The Fourth California Islands Symposium: Update on the Status of Resources
Edited by W. L. Halvorson and G. J. Maender. 1994. Santa Barbara Museum of Natural History, Santa Barbara, CA.

A Slice of Immature Arc Rocks Marooned on Santa Cruz Island, California

Janet Hammond Gordon[1] and Peter W. Weigand[2]

[1]Physical Sciences Department, Pasadena City College, Pasadena, CA 91106-2003
Tel. (818) 585-7140; Fax (818) 585-7910
[2]Department of Geological Sciences, California State University, Northridge, CA 91330-8266
Tel. (818) 885-3541; Fax (818) 885-2820

Abstract. The Willows Plutonic Complex is a heterogeneous body with abundant hornblende gabbro, lesser amounts of hornblende diorite and tonalite, and minor hypabyssal and ultramafic rocks. It is exposed mostly as a 10-km^2 area south of the Santa Cruz Island fault and is bounded by the high-angle Valley Anchorage fault. The complex is tectonically disrupted, and original field relationships are obscured. Many rocks are altered and contain secondary amphibole, epidote, and chlorite.

A new Ar-Ar hornblende age for the complex of 152.4 ± 1.0 Ma, somewhat younger than a previously reported U-Pb zircon age of 162 ± 3 Ma, can be interpreted as a cooling age. Chemically, the rocks are transitional from tholeiitic to calc-alkaline. They are highly calcic and have low K_2O and TiO_2 concentrations and a high Al_2O_3 content. Initial $^{87}Sr/^{86}Sr$ ratios are 0.70341 to 0.70366. Rare-earth element (REE) concentrations are 2–20 times chrondites with slight to moderate light REE enrichment. These characteristics indicate that the complex originated as part of an oceanic island arc and not as a piece of oceanic crust produced at a mid-oceanic ridge.

Incompatible-element spider diagrams for Willows complex gabbros show a high Nb content compared to that of mid-oceanic ridge basalts and mature island-arc basalts. This suggests that the Willows rocks formed in an immature ensimatic arc. Incompatible trace-element ratios suggest that the diversity of compositions in the complex is not due solely to fractionation but may be related to a heterogeneous mantle source or different degrees of partial melting.

In chemical composition and age the Willows rocks are similar to gabbroic bodies in the Peninsular Ranges Batholith and the Smartville Complex of the Sierra Nevada, which has also been interpreted as originating in an island-arc setting.

Keywords: Gabbro; island arcs; Jurassic; geochemistry; Santa Cruz Island; Peninsular Ranges Batholith.

Introduction

The Willows Plutonic Complex is a fault-bounded gabbroic intrusion exposed on Santa Cruz Island (Fig. 1). The island is a geologically complicated area even though it is only about 35 km long and not more than 12 km wide. Its most prominent geological feature is the Santa Cruz Island fault, which bisects the island lengthwise. The fault divides Miocene volcanic and sedimentary rocks on the north from Jurassic and other Tertiary rocks on the south. The Jurassic rocks form an elongate body parallel to the fault and include the Santa Cruz Island Schist, the Willows Plutonic Complex, and the Alamos pluton.

The Willows Plutonic Complex forms an approximately 10-km^2 slice bounded by the North and South Valley Anchorage faults. Willows rocks are also intimately mixed with Santa Cruz Island Schist along the western end of the Santa Cruz Island fault zone, and a small area of the plutonic complex is exposed south of the Willows fault, where it is overlain by the San Onofre Breccia. The most abundant rock in the complex is hornblende gabbro with subsidiary amounts of hornblende diorite and tonalite and minor occurrences of hypabyssal and ultramafic rocks including clinopyroxenite, hornblendite, and peridotite.

Although the Santa Cruz Island Schist and the Willows Plutonic Complex are everywhere in fault contact, Hill (1975) interpreted meta-hypabyssal rocks within the schist as intrusions from the Willows Plutonic Complex. Sorensen (1985) suggested that metavolcanic rocks in the schist are sufficiently similar to the Willows Plutonic Complex to be correlated. The Alamos pluton, a tonalite that is younger than the Willows Plutonic Complex, intrudes the schist. Metamorphism of the schist may be related to both episodes of plutonism (Hill 1975).

The work of Hill (1975, 1976), who described the petrography of the complex and summarized the available geochronologic data, and of Sorensen (1984, 1985), who made a preliminary geochemical study, added fuel to the debate regarding the origin of the Willows rocks. Some workers (Platt and Stuart 1974; Hill 1976; Hopson et al. 1981) have proposed that the Willows Plutonic Complex is a dismembered portion of the Coast Range

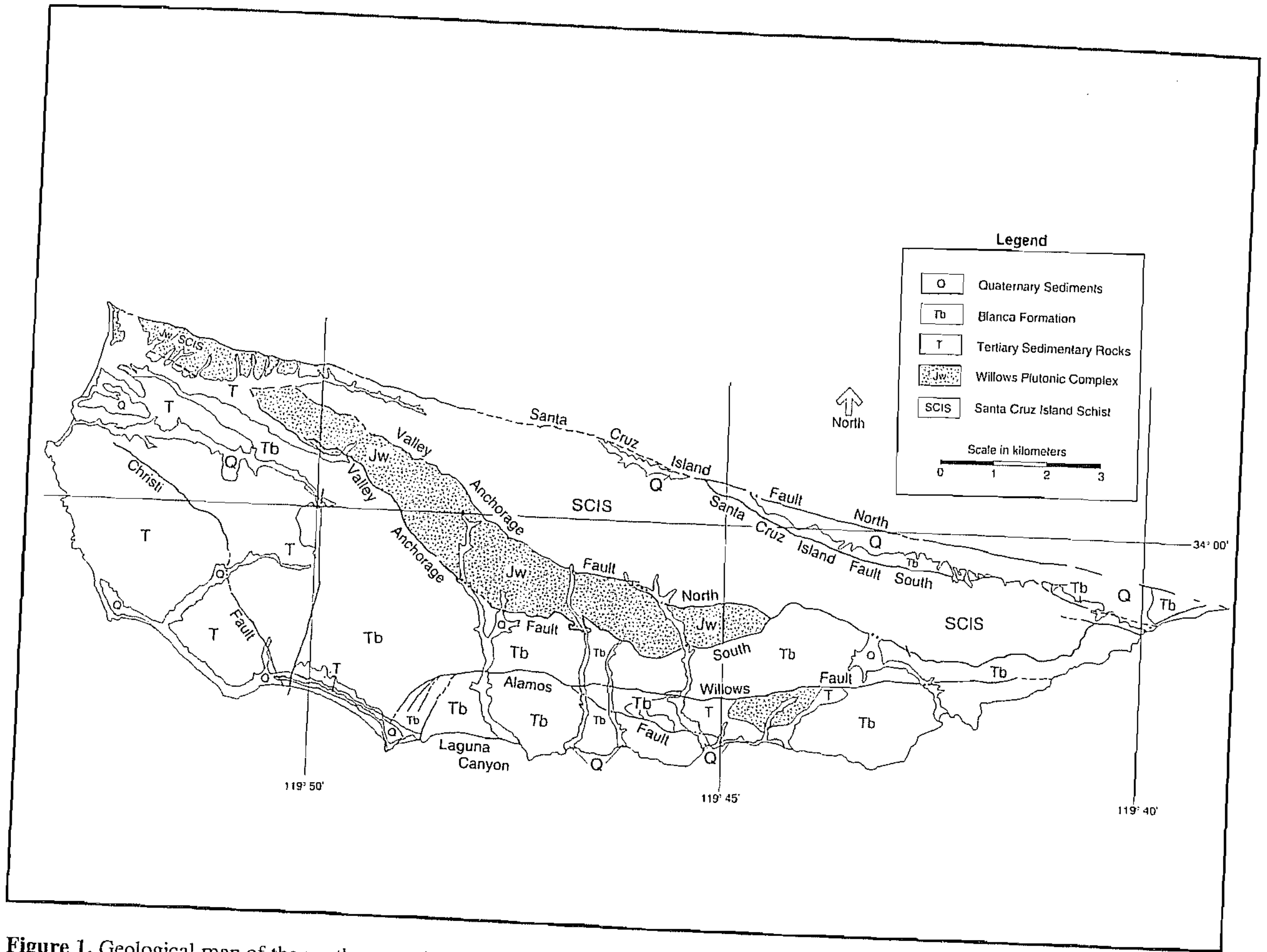

Figure 1. Geological map of the southern portion of Santa Cruz Island modified from Weaver and Nolf (1969).

ophiolite, whereas Sorensen described it as an island arc assemblage. It will be argued on the basis of data presented herein that the Willows Plutonic Complex originated as part of an immature ensimatic arc. As such, it has affinities with Jurassic gabbro-diorite complexes of the Sierra Nevada and the Peninsular Ranges.

The Willows Plutonic Complex is a very heterogenous body exposed as small outcrops on ridges and in gullies. Outcrops near faults are badly shattered, and some rocks are pervasively altered. Consequently, sampling is often confined to almost miscellaneous fragments, and estimating the extent of different rock types or reconstructing their spatial relationships is impractical.

Geochronology

Previously reported age data summarized in Mattinson and Hill (1976) for the Willows Plutonic Complex are K-Ar hornblende cooling ages of 142–147 Ma and a U-Pb zircon age of 162 ± 3 Ma. They also report a somewhat younger U-Pb zircon age, 141 ± 3 Ma, for the nearby Alamos pluton. We have obtained an Ar-Ar plateau age generated from incremental laser heating of a hornblende crystal separated from sample WL-5, which yields an age of 152.4 ± 1.0 Ma (Fig. 2). The euhedral crystal was from a very coarse-grained dike rock that may represent late-stage magmatic activity. This 152-Ma age can be interpreted as a cooling age, whereas the 162-Ma U-Pb zircon age is the crystallization age. The possibly correlative gabbros of the Peninsular Ranges Batholith have K-Ar cooling ages of as old as 143 Ma (Walawender et al. 1991), and similar gabbros of the Smartville

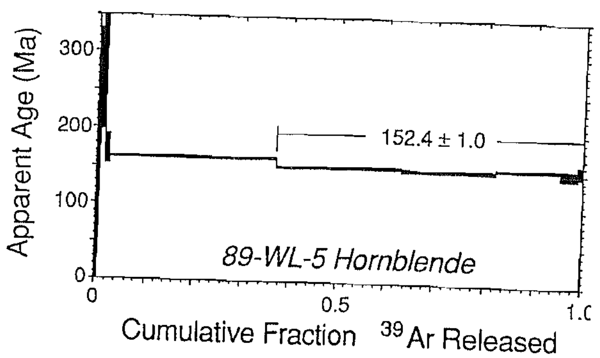

Figure 2. Ar-Ar hornblende plateau age for sample 89-WL-5.

Complex of the Sierra Nevada have U-Pb zircon crystallization ages of about 160 Ma (Beiersdorfer et al. 1991).

Petrography

Although there are some homogeneous masses of hornblende gabbro and diorite exposed in the Willows Plutonic Complex, an important feature is the heterogeneity observable on an outcrop or even hand-specimen scale. Many of the mafic rocks are webbed with small, centimeter-scale dikes of tonalite. Elsewhere thicker porphyro-aphanitic, as well as very coarse-grained dikes of various compositions, intrude the complex.

The texture of the massive gabbro is variable, but typically it is medium- to coarse-grained and equigranular with intergranular augite partially or completely replaced by hornblende. The augite has thin hornblende rinds, or it persists as altered cores in only the largest hornblende crystals. Fine-grained hornblende replacing augite is considered a secondary phase. In contrast, some of the coarse-grained gabbro contains large euhedral blades of primary magmatic hornblende. Opaque minerals constitute less than 5% of the gabbros.

The less abundant tonalitic rocks contain up to 30% quartz and 20% hornblende as well as plagioclase and minor opaque minerals. Hill (1976) gave a detailed description of these rocks as well as the minor amounts of hornblende bronzite augite gabbro and ultramafic rocks in the complex.

Many of the rocks are altered, some to the extent that the original texture is obscured. Plagioclase is commonly sausseritized, and chlorite may replace mafic minerals. Evidence for post-magmatic tectonic activity in the complex can be found in some samples. This evidence includes quartz with undulatory extinction, penetrative mirco-fractures, mortar texture, and metamorphic foliation. Samples that contain sausserite or chlorite tend to have irregular rare-earth patterns and be depleted in alkalies compared to fresh samples. Consequently, only fresh samples will be considered in the geochemical discussion.

Geochemical Characteristics

The rocks of Willows Plutonic Complex can be subdivided into 3 groups on the basis of chemical composition (Fig. 3a): low-titanium gabbroic rocks (TiO_2 < 0.4 and SiO_2 < 53.0 wt %), high-titanium gabbroic rocks

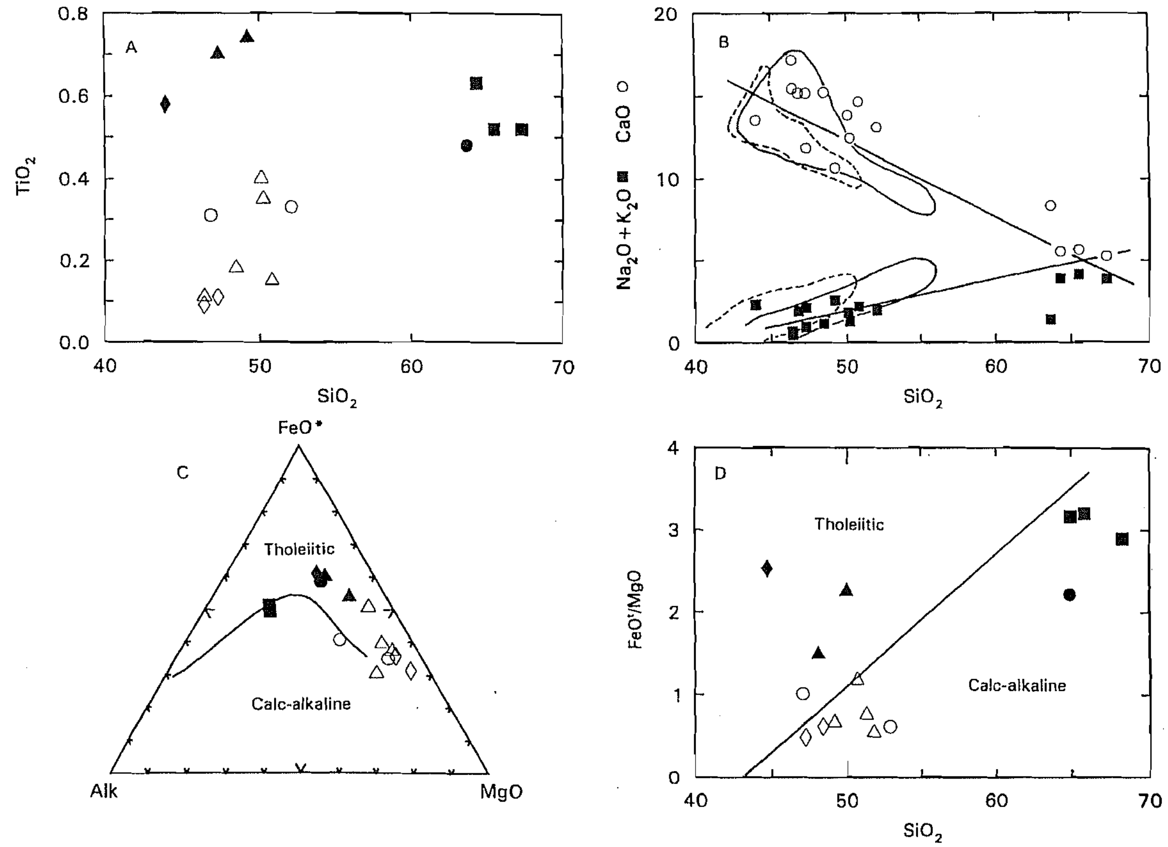

Figure 3. Filled symbols are high-titanium rocks; open symbols are low titanium. Δ = gabbro; ◊ = cumulate gabbro; o = basaltic dikes; □ = tonalite. **3A.** TiO_2 vs SiO_2 for Willows Plutonic Complex. **3B.** Alkali-lime index of Peacock (1931). Fields enclosed by solid lines are for Smartville gabbros (Beard and Day 1988); dashed lines are for Los Pinos gabbros (Walawender 1976). **3C.** AFM diagram (after Irvine and Baragar 1971). **3D.** FeO'/MgO vs SiO_2 discrimination diagram. (FeO' indicates total iron as FeO, data recalculated to a water-free basis, after Miyashiro 1974).

(TiO_2 > 0.4 and SiO_2 < 53), and tonalitic rocks (SiO_2 > 60), which are also high in titanium. The alkali-lime index for the data set as a whole is about 66 (Fig. 3b), which indicates that the Willows complex is unusually calcic. The AFM discrimination diagram (Irvine and Baragar 1971; Fig. 3c) classifies the rocks as tholeiitic to calc-alkaline in character. Using FeO^t/MgO vs SiO_2 as a criterion, however, the data plot mostly in the calc-alkaline field (Fig. 3d). When rocks from the data set (Table 1) with less than 53% SiO_2 are plotted on a tectonic discrimination diagram (Fig. 4), they fall mostly into the calc-alkaline basalt field with some overlap into the island-arc tholeiite field. No samples plot in the mid-ocean ridge basalt (MORB) field.

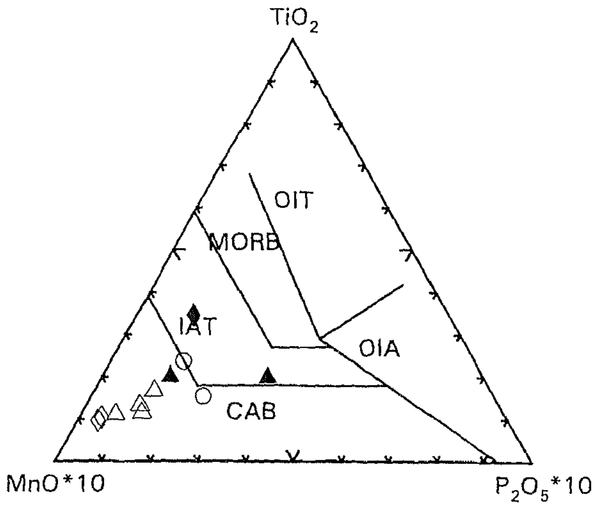

Figure 4. Tectonic discrimination diagram (Mullen 1983) showing Willows rocks with SiO_2 < 52 wt %. **CAB** = calc-alkaline basalts; **IAT** = island-arc tholeiites; **MORB** = mid-ocean ridge basalts; **OIT** = ocean island tholeiites; **OIA** = ocean island alkali basalts. Symbols are defined in Figure 3.

These characteristics of the Willows Plutonic Complex suggest that it originated as an island arc and not at a mid-ocean ridge. Normal ocean-ridge rocks are tholeiitic, but island arcs have a range of compositions. For example, as arcs mature, they shift from tholeiitic to calc-alkaline through time. Also, transitional rocks are found near the trench in some mature island arcs (e.g., Wilson 1989).

The range in TiO_2 concentrations is also compatible with an island-arc origin. Island-arc volcanic rocks are low in TiO_2, and typically contain 0.3 to 1.4 wt %, whereas ocean ridge basalts are likely to have > 1.4% TiO_2 (Basaltic Volcanism Study Project 1981). It is interesting to note that the high-titanium Willows samples are mostly classified as tholeiitic, whereas the low titanium samples are calc-alkaline in Figures 3d and 4.

The Willows complex is high in Al_2O_3 (Table 1), as are island-arc rocks. Basaltic rocks in island arcs generally have compositions of 16–20 wt % Al_2O_3 (Basaltic Volcanism Study Project 1981). Alumina content in excess of 20% in some of the Willows samples can be attributed to cumulate rocks.

This study has not yet been extended to mineral chemistry, but Sorensen (1984) reports 6 plagioclase analyses for the complex. Plagioclase in hornblende gabbros ranges from An_{51} to An_{75}; in a 2-pyroxene gabbro the range is An_{70} to An_{91}. These compositions are compatible with the very calcic nature of the complex and fit with, but are not diagnostic of, an island-arc origin (cf. Wilson 1989).

Strontium isotope analyses of whole rock samples (Table 2) indicate present-day $^{87}Sr/^{86}Sr$ ratios for the Willows complex of 0.70342 ± 9 to 0.70372 ± 7 that correspond to initial ratios of 0.70341 to 0.70366 for an assumed age of 162 Ma. Initial $^{87}Sr/^{86}Sr$ ratios for island-arc rocks are generally greater than 0.703, whereas initial ratios of MORB are generally less than 0.703, except that plume-related and transitional MORB may be higher (Basaltic Volcanism Study Project 1981).

Rare-earth element (REE) abundances in the Willows Plutonic Complex are 2–20 times those of chondrites, and normalized patterns are nearly flat or slightly enriched in light REE with the exception of patterns for 2 dikes that are more strongly light-REE enriched (Fig. 5a). Except for the 2 dikes, the patterns cluster into 2 subparallel groups, 1 of which is slightly more REE-enriched. Samples in the upper group all belong to the high-titanium group (see Fig. 3a) and include 2 tonalites and a hornblende quartz gabbro as well as hornblende gabbro. The REE patterns for these enriched samples correspond closely to patterns for typical island-arc tholeiitic basalts (Wilson 1989). In contrast, the patterns of most MORBs are light-REE depleted, and only rarely are they even slightly light-REE enriched (Basaltic Volcanism Study Project 1981).

The lower group of patterns on Figure 5a is composed of all low-TiO_2 samples except for one. The 2 patterns with the lowest LREE abundances and positive Eu anomalies are samples with very high Al_2O_3 and CaO concentrations (> 24 and 14 wt %, respectively), which fits the interpretation that positive Eu anomalies indicate the accumulation of plagioclase.

Spider diagrams for non-cumulate gabbros of the Willows Plutonic Complex offer the best comparison with diagrams for basalts from mid-ocean ridge and arc settings (Fig 6). On a MORB-normalized diagram, basalts of normal ocean-ridge compositions will form a nearly horizontal pattern with a value of one. Patterns for transitional to enriched MORB differ by being convex upward from Sr through P with enrichments of up to 10 times normal MORB (e.g., Fig. 6b). The patterns for the Willows gabbros are unlike these. The gabbros are depleted relative to MORB from Ce to Yb, and although Ta and Nb are high in the manner of enriched MORB, they lack the corresponding high K values.

Table 1. Geochemical data for selected samples from the Willows Plutonic Complex.

	WL 4	WL 5	WL 6	WL 7	WL 10	WL 12	WL 14	WL 15
SiO_2	46.42	46.81	46.40	47.28	50.80	64.30	52.07	67.30
TiO_2	0.11	0.31	0.09	0.11	0.15	0.63	0.33	0.52
Al_2O_3	16.02	27.18	20.80	20.89	17.02	15.58	11.03	13.70
FeO_T	6.33	4.04	4.30	5.06	4.59	6.12	7.59	5.72
MnO	0.11	0.08	0.08	0.09	0.11	0.12	0.13	0.12
MgO	13.19	3.97	8.73	8.15	8.31	1.93	12.12	1.97
CaO	15.51	15.22	17.20	15.21	14.71	5.56	13.16	5.29
Na_2O	0.45	1.83	0.60	0.91	1.92	3.78	1.26	3.64
K_2O	0.04	0.06	0.07	0.03	0.25	0.09	0.68	0.18
P_2O_5	0.01	0.02	< 0.01	< 0.01	0.01	0.87	0.05	0.06
H_2O^+	3.08	1.27	1.70	1.95	1.81	1.17	1.29	0.93
Sum	101.27	100.79	99.97	99.68	99.68	100.15	99.71	99.43
V	—	—	100	—	—	—	—	160
Cr	213	34	213	87	154	5.6	647	3
Ni	99	30	60	45	52	1.2	94	6
Co	—	—	30	—	—	—	—	17
Cu	—	—	141	—	—	—	—	20.2
Zn	—	—	25.6	—	—	—	—	56.8
Ga	10	19.3	13.4	11	11	16	13	19.1
Li	—	—	BD	—	—	—	—	3
Sc	—	—	30.6	—	—	—	—	20.7
Rb	2.5	1.5	0.35	2.1	4.2	2.1	2.2	1.91
Sr	159	412	214	241	211	195	183	166
Ba	BD	—	BD	BD	BD	BD	—	88
Y	5	8	2	5.5	4	26	6	23
Zr	1.1	12	45	3.6	11	104	26	75
Nb	0.1	4.7	24	0.7	0.5	34	3.7	33
Ta	1.2	2	0.9	0.7	0.9	5.5	1.2	7.6
Hf	0.7	1.3	BD	1.2	1.2	3	1.6	1.6
Th	BD	—	BD	BD	BD	0.3	0.5	1
U	0.1	0.1	BD	0.1	0.1	0.1	0.1	0.2
La	—	1.6	0.6	—	1.4	7.6	3.7	5.2
Ce	—	3.6	0.6	—	2.7	—	7.1	13.3
Pr	—	0.6	0.1	—	0.4	—	0.9	2.4
Nd	—	3.3	0.8	—	1.7	—	4.3	10.7
Sm	—	1.1	0.1	—	0.5	—	1.2	3
Eu	—	0.58	0.06	—	0.25	—	0.38	0.76
Gd	—	1.3	BD	—	0.7	—	1.2	3.8
Tb	—	0.2	BD	—	BD	—	0.2	0.6
Dy	—	1.5	0.3	—	0.8	—	1.2	5.1
Ho	—	0.3	0.07	—	0.2	—	0.2	1.16
Er	—	0.9	0.3	—	0.5	—	0.7	3
Tm	—	0.1	BD	—	BD	—	BD	0.4
Yb	—	0.8	BD	—	0.4	—	0.6	2.5
Lu	—	0.11	BD	—	0.07	—	0.10	0.43

Key: BD = Below detection; "—" = Not analyzed. Notes: Major oxides are in wt %. FeO_T is total Fe as FeO. Trace elements in parts per million (ppm).

Table 2. Strontium isotopic data.

Sample	Sr ppm	Rb ppm	$^{87}Sr/^{86}Sr_m$	$^{87}Sr/^{86}Sr_i$
WD 2	301	2.82	0.70372 ± 7	0.70366
WD 3	240	1.00	0.70357 ± 6	0.70354
WD 6	174	1.80	0.70370 ± 4	0.70363
WD 10	218	0.71	0.70343 ± 9	0.70341
WL 6	214	0.35	0.70367 ± 5	0.70365
WL 15	166	1.91	0.70352 ± 4	0.70344

Key: m = measured; i = initial. Note: Initial ratios calculated using an age of 162 Ma.

Spider diagrams for the Willows gabbros are more like those for island arcs shown in Figure 6b. Data for the South Sandwich Islands represent a short-lived tholeiitic intra-oceanic arc; those for Krakatoa represent the western margin of the Java arc, which is transitional between tholeiitic and calc-alkaline (Pearce 1983). The Willows gabbro data are significantly different from these only in the pronounced enrichment of Ta and Nb. The positive spike for Nb in the Willows Plutonic Complex patterns is unusual because arc rocks of a broad spectrum of compositions are depleted, sometimes strongly, in Nb (Pearce 1982). Since these samples were agate-ground prior to analysis, the enrichment in Nb appears to be an original geochemical characteristic of these rocks.

Petrogenetic Interpretation

These data provide abundant evidence that the Willows Plutonic Complex originated as an island arc. It can also be argued that the arc was immature. Generally, the abundance of gabbro in the complex fits with the observation that magmas of basaltic composition predominate in immature arcs (Wilson 1989). More specifically, the unusual Nb enrichment fits with an immature arc origin. Enrichment in Nb is normal for within-plate basalts, especially for those produced by low fractions of partial melting. Niobium enrichment can also be found in transitional or alkaline MORBs. The usual Nb depletion in island-arc rocks is attributed to the lack of Nb in material contributed to the mantle wedge by the subducting plate. Niobium is also depleted due to the higher percentages of partial melting in arc settings (Wilson 1989).

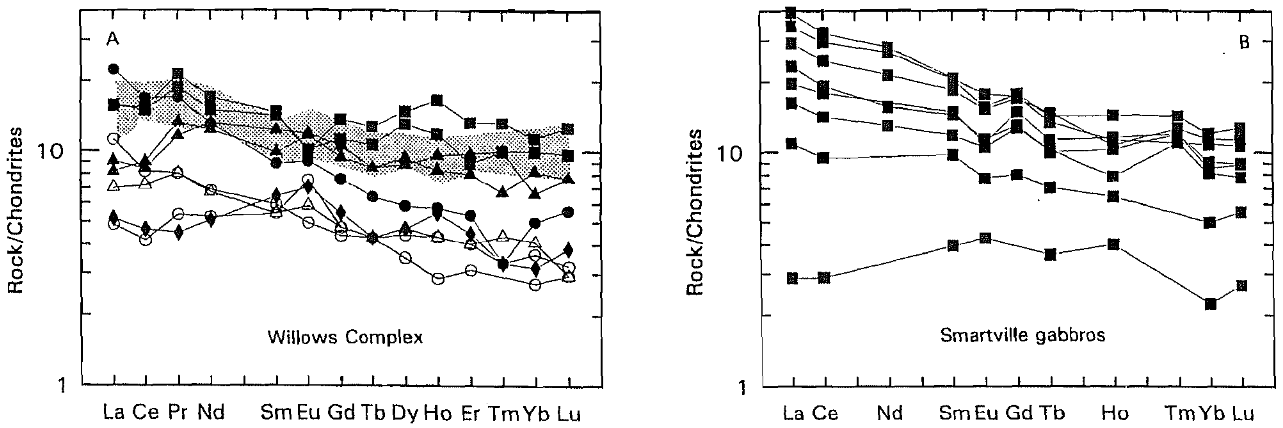

Figure 5. Rare-earth element patterns. (Chondrite normalization values of Nakamura 1974.) **5A.** Willows complex rocks. Symbols are defined in Figure 3. Shaded area is typical range of patterns for island-arc tholeiitic basalts (Wilson 1989). **5B.** Smartville complex gabbros (data from Beard and Day 1988).

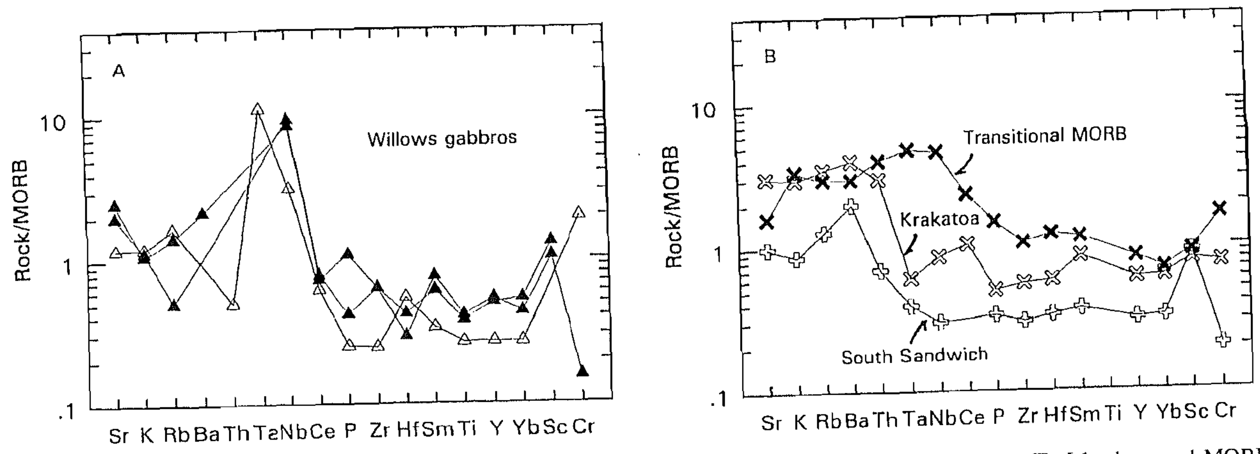

Figure 6. Spider diagrams (MORB normalization values of Pearce 1983). **6A.** Willows complex gabbros. **6B.** Island arc and MORB basalts. **Crosses** = South Sandwich Islands tholeiitic basalt; **open Xs** = Krakatoa transitional calc-alkaline to tholeiitic basalt; **filled Xs** = transitional MORB. Data from Pearce (1982, 1983).

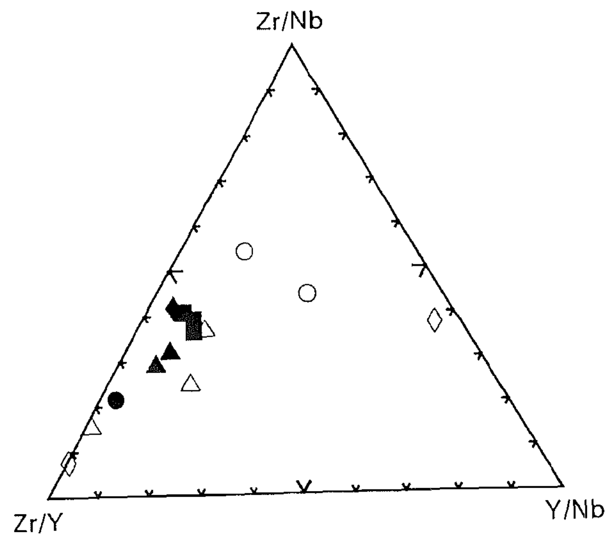

Figure 7. Incompatible-element ratios for Willows Plutonic Complex. Diagram is designed to detect variations in rock chemistry produced by processes other than fractional crystallization (Myers and Breitkopf 1989). See discussion.

These factors dilute the Nb concentration in island-arc rocks compared to that in a relatively low-melt fraction from normal suboceanic mantle.

If the Willows Plutonic Complex is the product of an immature island arc on ensimatic crust, then the contribution of the subducting slab to the overlying mantle wedge could still have been small, and the mantle would have retained its suboceanic character. Modest melt fractions in the early stages of arc growth from such a mantle source would be enriched in Nb. The low $^{87}Sr/^{86}Sr$ ratios of the Willows rocks are compatible with this scenario, because as contributions from the slab increase, so does this ratio. The ratios for the Willows rocks are increased little over those typical for MORB.

It is worth noting that the proposed small melt fraction from nearly normal suboceanic mantle should also lead to enrichment in Ti and P, yet they are depleted in Willows rocks. An explanation for this lies in the cumulate nature of the plutonic rocks. The depletion is strongest in the most plagioclase-rich samples (e.g., samples WL 6 and WL 7, Table 1). These rocks are apatite free, and it can be assumed that P concentrated in the remaining magma as accumulation was taking place in the plutons. Titanium could be partially accommodated in accumulating augite and later hornblende, but iron oxide minerals are present in only trace amounts, and Ti is also likely to have been fractionated into the remaining magma.

The diversity of rock types within the complex is in part due to fractional crystallization. Some of the gabbros are clearly cumulates as evidenced by high concentrations of Al_2O_3 and CaO and corresponding anorthite-rich plagioclase. These rocks, the layered gabbros, as well as the ultramafic rocks likely represent products of crystal accumulation on the floors of the magma chamber.

However, simple crystal fractionation cannot be the only process producing diversity. If it were, there would be more coherent trends on Harker diagrams (e.g., Figs. 3a and 3b). Incompatible-element ratios can be used to test the influence of non-differentiation process. The ratios of these elements should stay nearly constant during fractional crystallization, and samples related by fractional crystallization should plot as a tight cluster on an incompatible-element ratio diagram such as Figure 7. A spread in the points indicates that a non-differentiation factor such as heterogeneity in the magma source had an important role (Myers and Breitkopf 1989). Data for the Willows Plutonic Complex show such a spread, and further investigation is needed to test for heterogeneity in the source or for variations in amounts of partial melting.

Regional Tectonic Context

The Willows Plutonic Complex is clearly not in its original position. Paleomagnetic data indicate that Santa Cruz Island has been rotated (Kamerling and Luyendyk 1979) and the island has been translated, perhaps a substantial distance, along the Santa Cruz Island fault (McLean and Howell 1985). Considerable question remains, however, as to how the Willows Plutonic Complex fits into the Late Jurassic paleogeography of the region.

Late Jurassic multiple-intrusive gabbroic complexes of calc-alkaline affinity are present in the Peninsular Ranges of southern California and Baja California. The spectrum of rock types is similar: peridotite, troctolite, gabbronorite, hornblende gabbro, diorite, and quartz diorite (Walawender and Smith 1980; Smith et al. 1983). The large proportion of hornblende gabbro from the western zone of the batholith, in particular, is reminiscent of the Willows Plutonic Complex. For example, the Los Pinos pluton is nearly as calcic as the Willows complex (Fig. 3b). Also, based on the data of Sorensen (1984), chemical composition of amphibole and plagioclase, An_{52-91}, in Willows gabbros is comparable with that for the Peninsular Ranges gabbros, An_{52-98} (Smith et al. 1983).

Late Jurassic gabbroic complexes are also present in the western Sierra Nevada. The Smartville Complex is an example of one of these. Interpreted as an ensimatic arc complex, it is about 160 Ma in age and consists of gabbro (including hornblende gabbro) to tonalite plutons that intruded into a volcanic pile during rifting of the arc (Beard and Day 1987, 1988). Like the Willows Plutonic Complex, the Smartville plutons are transitional between calc-alkaline and tholeiitic, and there is a strong similarity in the slopes and shapes of REE patterns (Fig. 5b). Unfortunately, Nb concentrations are not reported with the Smartville data, so no comparisons can be made with this interesting element.

One of the particularly appealing aspects of viewing the Willows Plutonic Complex as comparable to the Smartville complex is the parallel history of the associated metamorphic rocks. The metamorphic rocks surrounding the Smartville gabbroic plutons contain possibly cogenetic volcanic rocks, and Beiersdorfer et al. (1991) considered that the metamorphism may have been the result of processes that occurred during construction of the arc. Hill (1976) and Sorensen (1985) reached a similar conclusion for the metavolcanic rocks in the Santa Cruz Island Schist.

Summary and Conclusions

The Willows Plutonic Complex is best interpreted as a mostly gabbroic fragment of an ensimatic island-arc complex. It is strongly calcic with an alkali-lime index of 66 and is transitional from tholeiitic to calc-alkaline in character. The initial $^{87}Sr/^{86}Sr$ ratios of 0.70344 to 0.70366 and rare-earth abundances for samples from the complex are compatible with an island-arc origin.

The Willows gabbros are enriched in Nb relative to MORB. This is unusual for island-arc rocks that are most often depleted in Nb, and it suggests that the Willows Plutonic Complex constitutes part of an immature arc with a mantle source that was still without a substantial component from the subducting plate.

The diversity of rocks in the complex is attributable in part to fractional crystallization. For example, some of the gabbro samples have cumulate compositions. However, differences in incompatible-element ratios from sample to sample suggest that heterogeneity in the mantle source or variations in degree of partial melting could contribute to the observed variations in rock composition.

The Willows Plutonic Complex is similar to other Jurassic gabbroic bodies in the Peninsular Ranges Batholith and the Sierra Nevada. In particular, it is akin to the Smartville Complex of the Sierra Nevada, which has been interpreted as an ensimatic arc complex.

Acknowledgements. We thank Lyndal Laughren of the University of California, Santa Barbara, Natural Reserve system for logistical support and The Nature Conservancy for permission to conduct field research on Santa Cruz Island. Bradley Dybel served as a student assistant for the project. T. E. Davis provided the Sr isotopic analyses, and the Ar-Ar age was determined by Paul Renne, Geochronology Center, Institute of Human Origins, Berkeley, California. J. Lawford Anderson and David Liggett reviewed the manuscript.

Literature Cited

Basaltic Volcanism Study Project. 1981. Basaltic volcanism on the terrestrial planets. Pergamon Press, New York. 1,286 pp.

Beard, J. S., and H. W. Day. 1987. The Smartville intrusive complex, northern Sierra Nevada, California, the core of a rifted volcanic arc. Geological Society of America Bulletin 99:779–791.

Beard, J. S., and H. W. Day. 1988. Petrology and emplacement of reversely zoned plutons in the Smartville complex, northern California. Journal of Petrology 29:965–995.

Beiersdorfer, R. E., J. S. Beard, H. W. Day, and E. M. Moores. 1991. Igneous and metamorphic features of the Smartville Complex, northern California. In: Geological Excursions in Southern California and Mexico (edited by M. J. Walawender and B. B. Hanan), Geological Society of America 1991 Annual Meeting Guidebook, pp. 68–92.

Hill, D. J. 1975. Geology of the Jurassic basement rocks, Santa Cruz Island, California. M.A. thesis. University of California, Santa Barbara. 126 pp.

Hill, D. J. 1976. Geology of the Jurassic basement rocks, Santa Cruz Island, California, and correlation with other Mesozoic basement terranes in California. In: Aspects of the geologic history of the California continental borderland (edited by D. G. Howell), Pacific Section, American Association of Petroleum Geologists, Miscellaneous Publication 24, pp. 16–46.

Hopson, C. A., J. M. Mattinson, and E. A. Pessagno, Jr. 1981. The Coast Range ophiolite. In: The Geotectonic Development of California (edited by W. G. Ernst), Rubey v. 1, Prentice-Hall, Inglewood Cliffs, New Jersey, pp. 418–510.

Irvine T. N., and W. R. S. Baragar. 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Science 8:523–548.

Kamerling, M. J., and B. P. Luyendyk. 1979. Tectonic rotations of the Santa Monica Mountains regions, western Transverse Ranges, California, suggested by paleomagnetic vectors. Geological Society of America Bulletin 90:331–337.

Mattinson, J. M., and D. J. Hill. 1976. Age of plutonic basement rocks, Santa Cruz Island, California. In: Aspects of the Geologic History of the California Continental Borderland (edited by D. G. Howell), Pacific Section, American Association of Petroleum Geologists, Miscellaneous Publication 24, pp. 53–58.

McLean, H., and D. G. Howell. 1985. Blanca turbidite system, California. In: Submarine Fans and Related Turbidite Systems (edited by A. H. Bouma, W. R. Normark and N. E. Barnes), Springer-Verlag, New York, pp. 167–172.

Miyashiro, A. 1974. Volcanic rock series in island arcs and active continental margins. Contributions to Mineralogy and Petrology 274:321–355.

Mullen, E. D. 1983. $MnO/TiO_2/P_2O_5$: A minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis. Earth and Planetary Science Letters 62:53–62.

Myers, R. E., and J. H. Breitkopf. 1989. Basalt geochemistry and tectonic settings: a new approach to relate tectonic and magmatic processes. Lithos 23:53–62.

Nakamura, N., 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. Geochimica et Cosmochemica Acta 38:757–775.

Peacock, M. A. 1931. Classification of igneous rock series. Journal of Geology 39:54–67.

Pearce, J. A. 1982. Trace element characteristics of lavas from destructive plate boundaries. In: Andesites: Orogenic Andesites and Related Rocks (edited by R. S. Thorpe), Chichester, Wiley, pp. 525–548.

Pearce, J. A. 1983. The role of sub-continental lithosphere in magma genesis at destructive plate margins. In: Continental Basalts and Mantle Xenoliths (edited by C. J. Hawkesworth and M. J. Norry), Nantwich, Shiva, pp. 230–249.

Platt, J. P., and C. J. Stuart. 1974. Newport-Inglewood fault zone, Los Angeles basin, California. American Association of Petroleum Geologists Bulletin 58:877–883.

Smith, T. E., C. H. Huang, M. J. Walawender, P. Cheung and C. Wheeler. 1983. The gabbroic rocks of the Peninsular Ranges Batholith, southern California: cumulate rocks associated with calc-alkalic basalts and andesites. Journal of Volcanology and Geochemical Research 18:249–278.

Sorensen, S. 1984. Petrology of basement rocks of the California continental borderland and the Los Angeles basin. Ph. D.Thesis. University of California, Los Angeles, 423 pp.

Sorensen, S. 1985. Petrologic evidence for Jurassic island-arc-like basement rocks in the southwestern Transverse Ranges and California Continental Borderland. Geological Society of America Bulletin 96:997–1006.

Walawender, M. J. 1976. Petrology and emplacement of the Los Pinos pluton, southern California. Canadian Journal of Earth Sciences 13:1288–1300.

Walawender, M. J., G. H. Girty, M. R. Lombardi, D. Kimbrough, M. S. Girty, and C. Anderson. 1991. A synthesis of recent work in the Peninsular Ranges Batholith. In: Geological Excursions in Southern California and Mexico (edited by M. J. Walawender and B. B. Hanan), Geological Society of America 1991 Annual Meeting Guidebook, pp. 297–312.

Walawender, M. J., and T. E. Smith. 1980. Geochemical and petrologic evolution of the basic plutons of the Peninsular Ranges Batholith, southern California. Journal of Geology 88:233–242.

Weaver, D. W., and B. Nolf (directors and compilers). 1969. Geology of Santa Cruz Island (map). In: Geology of the Northern Channel Islands (edited by D. W. Weaver, D. P. Doerner, and B. Nolf), American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, Pacific Sections, Special Publication, scale: 1:24,000.

Wilson, M. 1989. Igneous petrogenesis. Unwin Hyman. Boston. 466 pp.

Woodhead, J. D. 1989. Geochemistry of the Mariana arc (western Pacific): source composition and processes. Chemical Geology 76:1–24.