise interpretation of the intercept ages. Some high-uranium populations of zircon are even more complex. For those zircons, the "primary" discordance patterns are overprinted by relatively recent, post-crystallization Pb loss. In some of these cases, step-wise dissolution techniques can successively strip away the individual zones within each zircon crystal that are highest in U, and hence the most damaged by radiation and susceptible to Pb loss (Mattinson,

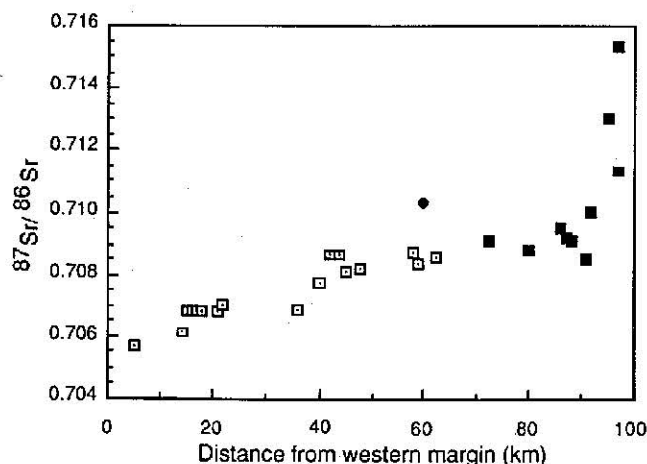


Figure 10. $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios for SCT granites projected onto the west to east line of section from Figure 2. Symbols as described in caption for Figure 6. Two specimens of the Barrett Ridge Gneiss and two specimens of southeastern granitoid with $\text{Sr}_i > 0.74$ and which would plot at 95 to 98 km have been omitted.

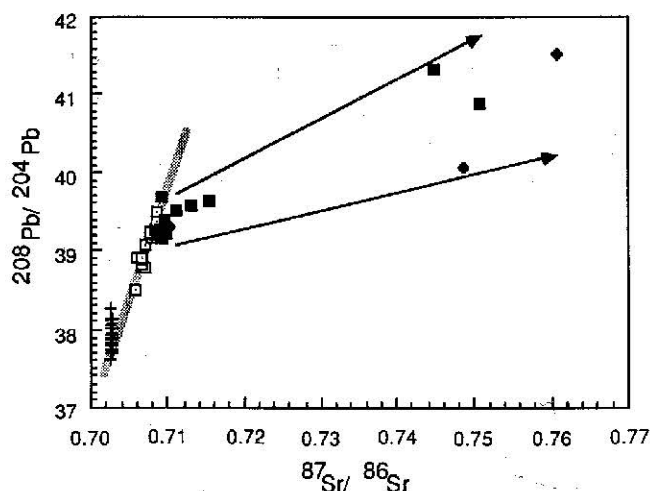


Figure 11. $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{208}\text{Pb}/^{204}\text{Pb}$ correlation diagram for SCT granites. Symbols as described in caption for Figure 6, except that the crosses represent the field of MORB from the Gorda-Juan de Fuca Ridge (Church and Tatsumoto, 1975) and from the East Pacific Rise at 21°N (Vidal and Clauer, 1981). Sr ratios are only available for a few of these samples, so "typical" MORB values in the range of 0.7025 to 0.7030 have been used. As in Figure 9, the heavy stippled line represents a possible mixing trend between primitive, MORB-like sources and evolved, crustal sources to generate a "main trend" for the SCT granitoids, and the solid arrows represent mixing with a third source, possibly the Barrett Ridge Gneiss.

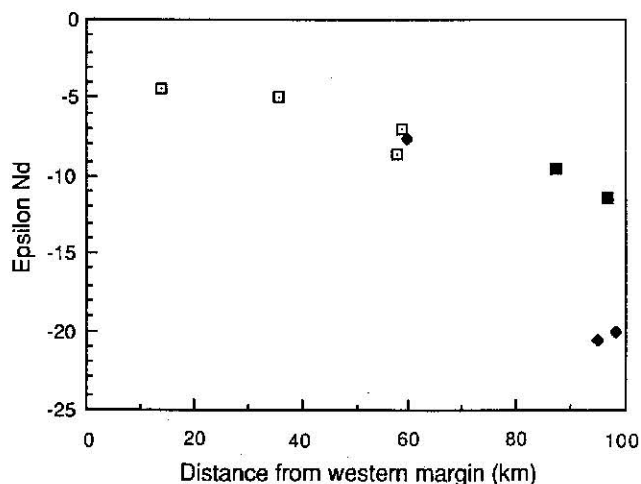


Figure 12. ϵ_{Nd} for selected SCT granitoids and metamorphic rocks projected onto the west to east line of section from Figure 2. Symbols as described in caption for Figure 6.

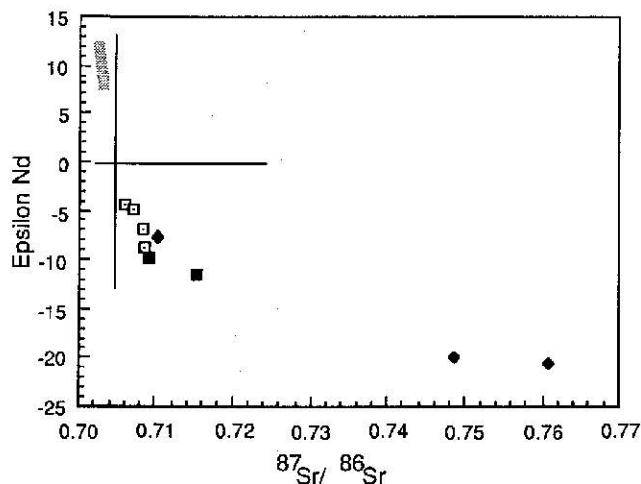


Figure 13. ϵ_{Nd} versus $^{87}\text{Sr}/^{86}\text{Sr}$ correlation diagram for selected SCT granitoids and metamorphic rocks. Symbols as described in caption for Figure 6. Epsilon values and Sr ratios are initial values for granitoids and values at time of granitoid emplacement for metamorphic rocks. Stippled area is field of MORB and intersecting lines represent "bulk earth" values (e.g., see Fig. 13.6 of Faurc, 1986).

1984, and in prep.). It is then possible to "see through" the recent discordance, and interpret the "primary" discordance; see, for example, Figure 5.

Despite these complexities, it is now possible to discuss with some confidence the ages and trends of ages throughout most of the SCT. This is most readily done with reference to a simple model: (1) the granitoids of the SCT were generated in a single magmatic arc (referred to herein as the "Salinian magmatic arc"); (2) the present SCT represents an inboard segment of this arc system; and (3) removal of slip along major, known fault systems within the SCT adequately restores the granitoids to their original positions relative to one another.

For the purposes of this chapter, emplacement ages of the granitoids are projected onto an east-west line of section across a palinspastic reconstruction of the SCT (Fig. 3). From this it becomes clear that the axis of magmatic activity migrated from west to east, across the SCT. The most westerly (and northerly) granitoids with well-determined ages were emplaced at about 100 to 110 Ma. Some are possibly older or younger (in the range of 120 or 95 Ma; see James 1984, 1986; Mattinson and James, 1985), but these determinations are less certain owing to complex mixtures of inheritance and discordance in the zircon populations.

The ages become systematically younger to the east and south; ages are as low as 76 to 78 Ma in the La Panza Range, Red Hills, and Barrett Ridge. The age progression can be interpreted either as a continuum (with considerable scatter), or as a "static arc" from about 110+ Ma to 95 Ma (0 to about 45 km) and a migrating arc (5 mm per year) from about 85 Ma to 75 Ma (45 to 100 km). More data would be required to choose confidently between these two possibilities, but the latter interpretation is very similar to that of Silver and others (1979) for part of the Peninsular Ranges batholith. Nevertheless, from the overall trend of west-to-east migration, two conclusions follow: first, as pointed out by Mattinson and James (1985), this age "polarity" indicates that the Salinian magmatic arc was west-facing; that is, the subduction zone was to the west of the arc. This may seem trivial in light of the present setting of the SCT along the western margin of North America, but it is important to recall that, based on paleomagnetic interpretations, the SCT may or may not be indigenous to North America. Second, the age progression of the granitoids suggests an *average* rate of eastward migration of about 3 to 4 mm per year, with bounding limits at about 2 and 5 mm per year. This estimate is subject to the uncertainties about the upper age limit for the westernmost granitoids, and to uncertainty about the true direction of "petrologic" cross-section across the tectonically slivered SCT, but is probably accurate within a factor of two. The SCT magmatic migration rate can be compared with a magmatic migration rate of 2.7 mm per year determined by Chen and Moore (1982) for part of the Sierran magmatic arc, and must be related to the evolution of the subduction system, with age, thermal state, or subduction rates.

Another major result emerges from the zircon data. As noted earlier, and as discussed in Mattinson and James (1985), zircon upper intercept ages on concordia diagrams reveal impor-

tant Precambrian contributions to the zircon populations in many of these Cretaceous granites. Zircons of appropriate age (up to about 1.7 Ga) and isotopic characteristics are present in the schist of the Sierra de Salinas, the Santa Cruz schist, and the Barrett Ridge gneiss (Mattinson, 1982a, 1983; Mattinson and James, 1985; James, 1984, 1986).

Common Pb

Initial or "common" Pb isotopic compositions of igneous rocks provide information about the long-term U/Pb and U/Th ratios in their source rocks. "Depleted" mantle, especially the source of mid-ocean ridge basalts (MORB), is characterized by low U/Pb ratios early in the Earth's history, and thus by relatively nonradiogenic Pb isotopes, especially $^{207}\text{Pb}/^{204}\text{Pb}$ (e.g., see Church and Tatsumoto, 1975). Highly differentiated continental crustal rocks are characterized by high U/Pb ratios, and thus, if sufficiently old, by relatively radiogenic Pb isotopes. Continental crustal rocks that have evolved radiogenic Pb early in their histories, then have been subjected to U-depleting high-grade metamorphism, have distinctive low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios with relatively high $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios (e.g., Tilton and Barreiro, 1980). Magmas derived by the melting or partial melting of such rocks, or contaminated by them, will bear distinctive Pb isotopic fingerprints that implicate their sources.

Compared with depleted mantle Pb, and even "average crustal Pb" (e.g., Stacey and Kramers, 1975), most of the SCT granitoids show a highly evolved Pb signature (Mattinson and James, 1985) suggesting at least partial derivation from old continental crustal rocks. From west to east, the initial Pb values for both uranogenic ^{206}Pb and ^{207}Pb (Figs. 6 and 7, respectively) and thorogenic ^{208}Pb (Fig. 8) show systematic increases across most of the SCT. Over the last 30 to 40 km, the ratios appear to level off; then, at the eastern end of the section, the $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ values drop, and the $^{208}\text{Pb}/^{204}\text{Pb}$ values increase sharply. A sample of the schist of the Sierra de Salinas collected from the southern Gabilan Range plots in the field of SCT granitoid Pb, near the end of the zone of systematic increase in all the Pb ratios. Pb from feldspar in the schist is approximately representative of total-rock Pb at the time of metamorphism or the last isotopic homogenization. Partial isotopic homogenization may have occurred around the time of pluton emplacement, according to U-Pb apatite ages for the schist (Mattinson, 1982a). Thus, the measured Pb isotopic composition of the schist reflects the isotopic composition in local country rock at the time of pluton generation and emplacement, and constitutes a possible end member for mixing via contamination or anatexis. Samples of the Barrett Ridge Gneiss, into which some of the southeasternmost SCT granitoids intrude, show low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios, along with moderately low $^{207}\text{Pb}/^{204}\text{Pb}$ ratios and relatively high $^{208}\text{Pb}/^{204}\text{Pb}$ ratios (Mattinson, 1983; Mattinson and James, 1985). This is strongly suggestive of an early moderate U (but not Th) depletion as a result of high-grade metamorphism of the gneiss. As in the case of the schist of the Sierra de Salinas, U-Pb

apatite ages for the gneiss (Mattinson, 1983) indicate isotopic equilibration at the time of pluton emplacement. Thus, the plotted gneiss values are possible mixing end members, as discussed below.

A plot of $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 9) is particularly revealing. Most of the SCT granitoids, along with the schist of the Sierra de Salinas, plot along a rather tightly constrained trend, especially in the $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot. This trend suggests mixing between less radiogenic sources (to the lower left in the diagram)—for example, MORB—and more evolved crustal sources, perhaps similar to the schist or some more radiogenic composition along the trend. Isotopic compositions from the more easterly SCT samples form a separate array, distinct from the “main trend.” They appear to lie on mixing lines between the upper (more radiogenic) end of the main SCT trend and end members with low $^{206}\text{Pb}/^{204}\text{Pb}$, high $^{208}\text{Pb}/^{204}\text{Pb}$ ratios like those that characterize the Barrett Ridge gneiss.

Initial Sr

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Sr_i) for SCT granitoids closely parallel the Pb data in both petrogenetic indications and age and geographic trends (Fig. 10). The Sr ratios show a systematic increase across the western and much of the central part of the SCT, then a possible leveling out, and finally a sharp increase in the easternmost part of the section. Sr_i from the western part of the cross section (the westernmost exposed part of the arc) is in the range of 0.7055 to 0.7070, still high relative to depleted mantle values (<0.7035) or western Sierran values (0.7040 to 0.7060; Kistler and Peterman, 1973). Younger and more easterly plutons have still higher Sr_i ; 0.7075 to 0.7090. The schist of the Sierra de Salinas had an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.71033 at the time of pluton emplacement, slightly higher than that for many of the plutons in the central part of the SCT where the schist is exposed. The easternmost plutons reach Sr_i values of 0.715, and small dikes and pegmatitic stringers within the Barrett Ridge gneiss are as high as 0.750. The latter must represent total or near total melts of the gneiss itself, which had Sr ratios of about 0.75 to 0.76, based on data from apatites which reequilibrated their U-Pb systems at the time of pluton emplacement.

A correlation diagram of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{208}\text{Pb}/^{204}\text{Pb}$ (Fig. 11) confirms the trends noted in the plot of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{208}\text{Pb}/^{204}\text{Pb}$. Most of the SCT data plot along a “main” trend that is linear and suggests mixing between a nonradiogenic (for example, MORB) end member and a more radiogenic, crustal end member. The easterly SCT samples are evidently “pulled off” the more radiogenic end of this main trend, by mixing with high $^{208}\text{Pb}/^{204}\text{Pb}$, high $^{87}\text{Sr}/^{86}\text{Sr}$ sources, similar in isotopic character to the Barrett Ridge gneiss.

Initial Nd

Limited $^{143}\text{Nd}/^{144}\text{Nd}$ data for SCT plutons and metamorphic rocks (Fig. 12) reflect the patterns seen in the other isotopic

systems almost perfectly, except that Nd and its parent element, Sm, show the well-known opposite sense of fractionation from the U-Pb and Rb-Sr systems. Thus, the westernmost samples have the most radiogenic $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (the least negative in the ϵ_{Nd} notation), and the easternmost samples have the least radiogenic or most negative values. As with Sr and Pb, the westernmost plutons are still quite “crustal,” with ϵ_{Nd} values only as high as -4.4. Central plutons range from -7 to -8.6; the Sierra de Salinas schist is in the same range (-7.6). The easternmost plutons range from -8.6 to -11.4; the Barrett Ridge gneiss is at -20.0 to -20.6. As with the other isotopic data, the Nd results reveal that even the westernmost exposed plutons of the SCT contain substantial crustal contributions, and that the proportion of crustal material increases systematically to the east.

A plot of ϵ_{Nd} versus Sr (Fig. 13), like the Pb-Pb and Pb-Sr plots (Figs. 9 and 11, respectively), strongly suggests that the granites of the SCT crystallized from magmas derived by mixing varying proportions of mantle materials and crust. The Nd data are too sparse at present to fully define such a mixing curve, but the similarities to the more complete data of DePaolo (1981) for the Sierra Nevada and Peninsular Ranges and the data of McCulloch and Chappell (1982) for granitoids from southeastern Australia are striking. The chief difference is that the Barrett Ridge gneiss, at -20 ϵ_{Nd} , is much more negative than the probable crustal end member in the McCulloch and Chappell (1982) study.

SUMMARY AND CONCLUSIONS

U-Pb geochronology of zircons and measurements of initial Pb, Sr, and Nd isotopic ratios from SCT granitic rocks and their associated metamorphic country rocks suggest that the granitic rocks were emplaced as a part of a coherent system—dubbed herein the “Salinian magmatic arc.” **By comparison with the better-known Sierra Nevada and Peninsular Ranges magmatic arcs, the present exposures of SCT granitic rocks, including those from the submerged Cordell Bank, may represent only the eastern part of the original arc (e.g., Page, 1982).** Nevertheless, the age data reveal that the exposed part of the arc was active in Cretaceous time, from about 100 to 110 Ma (or perhaps 120 Ma) to about 76 Ma. During this time, the axis of active magmatism migrated to the east at an average rate of about 3 to 4 mm per year, comparable to the rate of migration in the central Sierra Nevada batholith as documented by Chen and Moore (1982).

The isotopic “signatures” of the SCT granitic rocks show marked and systematic variations with time and geographic position, providing important clues about the petrogenesis of magmas that fed the arc. The earliest (and most westerly) of the granitic rocks are the least radiogenic in terms of Pb and Sr isotopes and the most radiogenic in terms of Nd isotopes. These characteristics are relative, however; even the most westerly rocks have Sr_i in the range of 0.7055 to 0.7070, and ϵ_{Nd} values of -4.4 compared to 0.7025 to 0.7030 and +8 to +12, respectively, for MORB. **The SCT values indicate the significant involvement of old continen-**

tal crustal rocks, perhaps as anatectic mixtures with, or as wall-rock contamination of, more primitive arc magmas. Toward the central part of the arc, the proportion of crustal material evidently increases, as indicated by rather smooth increases in all the initial Pb isotopic ratios and Sr_i , and more negative ϵ_{Nd} values. The proportion of inherited zircon in the granitic rocks also increases (Mattinson and James, 1985).

Pb, Sr, and Nd isotopic ratios of the schist of the Sierra de Salinas are very similar to those for the central arc granites. Moreover, the schist contains abundant detrital zircons of Precambrian age, similar to those that occur as inherited cores in many of the granitic zircon populations. Thus it is tempting to suggest that equivalents of the schist at greater depth have melted and mixed with more mafic, subduction-derived magmas to give rise to the granitic rocks presently exposed at the surface in the northwestern and central parts of the SCT. The youngest (and most easterly) granitic rocks deviate from this simple mixing trend. Instead, their isotopic ratios are pulled toward a very distinctive third component: an old, high-grade metamorphic source characterized by high $^{208}Pb/^{204}Pb$ ratios, very high $^{87}Sr/^{86}Sr$ ratios, and very negative ϵ_{Nd} values. These same isotopic characteristics are seen in the Barrett Ridge gneiss. Thus the gneiss, or similar rocks at depth, appears to be a likely candidate for the third end member.

The west-to-east trends in isotopic ratios displayed by the granitic rocks could be explained in two ways. In one alternative, migration of the locus of magmatism to the east with time would result in the interaction of the rising magmas with progressively thicker parts of a continental-margin wedge of metasedimentary rocks. Thus, the oldest granitic rocks would be only moderately contaminated by the thin end of the wedge. The younger magmas would rise into the thicker part of the wedge, with extensive anatexis and hybridization, such that the isotopic systematics of the granites would be dominated by the metasedimentary signature. The Barrett Ridge gneiss, or similar rocks at depth, possibly representing the edge of the old craton (as opposed to the younger metasedimentary wedge derived from the old craton), may have become involved in anatexis and mixing as the axis of magma-

tism finally migrated across this edge. The sharpness of this isotopic boundary and the fact that the distinctive high-grade isotopic signature of the gneiss is not shared by the metasedimentary rocks of the Sierra de Salinas suggest that the gneiss is separated from the rocks to the west by a significant pre-Late Cretaceous tectonic boundary.

An alternative possibility for the isotopic gradients, at least in the western and central parts of the arc, is that the younger (and coincidentally more easterly) magmas incorporated a greater proportion of crustal material because earlier melts rising through the crust had already raised regional temperatures. This would permit more anatexis to take place with time in the arc system. Possibly some combination of the geographic and thermal effects is responsible for the overall pattern across the Salinian magmatic arc.

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