Reconstruction of Crustal Blocks Of California on the Basis of Initial Strontium Isotopic Compositions Of Mesozoic Granitic Rocks

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1071

Reconstruction of Crustal Blocks Of California on the Basis of Initial Strontium Isotopic Compositions Of Mesozoic Granitic Rocks

By RONALD W. KISTLER *and* ZELL E. PETERMAN

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1071

A study of regional variation of initial strontium isotopic composition of Mesozoic granitic rocks in California

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1978

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

Library of Congress Catalog-card Number 78-600103

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Stock No. 024-001-03109-4

CONTENTS

ILLUSTRATIONS

TABLES

RECONSTRUCTION OF CRUSTAL BLOCKS OF CALIFORNIA ON THE BASIS OF INITIAL STRONTIUM ISOTOPIC COMPOSITIONS OF MESOZOIC GRANITIC ROCKS

By RONALD W. KISTLER and ZELL E. PETERMAN

ABSTRACT

Initial $^{87}Sr/^{86}Sr$ was determined for samples of Mesozoic granitic rocks in the vicinity of the Garlock fault zone in California. These data along with similar data from the Sierra Nevada and along the San Andreas fault system permit a reconstruction of basement rocks offset by the Cenozoic lateral faulting along both the San Andreas and Garlock fault systems.

The location of the line of initial $^{87}Sr/^{86}Sr$ = 0.7060 can be related to the edge of the Precambrian continental crust in the western United States. Our model explains the present configuration of the edge of Precambrian continental crust as the result of two stages of rifting that occurred about 1,250 to 800 m.y. ago, during Belt sedimentation, and about 600 to 350 m.y. ago, prior to and during the development of the Cordilleran geosyncline and to left-lateral translation along a locus of disturbance identified in the central Mojave Desert. The variations in Rb, Sr, and initial $^{87}Sr/^{86}Sr$ of the Mesozoic granitic rocks are interpreted as due to variations in composition and age of the source materials of the granitic rocks. The variations of Rb, Sr, and initial $^{87}Sr/^{86}Sr$ in Mesozoic granitic rocks, the sedimentation history during the late Precambrian and Paleozoic, and the geographic position of loci of Mesozoic magmatism in the western United States are related to the development of the continental margin and different types of lithosphere during rifting.

INTRODUCTION

The isotopic composition of strontium was determined for specimens of granitic rocks in the vicinity of the Garlock fault, in the southern Sierra Nevada, and in the northern Mojave Desert of California. Values for Rb, Sr, K/Sr, K/Rb, $^{87}Sr/^{86}Sr$, initial $^{87}Sr/^{86}Sr$, and age for each specimen are given in table 1. Chemical analyses of some of these rocks are given in table 2, and K-Ar ages of some are listed in table 3. Locations of specimens investigated are shown in figure 1, and petrographic descriptions and sample locations are given in the Appendix. Analytical techniques for Rb, Sr, and $^{87}Sr/^{86}Sr$ are the same as those described in Kistler and Peterman (1973), and those for K-Ar dates are the same as those described in Kistler (1968).

Previously, we found (Kistler and Peterman, 1973) that initial $^{87}Sr/^{86}Sr$ (hereafter called r_i) values in Mesozoic granitic rocks to the north of the Garlock fault in California show a systematic areal variation, independent of age, and that the r_i of superjacent upper Cenozoic basalts and andesites in that area show the same areal variation. We suggested that the boundary between granitic rocks with r_i less than 0.7060 and greater than 0.7060 was coincident with the seaward edge of marine miogeosynclinal sedimentation during the late Precambrian and Paleozoic in California, that is, the edge of the Paleozoic continental shelf. Armstrong, Taubeneck, and Hales (1977) established that the r_i of Mesozoic granitic rocks and Cenozoic volcanic rocks had the same relation in Washington and Idaho to Precambrian and Paleozoic sedimentation.

One goal of the present study was to extend to the vicinity of the Garlock fault distinctive pattens of r_i previously established in the Sierra Nevada north of the Garlock fault by us (Kistler and Peterman, 1973) and along the San Andreas fault system (Kistler and others, 1973). Offsets of the pattern of r_i along these fault systems could then be used to help establish limits of Cenozoic displacements along them.

The pattern of variation of strontium isotopes of Mesozoic granitic rocks in California appears to indicate that the State is composed of four fundamentally different types of crust. The boundaries between these crustal types where presently known are indicated in figure 2. The first type is crust that has been intruded by Mesozoic granitic rocks that are principally granodiorite and quartz monzonite and that have r_i greater than 0.7060. The second type is crust that has been intruded by Mesozoic granitic rocks that are principally tonalite and granodiorite and have r_i greater than 0.7040 but less than 0.7060; this can be subdivided into two types on the basis of trace-elements abundances in Mesozoic granitic rocks that intrude it. The third type is crust intruded by Mesozoic granitic rocks that are principally quartz diorite

Table 1.—*Strontium analytical data*

[n.d. = not determined K_2O and Na_2O determined by L.B. Schlocker. Rb and Sr determined by W.P.Doering $^{87}Sr/^{86}Sr$ determined by R.A. Hildreth and R.W. Kistler]

Specimen No.	Map No.	Wt percent K_2O	Wt percent Na_2O	Rb (ppm)	Sr (ppm)	Weight ratios Rb/Sr	Weight ratios K/Rb	Weight ratios K/Sr	Atom ratios $^{87}Sr/^{86}Sr$	Atom ratios r_i	Age (m.y.)
Sr 1–73 -------	1	1.79	3.16	77.2	360	0.215	193	41.4	0.7048	0.7038	120
Sr 2–73 -------	2	1.76	4.02	57.7	399	.145	253	36.6	.7050	.7043	120
Sr 3–73 -------	3	1.71	3.45	44.0	514	.086	323	27.6	.7036	.7032	120
Sr 4–73 -------	4	3.01	2.96	146.	249	.586	171	100.4	.7089	.7061	120
Sr 5–73 -------	5	3.40	2.81	154.	238	.646	183	118.5	.7084	.7053	120
Sr 6–73 -------	6	3.38	4.00	140.	349	.401	201	80.5	.7073	.7058	90
Sr 8–73 -------	7	2.87	3.82	98.	737	.133	243	32.3	.7080	.7075	90
Sr 9–73 -------	8	2.39	3.91	81.8	695	.118	242	28.5	.7084	.7080	90
Sr 10–73 ------	9	2.84	3.70	89.6	634	.141	263	37.2	.7076	.7070	90
Sr 11–73 ------	10	4.92	3.13	118.	609	.193	346	67.0	.7084	7077	90
Sr 12–73 ------	11	2.45	4.56	80.1	612	.131	253	33.2	.7062	.7058	81
Sr 14–73 ------	12	2.00	3.91	55.0	347	.159	302	47.8	.7055	.7050	80
Sr 15–73 ------	13	1.70	3.68	53.8	341	.158	262	41.3	.7060	.7055	81
Sr 16–73 ------	14	3.83	3.50	98.1	382	.257	324	83.2	.7062	.7042	210
SR 17–73 -----	15	2.45	4.33	72.0	848	.085	282	23.9	.7069	.7066	90
Sr 18–73 ------	16	3.29	4.50	108.	731	.148	253	37.3	.7092	.7081	180
Sr 19–73 ------	17	3.03	3.32	105.	350	.301	239	71.7	.7065	.7041	200
Sr 20–73 ------	18	4.76	3.45	132.	339	.390	299	116.5	.7089	.7060	180
COS 10–2 -----	19	n.d.	n.d.	80.1	485	.165	—	—	.7057	.7041	200
COS 13–42–2 ---	20	n.d.	n.d.	10.3	664	.016	—	—	.7062	.7060	180
A3 ---------	21	n.d.	n.d.	169.	261	.548	—	—	.7106	.7064	184
A6 ---------	22	n.d.	n.d.	57.7	686	.084	—	—	.7047	.7041	200
D15 ---------	23	n.d.	n.d.	146.	489	.299	—	—	.7094	.7070	210
D16 ---------	24	n.d.	n.d.	203.	311	.653	—	—	.7130	.7070	210
E12 ---------	25	n.d.	n.d.	89.	592	.150	—	—	.7083	.7070	210
C–203 -------	27	3.63	3.62	144.	345	.417	225	89.1	.7182	—	p€(?)
C–204 -------	28	4.33	3.17	180.	219	.824	211	174.	.7174	—	p€(?)
C–201 -------	29	1.58	3.97	27.7	970	.029	473	13.5	.7063	.7063	13
E10 ---------	26	n.d.	n.d.	139.	171	.815	—	—	.7107	.7070	100

Table 2.—*Chemical analyses of granitic rocks*

[Analyst, H. Smith]

Spec. No.	1–73	2–73	3–73	4–73	5–73	6–73	8–73	9–73	10–73	11–73	12–73	15–73	16–73	17–73	18–73	19–73	20–73
SiO_2 ---	63.2	68.7	65.8	65.8	65.1	68.1	65.8	63.8	63.8	72.7	59.0	61.8	71.9	62.1	68.4	65.8	70.3
Al_2O_3 --	16.5	15.7	15.9	15.1	15.2	15.9	16.2	17.1	16.3	14.0	16.8	16.8	14.5	15.6	16.3	15:8	15.2
Fe_2O_3 -	0.7	1.1	1.6	0.3	1.0	1.3	1.5	1.3	1.7	0.90	1.4	1.2	0.90	0.40	1.8	2.1	1.5
FeO ---	4.3	2.2	2.6	3.8	3.8	2.0	2.6	3.5	3.4	0.96	4.5	4.7	1.2	4.5	1.3	2.5	1.3
MgO --	2.8	1.2	2.1	2.0	2.2	0.9	1.2	1.3	2.1	0.30	2.6	2.2	0.36	1.8	0.70	2.0	0.68
CaO ---	5.8	3.8	5.0	4.2	3.9	2.4	3.5	3.9	4.5	1.5	5.2	4.6	2.0	4.9	2.7	4.3	1.9
Na_2O --	3.3	4.2	3.8	3.1	2.9	4.1	4.0	4.1	3.7	3.1	4.7	4.1	3.5	4.5	4.6	3.5	3.4
K_2O ---	1.8	1.8	1.8	3.0	3.6	3.3	2.9	2.5	2.8	5.0	2.6	1.7	3.8	2.5	3.4	3.1	4.8
H_2O^+ --	0.53	0.54	0.52	0.49	0.45	0.64	0.52	0.81	0.45	0.27	0.75	0.79	0.33	0.52	0.25	0.57	0.58
H_2O^- --	0.25	0.26	0.28	0.29	0.23	0.27	0.38	0.29	0.28	0.25	0.35	0.31	0.36	0.28	0.33	0.28	0.27
TiO_2 --	0.62	0.44	0.52	0.57	0.66	0.52	0.77	0.82	0.87	0.20	1.2	0.91	0.19	1.1	0.35	0.56	0.36
P_2O_5 --	0.15	0.14	0.16	0.12	0.11	0.21	0.23	0.25	0.23	0.06	0.38	0.22	0.08	0.35	0.15	0.14	0.13
MnO --	0.07	0.04	0.08	0.06	0.06	0.04	0.04	0.04	0.06	0.00	0.10	0.09	0.06	0.06	0.04	0.08	0.05
CO_2 ---	0.03	0.05	0.04	0.02	0.05	0.02	0.03	0.02	0.04	0.06	0.08	0.08	0.06	0.24	0.08	0.04	0.08
Sum	100	100	100	99	99	100	100	100	100	99	100	100	99	99	100	101	101

TABLE 3.—*Potassium-argon dates*

[K_2O determined by L. B. Schlocker. Moles $^{40}Ar_{rad}$ determined by R. W. Kistler]

Map No.	Mineral	K_2O (wt percent)	$^{40}Ar_{rad}$ (x 10^{-11} moles/gm)	$^{40}Ar_{rad}$ (percent)	Age (m.y.)
6 -------------------	Biotite	8.81	88.71	77	67.1 ± 1.7
7 -------------------	—do—	9.36	110.99	94	78.7 ± 2.0
8 -------------------	—do—	9.16	103.07	70	74.8 ± 1.9
10 -------------------	—do—	7.22	77.22	75	71.1 ± 1.8
15 -------------------	—do—	8.77	23.67	50	18.2 ± 0.5
	Hornblende	1.62	18.12	44	74.2 ± 1.9
17 -------------------	Biotite	8.64	184.40	91	139.5 ± 3.5
	Hornblende	.55	10.72	28	127.4 ± 8.0
18 -------------------	Biotite	8.48	95.48	87	74.8 ± 1.9
27 -------------------	—do—	8.11	138.98	79	112.7 ± 2.8
28 -------------------	—do—	6.90	92.83	92	89.0 ± 2.3

and trondjhemite and have r_i less than 0.7040; this third type is also characterized by the principal exposures of ophiolites in California. The fourth type is Franciscan melange.

In our original study of r_i in Mesozoic granitic rocks (Kistler and Peterman, 1973), we found not only that a simple pattern of variation in chemistry and r_i of Mesozoic and Cenozoic igneous rocks exists in California, but that variations in chemistry and r_i could not be related to depths of magma generation along subduction zones or to the age of the igneous activity. However, the variation was dependent on geographic position of specimens investigated and was correlated with long-lived crustal features. Granitic rocks with r_i greater than 0.7060 were intruded into regions with a crust as much as 50 km thick and in many areas with exposures of Precambrian crystalline rocks (Oliver, 1977). Similar studies (Early and Silver, 1973; Kistler

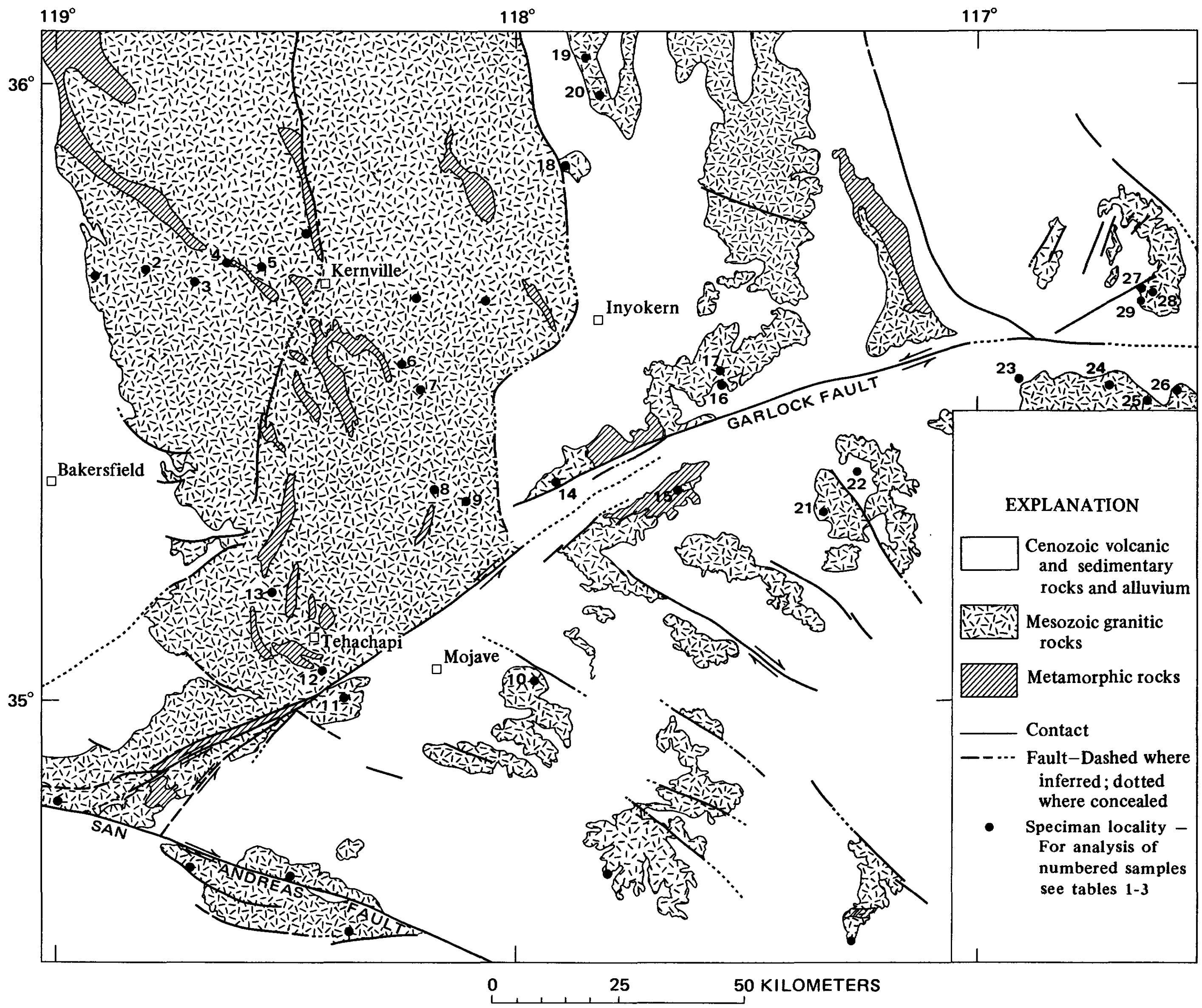

FIGURE 1.—Generalized geologic map of vicinity of Garlock fault zone, California (modified from Dibblee, 1960) showing specimen localities of granitic rocks investigated for present study. Unnumbered sample localities are from Kistler and Peterman (1973) and Kistler, Peterman, Ross, and Gottfried (1973).

and others, 1973; Kistler, 1974; Armstrong and others, 1977; Petö and Armstrong, 1976; Le Conteur and Templeman-Kluit, 1976) have simply reinforced this observation. As a consequence, we conclude that areas in the western United States intruded by Mesozoic granitic rocks with r_i greater than 0.7060 are underlain by ensialic crust.

Considering the line $r_i = 0.7060$ as a reflection of limits of Precambrian continental crust and the edge of the paleozoic continental shelf gives further insight into the reasons for the location of loci of magmatism of different ages and into the nature of the source materials for the granitic rocks. This insight is especially clear after the disrupted boundaries of the isotopic pattern are restored along the San Andreas and Garlock fault systems and the resultant pattern is related both to a known Precambrian aulocogen in the Death Valley region and to the age and type of sediments deposited in the Paleozoic cordilleran geosyncline along the margin of the western United States.

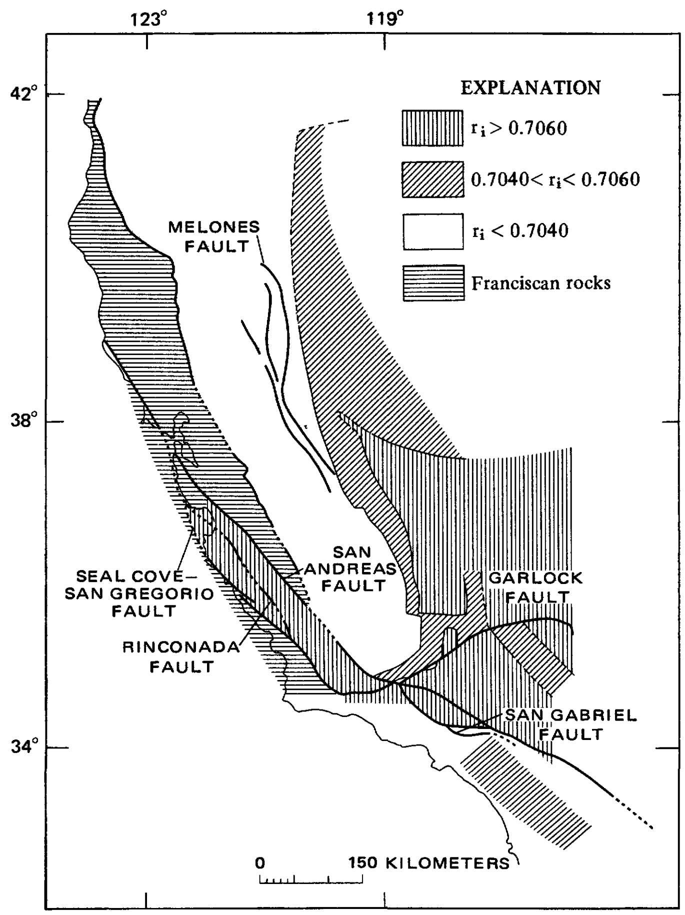

FIGURE 2.—Generalized geologic map of California showing boundaries between four different crustal types characterized by Mesozoic granitic rocks with distinctive r_i.

FAULT BLOCK RECONSTRUCTION

In order to test suggested offsets of basement rocks to the west of the San Andreas fault, Kistler, Peterman, Ross, and Gottfried (1973) determined the r_i of Mesozoic granitic rocks in the vicinity of the San Andreas fault zone from the Gualala area in the north into the southern California batholith in the south. Two stages of motion of basement terrane were utilized to bring the granitic rocks with distinctive r_i to the west of the San Andreas fault zone into a reasonable prefault configuration adjacent to granitic rocks in the Mojave Desert east of the fault. For the first stage, which is required to restore about 320 km of post-lower Miocene offset, the entire length of the present-day San Andreas fault (fig. 2) and the San Gabriel fault zone was considered the break between lithosphere blocks (Anderson, 1971; Crowell, 1968). After this restoration, granitic rocks from Ben Lomond to Bodega Head remain in an apparently anomalous position to the west of the Great Valley. Stratigraphic studies indicate these rocks arrived in this position during Late Cretaceous and Paleocene time and provided debris to Eocene submarine fan deposits, some of which are now cut by the San Andreas fault (Nilsen and Clarke, 1975). The second stage, along a proto-San Andreas fault, utilized the San Andreas fault north of the Garlock fault, the southern part of the Sur-Nacimiento fault, and the Reliz-Espinosa-San Marcos-Rinconada fault zone to restore granitic rocks from Ben Lomond to Bodega Head to a possible pre-Late Cretaceous position to the south (Kistler and others, 1973).

The second-stage restoration of Kistler, Peterman, Ross, and Gottfried (1973) indicated about 150 km of pre-middle Eocene, post-Late Cretaceous motion along the Reliz-Espinosa-San Marcos-Rinconada fault zone in the interior of the Salinian block. However, only about 60 km of pre-Miocene lateral displacement is likely along the south end of this fault zone (Dibblee, 1972, 1976), and the new strontium isotopic data indicate that the Ben Lomond region is not in an anomalous position. An additional fault or process is necessary, however, to remove granitic rocks from Montara to Bodega Head from their anomalous position west of the Great Valley. Up to 100 km of late Cenozoic right-lateral displacement is suggested for the Seal Cove-San Gregorio fault zone, a western branch of the San Andreas fault system (Silver, 1975; Graham, 1975; Dibblee, 1976). If 100 km of right-lateral displacement is removed along the Seal Cove-San Gregorio fault zone, however, the granitic rocks from Montara to Bodega Head would no longer be in a position suitable to shed debris into lower Tertiary submarine fans in the location shown by Nilsen and Clarke (1975). Early Cenozoic lateral displacement of up to 50 km in the interior of the Salinian terrane along the San Juan fault and the Rinconada fault zone of Dibblee (1976) is possible, but the configuration of the isotopic pattern does not require any pre-Miocene Cenozoic lateral displacement of continental basement rocks along this segment of the California borderlands.

Smith (1962), on the basis of apparent offsets of dike swarms in Mesozoic granitic rocks, suggested about 64 km of Cenozoic left-lateral displacement along the Garlock fault. Subsequent geologic studies in the vicinity of the fault have supported Smith's conclusion, as summarized by Davis and Burchfiel (1973). Troxel, Wright, and Jahns (1972), Davis and Burchfiel (1973), and Garfunkel (1974) concluded that the Garlock fault is a continental transform related to Cenozoic crustal extension in the Great Basin and that displacement along it is not everywhere the same. Offsets in the strontium isotopic pattern in the vicinity of the Garlock fault zone indicate a maximum of about 52 km of displacement along the fault.

In figure 3, major post-Miocene right-lateral displacements of continental rocks along the San Andreas and San Gabriel fault zones have been removed from the California borderlands (Kistler and others, 1973). In addition, 52 km of left-lateral displacement has been removed along the Garlock fault. Post-Late Cretaceous and Pre-middle Eocene displacement of 50 km could be removed from the Reliz-Espinosa-San Marcos-Rinconada fault zone of Dibblee (1972) and its extension, the King City fault zone of Ross and Brabb (1973), but this displacement provides no improvement in alinement of r_i and is not shown. The sliver of basement bounded by the San Gabriel and San Juan fault zones may be shown in a too southerly position in figure 3, because geologic evidence indicates a right-lateral offset of only 40 km on the San Gabriel fault zone (Crowell, 1952; Dibblee, 1968). If the geologic estimates of displacement along the San Gabriel fault zone are correct, the sliver bounded by the San Gabriel and San Juan fault zones would have to lie further to the north. If this were the case, considerable right-lateral slip along the San Juan fault zone would have to be removed to place the rest of the Salinian block in the position shown. As much as 37 km of post-lower Tertiary right-lateral slip has been suggested for this fault, and earlier movements with the same sense may also have occurred along it (Dibblee, 1976, p. 21). The strontium data do not uniquely define a position for this sliver in the interior of the Salinian block, and its position in figure 3 is established only if there is no internal deformation within the block, an unlikely possibility (Garfunkel, 1974).

The continuity of r_i across the San Andreas fault zone to the south of Ben Lomond and across the Garlock fault zone after the indicated restoration is remarkable. An 80-km restoration along the Seal Cove-San Gregorio-Palo Colorado fault zone would juxtapose granitic rocks with similar r_i (0.7061 to 0.7068) at Bodega Head, Point Reyes, Montara, and the Farallon Islands. These granitic rocks still appear to be in an anomalous position relative to sedimentary rocks of the Great Valley sequence of late Mesozoic to Tertiary age. However, moving them further south laterally along a fault does not produce a post-Late Cretaceous pre-middle Eocene juxtaposition of r_i that is any better than that in the position shown. The position of these granitic rocks shown in figure 3 places them just west of the junction between Franciscan melange and the Great Valley sequence—the Coast Range thrust. The projection of this junction south lines up with a zone of ultramafic rocks in the western part of the northern Santa Lucia Range (Ross, 1976). We believe that the Coast Range thrust and the zone of Ultramafic rocks may be related. If so, the granitic rocks under discussion could have arrived from the west to their apparently anomalous position prior to the Paleocene and early Eocene and, in effect, could be part of the Franciscan melange. It should be noted that their r_i values are derived on the assumption that these granitic rocks are about 110 m.y. old (Mattinson and others, 1972; Kistler and others, 1973). However, this age has never been established unequivocally, as zircon ages from these rocks are discordant and indicate a pre-Mesozoic component (Mattinson and others, 1972) in the zircon populations. Plotting the raw RbSr data from granitic rocks from Bodega Head, Point Reyes, and Farallon Islands (Kistler and others, 1973) on a strontium evolution diagram yields an apparent age of about 200 m.y. and a common r_i of 0.7058. If the pluton at Montara is assumed to have the same r_i, its age is about 320 m.y. These calculations are not meant to indicate real ages; they are meant to show that the granitic rocks are possibly older than Mesozoic and possibly have an r_i less than 0.7060.

The small exposures of granitic rocks from Montara to Bodega Head are the isotopically unusual rocks of the Salinian block. The oldest strata of the Gualala basin to the north of Bodega Head lie on spilitic volcanic rocks similar to those of the Franciscan Formation and with oceanic affinities (Wentworth, 1966). The other basins of early Tertiary sedimentation are

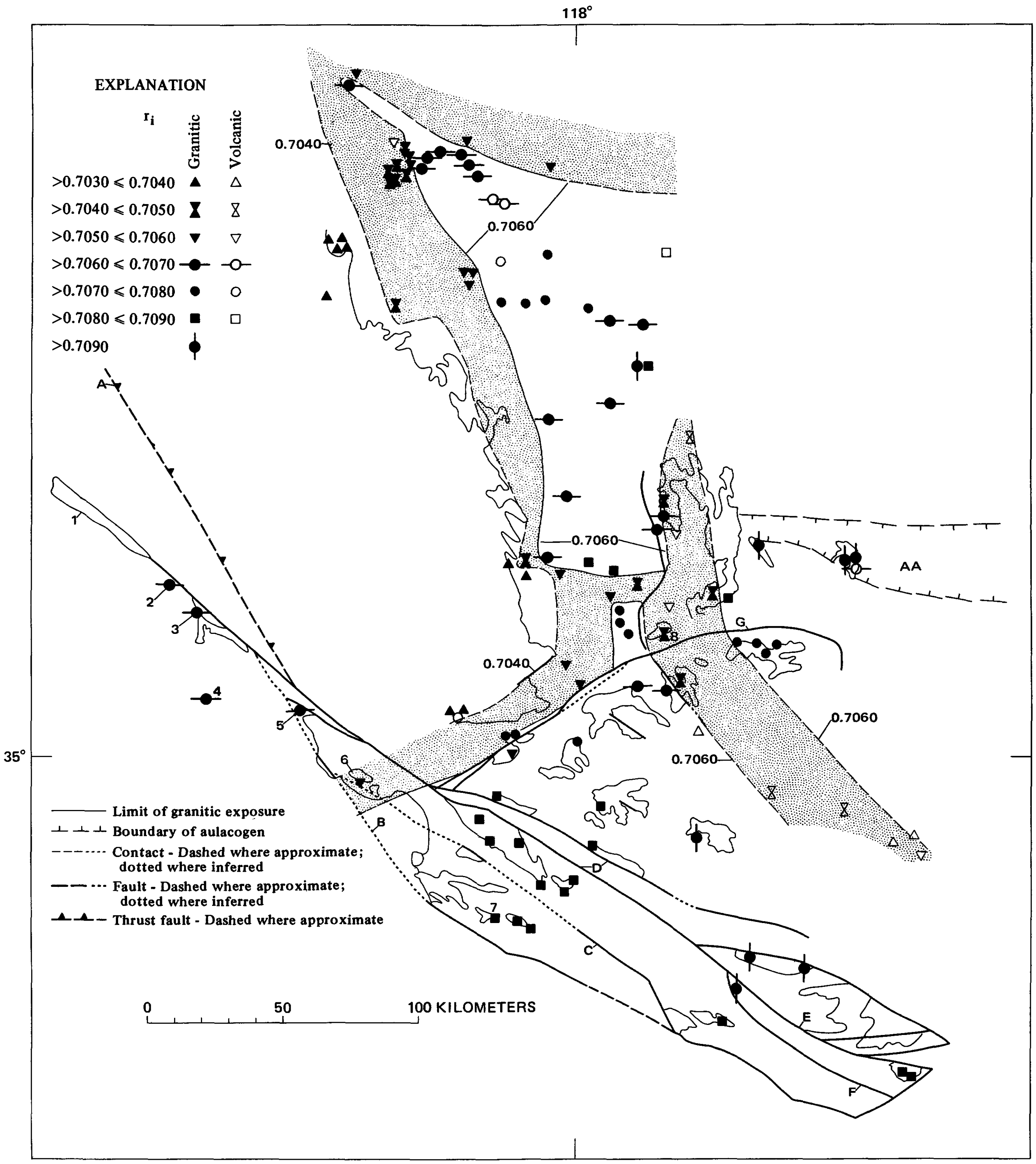

FIGURE 3.—Distribution of r_i of Mesozoic granitic rocks and mafic Cenozoic volcanic rocks with late Cenozoic lateral displacements removed from San Andreas and Garlock fault systems. Stippled area is where $0.704 < r_i < 0.706$. Locations of geographic features mentioned in text are: (1) Gualala area, (2) Bodega Head, (3) Point Reyes, (4) Farallon Islands, (5) Montara, (6) Ben Lomond, (7) Santa Lucia Mountains, (8) El Paso Mountains, (AA)—Amargosa aulacogen. Faults mentioned in text are: (A) Coast Range thrust, (B) Seal Cove-San Gregorio, (C) Rinconada, (D) San Andreas, (E) San Gabriel, (F) San Juan, (G) Garlock. Thin lines outline areas of Mesozoic granite rocks (see fig. 1). Reconstruction along faults is made relative to a fixed Mojave block.

suggested to have formed by slicing and fragmentation of continental crust along transform boundaries, and some may be floored by oceanic crust (Nilsen and Clarke, 1975). With these facts in mind and because there is no compelling reason to shift to the south the granitic exposures from Montara to Bodega Head, we suggest these grantitic rocks may represent the deeply exposed rocks of a volcanic arc terrane that were emplaced from the west into their positions shown in figure 3 during the Late Cretaceous and Paleocene.

DEVELOPMENT OF THE CONTINENTAL MARGIN

Another noteworthy feature of the pattern of r_i after these major fault displacements are removed is an area in the southern Sierra Nevada and central Mojave Desert characterized by Mesozoic granitic rocks and late Cenozoic volcanic rocks with r_i between 0.7040 and 0.7060 between terranes intruded by Mesozoic granitic rocks with r_i greater than 0.7060. The r_i of Mesozoic granitic rocks in this area indicates a discontinuity underlain by ensimatic crust between two areas underlain by ensialic crust. The northern (eastern) terrane characterized by Mesozoic granitic rocks with r_i greater than 0.7060 we will call Sierran, and the southern (western) terrane characterized by Mesozoic granitic rocks with r_i greater than 0.7060 we will call Salinian-western Mojave. The time of formation of the discontinuity between the Salinian-western Mojave and the Sierran ensialic terranes is only surmised from geologic features in its vicinity; these features are discussed below. The systematics of the isotopic data from granitic rocks in the discontuinuity are compatible with the timing inferred from the geologic considerations.

A trough that controlled the Pahrump Group and subsequent Precambrian sedimentation, named the Amargosa aulacogen (Wright and others, 1974), occurs within the Sierran terrane (fig. 3) immediately east of the discontinuity between the ensialic terranes. The basal sedimentary unit in the trough, the Crystal Spring Formation, is intruded by basaltic dikes and sills of probable 1,200 m.y. age and lies unconformably on crystalline basement of approximately 1,700 m.y. age. The proximity of the aulacogen to the discontinuity between ensialic terranes suggests that these features are related: the aulacogen would be the failed arm of a triple junction (Burke and Dewey, 1973; Hoffman and others, 1974) with the other arms represented by the ensimatic terrane in the southern Sierra Nevada and central Mojave Desert now characterized in part by Mesozoic granitic rocks and Cenozoic basalts with r_i less than 0.7060. These relations suggest the discontinuity could have formed as long as 1,200 m.y. ago.

The time of the formation of the discontinuity between the Sierran and Salinian-western Mojave terranes is also limited by the oldest crystal rocks within the discontinuity; these old rocks unfortunately are known only poorly. The oldest of these known include metamorphosed Paleozoic sedimentary rocks and volcanic rocks. Ordovician oceanic sedimentary rocks occur in the El Paso Mountains (fig. 3), but because these strata have affinities to western-facies eugeosynclinal rocks of the Cordilleran geosyncline, they are considered by some workers to be allochthonous and emplaced from the west (Poole, 1974). Other metamorphosed carbonates and eugeosynclinal rocks of Paleozoic age lie in the discontinuity south of the Garlock fault in the central Mojave Desert (Jennings and others, 1962). These rocks are flanked on both the east and the west by outcrops of Precambrian crystalline basement of approximately 1,700 m.y. age and by miogeosynclinal rocks of Paleozoic age (Stewart and Poole, 1975).

The strontium isotopic systematics of Mesozoic granitic rocks in the discontinuity with r_i less than 0.7060, as discussed below, are compatible with the development of the discontinuity during Precambrian continental rifting at the time of formation of the aulacogen. However, geologic evidence indicates that parts of the discontinuity were reactivated or became active during renewed rifting of the North American continent immediately prior to sedimentation in the Cordilleran geosyncline. If the interpretations above are correct, the Salinian-western Mojave terrane was a continental mass that lay west of the site of Paleozoic eugeosynclinal sedimentation in the Cordilleran geosyncline. Its present position in southern California is the result of subsequent Mesozoic convergence along the western margin of North America; it may result in part from about 800 km of middle Mesozoic left-lateral displacement along the extension of the zone of disruption of Precambrian basement, as described by Silver and Anderson (1974).

Figure 4 shows the configuration, where presently known, of the lines $r_i = 0.7040$ and $r_i = 0.7060$ on an outline map of the western United States after removal of lateral displacements along the San Andreas and Garlock fault systems. The configuration of these lines in Idaho and Washington is from Armstrong, Taubeneck, and Hales (1977). The line $r_i = 0.7060$ marks the boundaries of ensialic crust and the seaward edge of late Precambrian and Paleozoic marine miogeosynclinal sedimentation along the Sierran terrane. The north-south trend of the edge of ancient continental crust in central Idaho and northern Nevada changes abruptly at about lat 38° N in central Nevada to westward, running into eastern California. At about long 120° W, the trend of the margin changes abruptly again to about north-south as far as the discontinuity between Sierran and Salinian-western Mojave terranes.

Lower Paleozoic strata in northern California, Oregon, and Idaho can be divided into three stratigraphic belts (Churkin, 1974). The western volcanic rock and graywacke belt occupies the region where the r_i of Mesozoic granitic rocks are less than 0.7040. The eastern belt of carbonate rock and quartzite occupies the region where r_i is greater than 0.7060. The central belt of graptolite shale and chert occupies the region where r_i of Mesozoic granitic rocks are between 0.7040 and 0.7060.

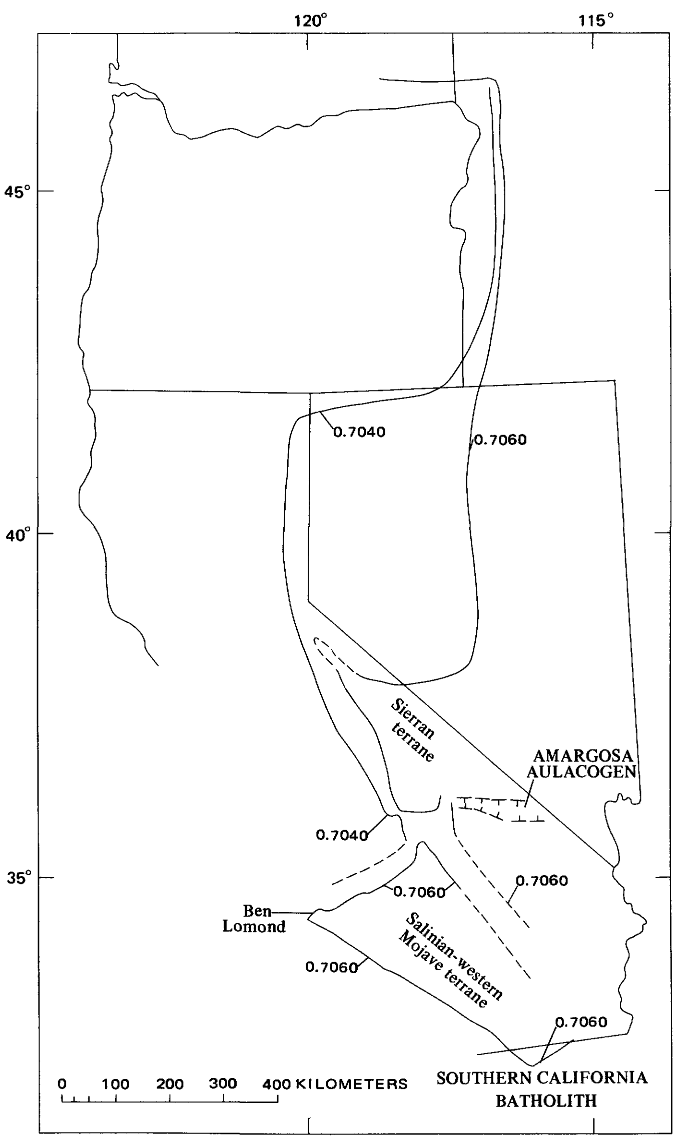

FIGURE 4.—Location and configurations of lines r_i = 0.7040 and 0.7060 in western United States. Displaced basement rocks along San Andreas and Garlock fault systems have been restored to positions shown in figure 3.

In the Mojave Desert, the geologic history of basement rocks and the record of Paleozoic sedimentation is only poorly known. This lack of knowledge is principally because of poor exposures of basement rocks and the poor fossil control in those rocks that are exposed. However, the remarkable correspondence between strontium isotopic ratios in Mesozoic granitic rocks and late Cenozoic mafic volcanic rocks and lower Paleozoic stratigraphy to the north suggests to us the following: the discontinuity between the Salinian-western Mojave and Sierran terranes defined by r_i between 0.7040 and 0.7060 in its Mesozoic granitic rocks is an indication of a Paleozoic sedimentation history in this discontinuity like that in the two belts of eugeosynclinal rocks to the north. If this postulate is correct, a puzzling exception in plate-tectonic models of Mesozoic igneous activity in California, Nevada, and Arizona can be resolved.

A locus of Jurassic magmatic activity along a northwest-southeast trend extends from southern Arizona to northwestern California and is crossed in the central Sierra Nevada by a locus of Cretaceous magmatic activity with a more northerly trend (Kistler and others, 1971, fig. 2; Kistler, 1974, fig. 2). These loci place older Mesozoic igneous rocks to the west of younger ones in Northern California and Nevada and younger Mesozoic igneous rocks to the west of older ones in southern California and Arizona. Of the many existing plate-tectonic models for the Mesozoic magmatic activity in California (Hamilton, 1969), none has accounted for the inland locus of Jurassic magmatism, extending from southern Arizona across the eastern Mojave Desert and into the Inyo-White Mountains in eastern California. In fact, the Jurassic magmatic activity in Arizona cuts the Precambrian craton and was hundreds of kilometers inland from the present continental margin. This fact led Kistler, Evernden, and Shaw (1971) to account for it as simply a locus of magmatism manifesting a linear zone of high heat flow in the mantle that had characteristics like present-day oceanic rises.

Continued geologic, geochronologic, and isotopic tracer studies have now identified other features associated with the inland locus of Jurassic magmatism. A zone of disruption that extends S 50° E from the southern Inyo Mountains into the Sierra Madre Occidental of Sonora offsets Precambrian crystalline rocks 1,725–1,800 m.y. old some 500 km in a left-lateral sense and lies along the locus of Jurassic magmatism; 700–800 km of left-lateral offset of Paleozoic depositional trends occurs near the same structure (Silver and Anderson, 1974). The discontinuity between the Sierran and Salinian-western Mojave terranes lies along the western margin of the Jurassic magmatic locus.

The apparent left-lateral shear zone identified by Silver and Anderson (1974) led these investigators to suggest that the locus of Jurassic magmatism marks the position of a former plate boundary. The coincidence of the discontinuity between the continental Sierran and Salinian-western Mojave terranes with the western margin of the Jurassic intrusive locus strengthens this concept.

Figure 4 shows the relative positions of the ensialic Salinian-western Mojave and Sierran terranes after removal of lateral displacements along the San Andreas and Garlock fault systems. Stewart and Poole (1975) have correlated two miogeosynclinal Precambrian and Paleozoic sections in the Salinian-western Mojave terrane with two similar stratigraphic sections in the Sierran terrane. This correlation requires that these two terranes have been in the same relative positions since the late Precambrian (Stewart and Poole, 1975). On the other hand, Silver and Anderson (1974) suggest a correlation of Precambrian and Paleozoic strata in the Sierran terrane with strata on the west side of the zone of disruption in the Precambrian basement about 800 km to the south. To us these differing interpretations indicate that individual stratigraphic sections do not uniquely define relative positions of deposition of sedimentary strata in the Cordilleran miogeosyncline. Apparent truncation and offset of ancient basement terrane, however, are provocative. Therefore, we tested where the Salinian-western Mojave terrane would lie in the early Mesozoic if its position shown in figure 4 resulted from a left-lateral displacement during the middle Mesozoic along the extension of the zone of disruption of Precambrian basement described by Silver and Anderson (1974). The position is shown in figure 5. Similar shapes and juxtaposition make it possible to speculate that the Salinian-western Mojave terrane once occupied the wide region between the $r_i = 0.7040$ and $r_i = 0.7060$ lines in northwestern Nevada.

We envision the configuration of the margin of continental crust, indicated by the line $r_i = 0.7060$ in the western United States (fig. 4), as developing in the following way. During the time of development of intracontinental basins that received the Belt Supergroup sediments, about 1,200 to 850 m.y. ago (Obradovich and Peterman, 1968), a true continental separation occurred along a locus now marked by the line $r_i = 0.7040$ (fig. 6A). Burke and Dewey (1973) propose a continental separation at this time, but their locus of separation is indicated to be well to the east of the line $r_i = 0.7040$. The western continental plate moved away, and its present location is unknown. This rifting event died out probably about 850 m.y. ago. Just prior to the Early Cambrian, rifting began again. The initial locus of the new separation is marked by the line $r_i = 0.7060$. In Washington and Idaho, the new locus of rifting coincided with the earlier locus and the lines $r_i = 0.7040$ and 0.7060 are essentially coincidental (Armstrong and others, 1977). In Nevada and California, the new locus of rifting extended into the continental terrane. As a consequence, the western plate consisted of both mafic lithosphere made 1,200–850 m.y. ago

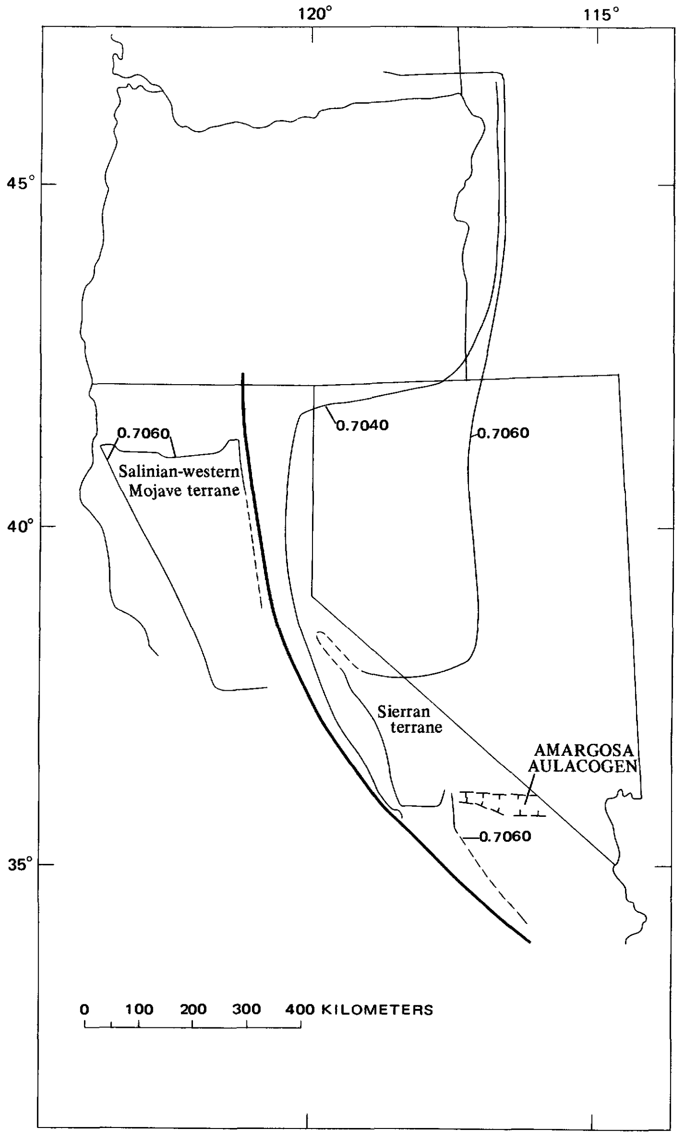

FIGURE 5.—Position of Salinian-western Mojave terrane after 800 km of left-lateral displacement is removed along extension of zone of dislocation in Precambrian basement described by Silver and Anderson (1974).

and older continental fragments, including the Salinian-western Mojave terrane (fig. 6*B*). During Mesozoic convergence along the western margin of North America, the continental fragments in the western plate were returned close to their former positions.

Accepting the rifting history as indicated in figure 6, material intruded into the rift zones would produce mafic (oceanic) lithosphere. We prefer to use the term mafic lithosphere because modern oceanic lithosphere is defined on the basis of seismic characteristics, and even though this ancient rift filling was probably oceanic crust, it is no longer identified as such seismically. This mantle-derived material would have different Rb, Sr, and r_i than the Precambrian lower continental crust. In the discussion that follows, we will show that the strontium isotopic systematics are compatible with deriving Mesozoic magmas west of the line r_i = 0.7060 from the lithosphere produced during the two rifting events in our model.

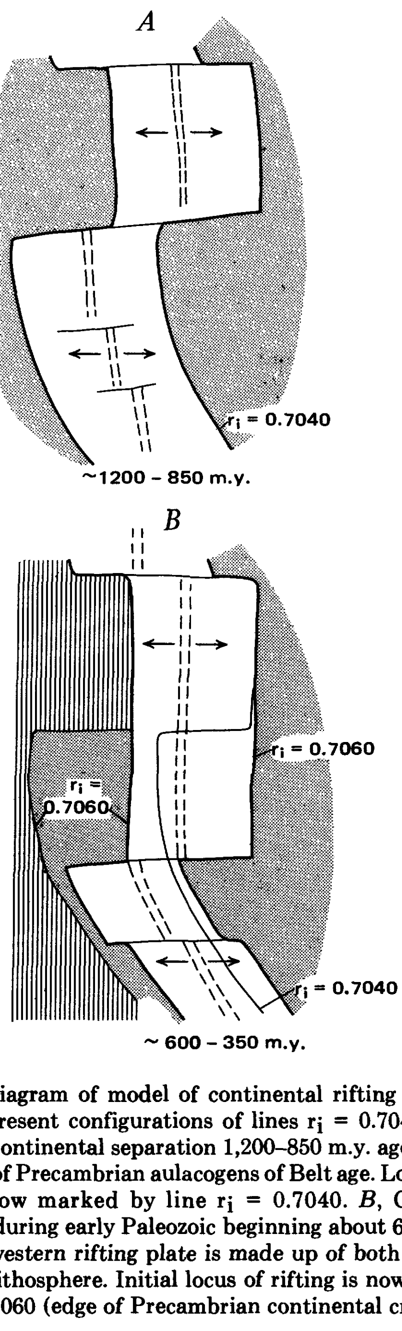

FIGURE 6.—Diagram of model of continental rifting used to account for present configurations of lines r_i = 0.7040 and r_i = 0.7060. *A*, Continental separation 1,200–850 m.y. ago during development of Precambrian aulacogens of Belt age. Locus of separation is now marked by line r_i = 0.7040. *B*, Continental separation during early Paleozoic beginning about 600 m.y. ago. Note that western rifting plate is made up of both continental and mafic lithosphere. Initial locus of rifting is now marked by line r_i = 0.7060 (edge of Precambrian continental crust).

TRACE ELEMENT VARIATIONS

Two values of r_i, 0.7040 and 0.7060, mark natural separations of Mesozoic granitic rocks in the Sierra Nevada into three types on K-Rb, K-Sr, and Rb/Sr-Rb variation diagrams (Kistler and Peterman, 1973). Using the alkali-lime index of classification of siliceous plutonic rocks (Peacock, 1931), calcic plutonic rocks have r_i less than 0.7060, and calc-alkalic granitic rocks have r_i values greater than 0.7060 (Kistler, 1974). Enough Rb, Sr, and r_i data now exist for California granitic rocks to make some general statements about elemental abundances in them relative to r_i.

Rubidium concentration and r_i (fig. 7) correlate in almost all the samples. For samples with r_i greater than 0.7040, Rb and SiO_2 are also positively correlated. Tie lines between some points join samples from mapped cogenetic granitic rock sequences. SiO_2 does not fall below 60 weight percent in the rocks investigated that have r_i greater than 0.7080 or below 55 weight percent in the rocks investigated that have r_i between 0.7040 and 0.7080. In granitic rocks with r_i greater than 0.7040, rubidium reaches a maximum concentration of about 200 ppm and the maximum SiO_2 content is about 75 weight percent. Three samples that plot in an anomalous position relative to other specimens with r_i less than 0.7040 are trondjhemites with SiO_2 that average 71 weight percent but contain lower Rb concentrations than any other specimens investigated.

Strontium concentration is plotted against r_i in figure 8 for each granitic rock specimen. Granitic rocks with r_i greater than 0.7060 have maximum values of about 800 ppm strontium in the most mafic specimens, and those with r_i less than 0.07060 have maximum values of about 650 ppm Sr in the most mafic specimens. Concentration of strontium in the most felsic rocks is about 100 ppm regardless of r_i.

When rubidium is plotted against strontium (fig. 9) for all granitic rocks investigated with r_i less than 0.7060 as well as for average oceanic basalts (Hart and others, 1970), points can be separated into three discrete groups. Points representing granitic rocks with r_i between 0.7030 and 0.7040 from the western Sierra Nevada lie along the oceanic basalt line and trend into

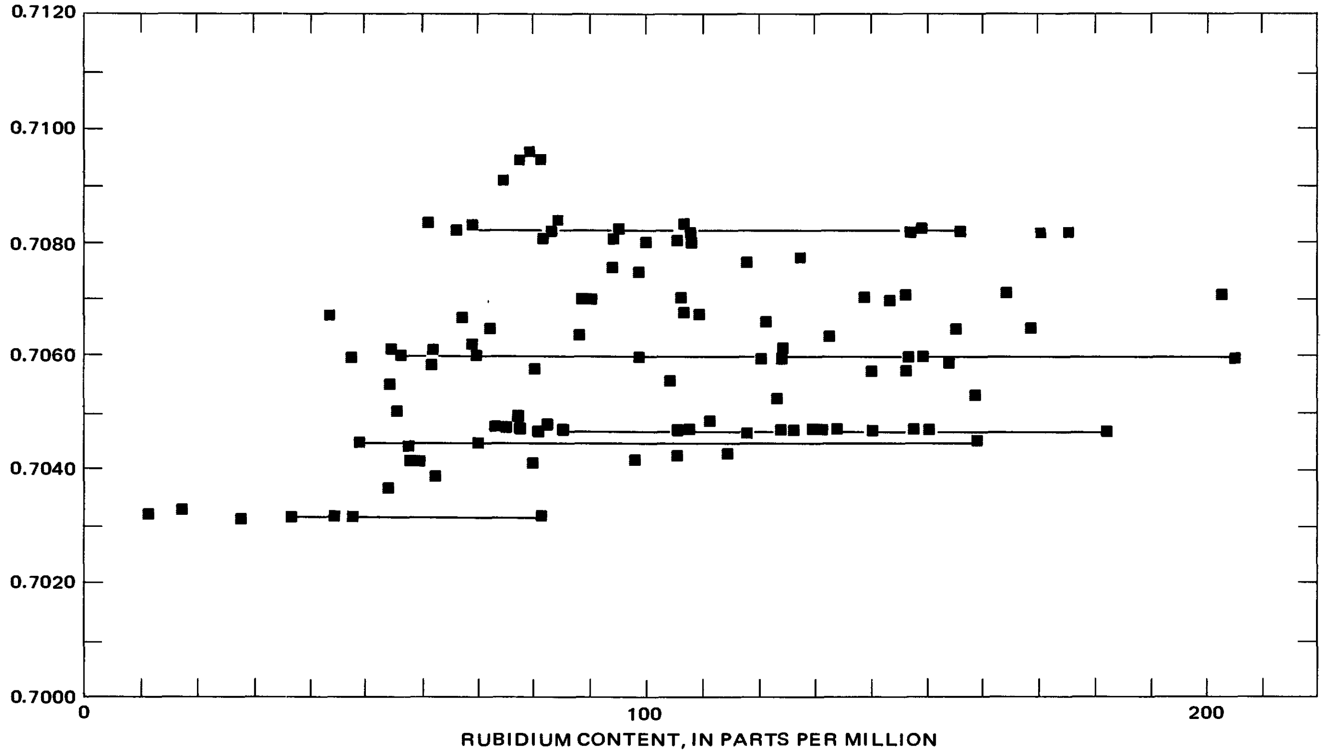

FIGURE 7.—Rb concentration plotted against initial $^{86}Sr/^{87}Sr$ values for specimens of Mesozoic granitic rocks in California. Lines join samples from mapped cogenetic granitic rock sequences.

the group of points representing Sierran granitic rocks with r_i between 0.7040 and 0.7060.Those specimens with Rb and Sr abundances equivalent to oceanic basalts are trondjhemites, and the others are tonalites.

Points representing other granitic rocks with r_i less than 0.7060 define two fields in figure 6. Granitic rock specimens from the southern California batholith, two specimens from the southern Sierra Nevada near Tehachapi, and the single specimen from Ben Lomond in the Salinian block lie in a field that does not overlap the field for granitic rocks in the Sierra Nevada with comparable r_i. The separation of granitic rocks into groups on the diagram that can have similar r_i but grossly different strontium concentration for any given rubidium concentration suggests that source materials for the southern California batholith and several of the granitic rocks in the southern Sierra Nevada had trace-element compositions different from the source materials that yielded granitic rocks with similar r_i in the Sierra Nevada. The difference could also reflect a different history for the source materials or simply result from a different depth of magma generation in a similar source. These granitic rocks lie at the south and north ends of the Salinian-western Mojave terrane.

Points representing granitic rocks with r_i greater than 0.7060 form a field that overlaps the field of granitic rocks in the Sierra Nevada with r_i between 0.7040 and 0.7060. These points are not shown in figure 9.

SOURCE MATERIALS FOR THE GRANITIC ROCKS

In order to account for the observed variation in r_i of Mesozoic granitic rocks north of the Garlock fault in California, Kistler and Peterman (1973) adopted a model in which the melts that resulted in the granitic rocks with r_i greater than 0.7060 were derived from a lower continental crust that acquired its chemical and isotopic characteristics about 1,700 m.y. ago and had a r_i of 0.7020 and Rb/Sr values that regionally varied between 0.06 and 0.10. If the source for the granitic rocks with r_i less than 0.7060 was assumed to have ac-

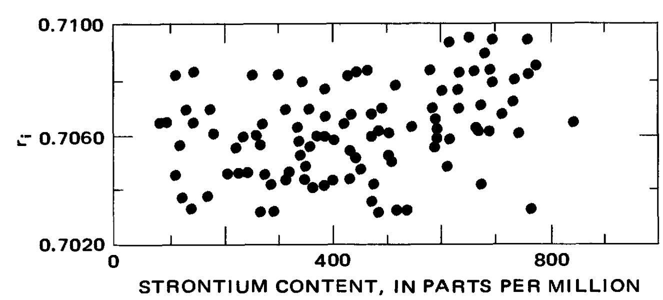

FIGURE 8.—Sr concentration plotted against r_i values for specimens of Mesozoic granitic rocks in California.

quired its Rb–Sr characteristics at the same time, the ratios required to produce the presently observed r_i variation range from 0.02 to 0.06. It was pointed out, however, that as the r_i values of the Mesozoic granitic rocks approach 0.7030, it becomes increasingly more difficult to decipher a possible pre-Mesozoic history for the source material on the basis of r_i data alone. We will refine our model for the pre-Mesozoic history of the source region for the Mesozoic granitic rocks with r_i less than 0.7060 on the basis of our model for development of the configuration of the western margin of ensialic crust (fig. 6).

We plotted Rb/Sr against r_i for Mesozoic granitic rocks in California (fig. 10). An isochron with r_i equals 0.7020 and 1,600-m.y. age (1,600 m.y. reference isochron used to account for the average 100 m.y. age of the granitic rocks investigated) is also shown on the diagram. With the data available only from the granitic rocks north of the Garlock fault (Kistler and Peterman, 1973), all points fell to the right of a 1,600-m.y. isochron on a similar diagram. This distribution was compatible with an increase in Rb/Sr in melts derived during partial melting and subsequent differentiation from a 1,600 m.y.-old source with $r_i = 0.7020$ and Rb/Sr between 0.02 and 0.10. The new data also fit this distribution except for two specimens with r_i greater than 0.7080. However, the most mafic specimens with r_i less than 0.7060 have Rb/Sr about twice that implied by the 1,600 m.y.-old source, and the most mafic specimens with r_i greater than 0.7060 have Rb/Sr only slightly higher than that implied by the source. We feel that these Rb/Sr differences are significant and bear on the history of the source materials for the granitic rocks.

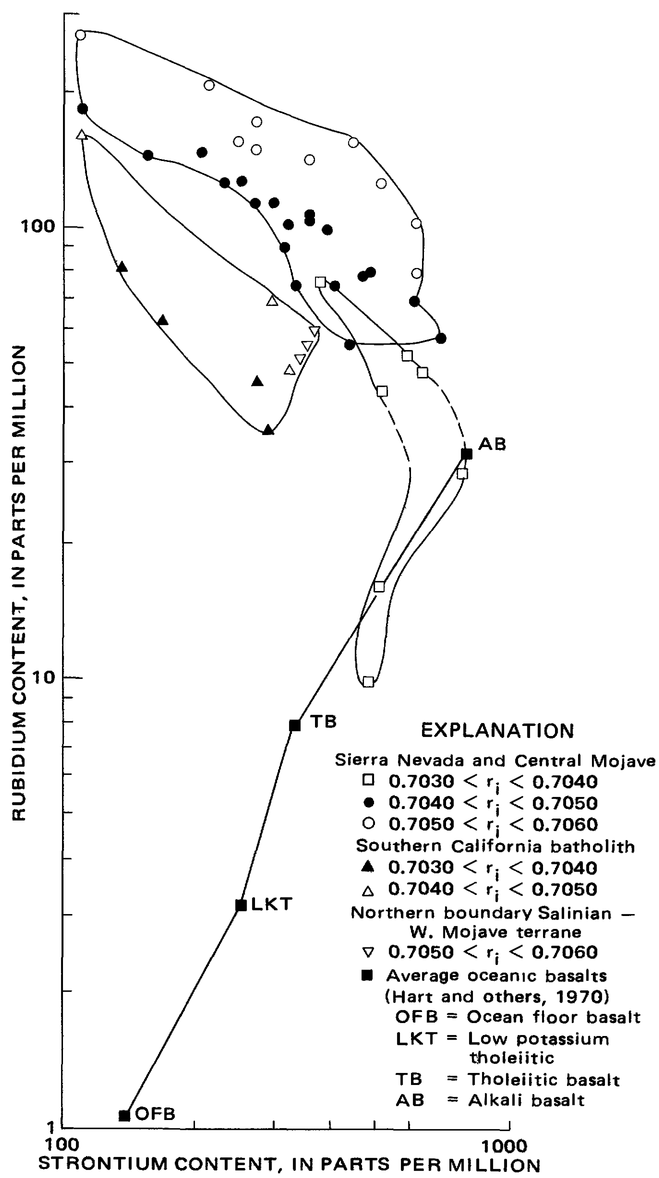

FIGURE 9.—Rubidium concentration relative to strontium concentration in California granitic rocks with r_i less than 0.7060.

If the source for all the Mesozoic granitic rocks in California formed 1,700 m.y. ago and had r_i of 0.7020 at that time, the relatively high values of Rb/Sr in the granitic rocks with r_i less than 0.7060 could be due to a lesser degree of partial melting of these source materials than the degree of partial melting of similar source material for granitic rocks with r_i greater than 0.7060. Rb/Sr is higher in the initial melt than in the granite source and would vary inversely with the degree of melting. However, in terms of major-element chemistry, granitic rocks with r_i less than 0.7060 are calcic, and those with r_i greater than 0.7060 are calc-alkalic (Kistler, 1974). This fact suggests that different abundances and ratios of large-ion lithophile elements in the groups of granitic rocks are due to processes other than degree of melting of similar sources, because lesser degrees of melting should, in terms of major elements, yield more alkalic rather than more calcic magmas. We will elaborate below.

Our model (fig. 6) indicates that the ensimatic lithosphere to the west of the Sierran terrane formed between about 600 and 350 m.y. ago. In figure 10, we have drawn a 500 m.y. isochron (500 m.y. isochron is used to account for the average 100 m.y. age of the granitic rocks investigated) with r_i of 0.7030. The r_i of 0.7030 was selected because this is the lowest measured by us in any Mesozoic and younger igneous rocks to the west of the 0.7060 line. All points for granitic rocks with r_i less than 0.7060 lie to the right of this isochron, a feature that is compatible with deriving the magmas represented by these granitic rocks from a source terrane about 600 m.y. old and characterized by Rb/Sr between 0.012 and 0.10. Granitic rocks with

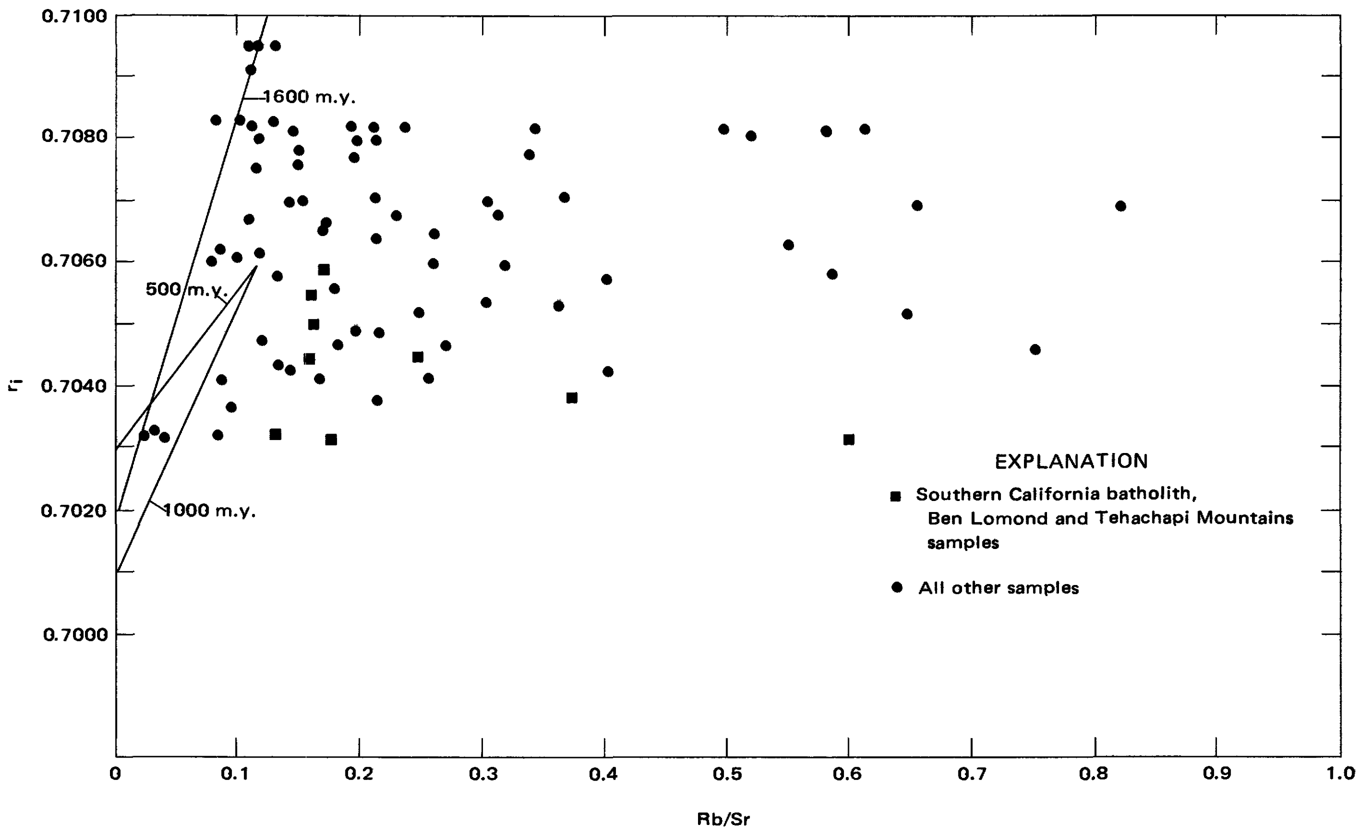

FIGURE 10.—Isochron plot for California granitic rocks. Rb/Sr plotted against r_i the 1,600-m.y., 1,100-m.y., and 500-m.y. isochrons shown for reference with regard to possible age of source material of granitic rocks as discussed in text.

r_i greater than 0.7060 could not be derived from a source terrane with these characteristics.

Southern California batholith specimens, located in an area extending south from the south edge of the Salinian-western Mojave terrane, and the four specimens with r_i less than 0.7060 along the north edge of the Salinian-western Mojave terrane (fig. 9), have generally lower Sr for any given Rb abundance than other California granitic rocks with equivalent r_i. This fact indicates that the source for these granitic rocks could have been depeleted in Sr relative to the source for the granitic rocks with similar r_i in the northern and western Sierra and in the eastern part of the discontinuity. The indicated depletion is compatible with a different source history and composition than that for the source of Sierran granitic rocks with similar r_i. The terrane into which these granitic rocks are intruded would be mafic lithosphere formed between 1,200 and 850 m.y. ago that became part of the western plate during the second rifting stage beginning in the Cambrian (fig. 6*B*). The lithosphere source material for these granitic rocks is older than that for granitic rocks with similar r_i in the Sierra Nevada, and it possibly formed with a r_i of around 0.7010. A 1,000-m.y. isochron (1,000-m.y. isochron used as an average age for the source) with this r_i lies close to the left of those points (shown as black squares in fig. 10) representing these granitic rocks.

SUMMARY AND CONCLUSIONS

Kistler, Evernden, and Shaw (1971) and Armstrong, Taubeneck, and Hales (1977) interpreted values of r_i greater than 0.7060 in Mesozoic granitic rocks in the western United States as being due to contamination of magmas with less radiogenic strontium by radiogenic strontium from the host rocks. We (Kistler and Peterman, 1973) tested the possibility of contamination by intruded wallrocks of granitic magmas for rocks with similar r_i and rejected the possibility. With the additional data available, including those of Armstrong, Taubeneck, and Hales (1977), we still reject contamination as a dominant cause of isotopic variation and consider variation in r_i as time dependent and reflecting Rb/Sr differences established much earlier in the source materials for the granitic magmas. Ages inferred for the source materials from the systematics of relation between Rb, Sr, and r_i in the granitic rocks are consistent with ages inferred for the sources from geologic considerations. This interpretation implies that the pattern of r_i of igneous rocks maps a lithosphere zone of melting, probably at a depth of 30 to 50 km, that intersects ancient crust of different ages and compositions.

An alternative to the constant depth zone of lithosphere melting to explain the variation in r_i has to be considered. The granitic rocks with r_i greater than 0.7060 also have the highest strontium concentrations (fig. 8). Partial melting of ensialic crust is not necessarily a unique source for increased Sr relative to partial melting of ensimatic crust. Also, a mixing model (mixed source, not mixed magmas) with basaltic (oceanic crust) and granitic (continental crust) end members should show a negative correlation between r_i and Sr. However, Hart and others (1970) showed a positive relation between depth to seismic zone and Sr concentration in overlying volcanic rocks in the major active subduction zones of the Pacific. Their model to account for this relationship utilized the concept of large-ion-lithophile "depleted" versus "undepleted" mantle as source materials for the eruptive magmas. The model could be modified to include "suboceanic" versus "subcontinental" mantle sources, and the depth aspect would not be ignored when the Sr contents of the samples most distant from the trench are so high. Even though the granitic rocks with high r_i are not alkalic, this may not be a discriminating factor. Many Cenozoic mafic lavas with high r_i are alkalic. With strontium concentration being a function of depth of melting, our major argument, the necessity of continental crust associated with the plutons having r_i greater than 0.7060 is unaffected. The r_i variation shows that the source yielding high–r_i magmas must have older and (or) higher Rb/Sr material than that yielding low–r_i magmas. Whether the r_i = 0.7060 contour reflects an "edge" or simply an intermediate degree of melting of the two end members that accomplished the same thing does not much affect the plate-tectonic interpretation. The low–r_i areas still reflect the contribution of the low–Rb/Sr end members and require some interpretation such as a rift that removed the high–Rb/Sr and (or) older parent. Both the constant-depth zone and variable-depth zone of lithosphere melting to account for the observed variation in r_i and Sr abundance in the Mesozoic granitic rocks in California are within regions of granitic magma generation considered possible according to experimental evidence summarized by Wylie, Huang, Stern, and Maaløe (1976).

The strontium isotope data support the concept of rifting of the western margin of North America during the time of Belt sedimentation (Burke and Dewey, 1973) and again at the inception of sedimentation in the Cordilleran geosyncline (Stewart, 1972; Churkin, 1974). Churkin's model of the early Paleozoic sedimentation history of western North America involves migration of frontal arc systems away from the continent and creation of interarc basins and marginal ocean basins that were sites of deposition of the sediments in the graptolite shale-chert belt. Churkin's concept requires the derivation of thick quartzite sequences in the graptolite shale-chert belt from the craton far to the east. The petrography and age of some of the quartzites in this belt have led other workers (Ketner, 1966; Gilluly and Gates, 1965) to deny the possibility of an eastern source and to appeal to an unknown continental source to the west to provide the materials for these units. Westward rifting of a continental fragment, possibly the Salinian-western Mojave terrane, from the area between lines r_i = 0.7040 and 0.7060 in northwestern Nevada and northeastern California beginning in the Cambrian (fig. 6*B*) would support the latter view.

Strontium-isotope studies of granite plutons have proved to be useful in tectonic studies. Investigations of possible offsets along transcurrent faults in the past have relied on apparent displacements of sedimentary rocks, because igneous and metamorphic basement rocks seldom have distinctive physical characteristics that can be correlated unequivocally over long distances. Current methods of classification of igneous rocks restrict their use as indicators of transcurrent fault displacement—granodiorites around the world look pretty much alike. However, in granodiorites investigated so far in California, r_i ranges from about 0.7040 to 0.7095. Strontium isotope ratios, therefore, provide an easily determined parameter in basement terrane with enough variation to test transcurrent offsets suggested by apparent displacement of superjacent sedimentary strata or other geologic features.

Our test of the suggestion of Silver and Anderson (1974), that a minimum of 500 km of left-lateral displacement during the middle Mesozoic occurred along the trend of the Jurassic locus of magmatism extending from California to Sonora, supports but does not prove the concept. We do not know where the locus of dislocation could be to the west of the Sierra Nevada nor its exact location in southern California; any or all of the faults in the Foothills fault system (Clark, 1960; Duffield and Sharp, 1975) are possible candidates in the Sierra Nevada. Clark (1960), Baird (1962), and Cebull (1972) have presented evidence for possible strike-slip displacement along the components of the Foothills fault system.

The model of two-stage rifting of the western margin of North America during the Precambrian and early Paleozoic not only helps to resolve the problem of source materials for quartzites in Paleozoic eugeosynclinal assemblages in northwestern Nevada and northern California but also helps to account for a sequence of lower Mesozoic quartzites, marbles, and pelitic schists exposed discontinuously in a belt of roof pendants in the western Sierra Nevada south of lat 38° N. The position of these rocks has been considered anomalous because they are separated from strata of similar age and lithology to the east by a belt of volcanic and sedimentary strata of similar age (Stanley and others, 1971). Source materials for the quartzite-carbonate sequence in the roof pendants would have to lie to the west, where none now exist. The western plate that encroached on North America during the early Mesozoic, however, was made up of both oceanic and continental material (fig. 6*B*). An ophiolite-melange sequence of Permian and Triassic age occurs in a belt parallel to and west of the western belt of lower Mesozoic sedimentary rock (Saleeby, 1975). This situation places the lower Mesozoic sedimentary rocks in the western belt in a trench of early Mesozoic age (Schweikert and Cowan, 1975). Continental fragments in the plate encroaching from the west would provide a source for the quartz sands in this sequence. The proposed minimum of 500 km of left-lateral middle Mesozoic disruption along this plate boundary (Silver and Anderson, 1974) would place the continental rocks of the western plate in a position that is now far to the south of the site of deposition of western belt lower Mesozoic sedimentary rocks.

Thus, the early Mesozoic trench associated with the converging plates lay to the east of the Salinian-western Mojave terrane and along the western margin of the Sierran terrane. Magmatic activity associated with this stage of convergence occurred along the northwest-southeast locus extending at least from northern California to south-central Arizona (Kistler and others, 1971). When continental parts of the western converging plate reached the trench, subduction was no longer possible. Continued convergence had to be relieved in a new trench developed to the west of the Salinian-western Mojave terrane, a trench now represented by Franciscan rocks. The late Mesozoic and Tertiary Great Valley sequence was deposited in the shadow of the Salinian-western Mojave terrane. The granitic rocks exposed discontinuously from Montara to Bodega Head (fig. 3) could have been brought to their apparently anomalous position west of the Great Valley sequence on the plate subducting beneath the Franciscan melange.

Our model (fig. 6) requires two stages of rifting of the western margin of North America and molds into compatibility modern tectonic theory and geologically determined sedimentation history. The configuration of the plate boundaries as indicated by the strontium isotopic pattern is a crucial factor in the development of the model. In addition, geochronologically determined magmatic history and isotope geochemistry permit a model to be developed for this same marginal configuration when it changed from accretionary to convergent. Reactivation of continental rift zones is apparently a common phenomenon (McConnell, 1972; Garson and Krs, 1976). A triple junction associated with continental rifting is inferred to be active now in southern Idaho (Prostka and Oriel, 1975), centered on the line r_i equals 0.7060. A geophysically defined axis of symmetry for the Great Basin (Eaton, 1976) extends from about lat 42° N to 34° N. The northern part of this axis lies near the line $r_i = 0.7060$, but the southern part is entirely in crust characterized by Mesozoic granitic rocks with r_i greater than 0.7060. If the axis is the locus of spreading under the Great Basin (Eaton, 1976), it is a modern analog of the rifting that occurred along the line $r_i = 0.7060$ prior to deposition in the Cordilleran geosyncline (fig.6*B*).

ROCK TYPE AND LOCALITY DESCRIPTION OF ROCKS INVESTIGATED

Sr 1–73 Hornblende quartz diorite, specimen locality 124 of Evernden and Kistler (1970).

Sr 2–73 Hornblende-bearing biotite quartz monzonite, specimen locality 125 of Evernden and Kistler (1970).

Sr 3–73 Foliated quartz diorite, 2.6 km east of Glennville on California Hwy. 155.

Sr 4–73 Sphene-bearing biotite-hornblende granodiorite, specimen locality 129 of Evernden and Kistler (1970).

Sr 5–73 Foliated biotite-hornblende granodiorite, specimen locality 130 of Evernden and Kistler (1970).

Sr 6–73 Porphyritic biotite quartz monzonite, 13.0 km south from junction of California Hwy. 178 on Kelso Valley Road.

Sr 8–73 Biotite quartz monzonite, 12.2 km south of locality Sr 6–73 on Kelso Valley Road.

Sr 9–73 Biotite quartz monzonite, on Jawbone Canyon Road, 5.5 km east of junction with Kelso Valley Road.

Sr 10–73 Biotite-hornblende granodiorite, on Jawbone Canyon Road, 12.6 km east of junction with Kelso Valley Road.

Sr 11–73 Biotite quartz monzonite, on California Hwy. 58, 18.7 km east of Mojave Calif. In small quarry on north side of road.

Sr 12–73 Biotite-hornblende quartz diorite, 17.4 km north of Willow Springs turnoff on Willow Springs-Tehachapi Road.

Sr 14–73 Biotite granodiorite, on road to Kern County Park, 3.2 km from park entrance.

Sr 15–73 Biotite-hornblende granodiorite, on California Hwy. 58, 13.2 km west of Tehachapi Railway Station.

Sr 16–73 Biotite quartz monzonite, first granitic rock outcrop on east side of Last Chance Canyon Road in El Paso Mountains. Triassic age for this granite (table 3) is from Armstrong and Suppe (1973).

Sr 17–73 Hornblende-biotite granodiorite, on county road, 1.2 km south of Randsburg, Calif.

Sr 18–73 Biotite quartz monzonite, 19.2 km north of junction with U.S. Hwy. 395 of county road, 0.4 km south of Johannesburg, Calif. on county road that intersects with California Hwy. 178.

Sr 19–73 Hornblende-biotite granodiorite, on road 2.3 km north of location of specimen Sr 18–73.

Sr 20–73 Foliated porphyritic biotite quartz monzonite, outcrop on east side of U.S. Hwy. 395 at Little Lake turnoff on road to lower Little Lake Ranch.

Cos 10–2 Biotite granodiorite, outcrop at center of south edge of sec. 10 T. 21 S., R. 38 E., Haiwee Reservoir, Calif. quadrangle.

Cos 13–42–2 Hornblende quartz diorite, outcrop in center of sec. 34, T. 21 S., R. 38 E., Haiwee Reservoir, Calif. quadrangle.

A3 Fine-grained porphyritic alaskite, outcrop at center of west edge of sec. 10, T. 30 S., R. 43 E., Cuddeback Lake, Calif. quadrangle.

A6 Sphene-bearing hornblende quartz diorite, outcrop on small hill, 0.4 km east of hill 3699 near center of north edge of T. 30 S., R. 44 E., Cuddeback Lake, Calif. quadrangle.

D15 Biotite-hornblende granodiorite, outcrop 305 m east of BM 2745 on Randsburg Road, Quail Mountains, Calif. quadrangle.

D16 Medium-grained biotite quartz monzonite, outcrop at 792 m on northwest-trending ridge in northeast corner of sec. 16, T. 17 N., R. 2 E., Quail Mountains, Calif. quadrangle.

E10 Biotite quartz monzonite, outcrop at Two Springs, Camp Irwin Military Reservation, Leach Lake, Calif. quadrangle.

E12 Medium-grained biotite quartz monzonite, outcrop at Desert King Spring, Camp Irwin Military Reservation, Leach Lake, Calif. quadrangle.

C–203 Gray biotite granite, outcrop at Black Magic Mines, Owlshead Mountains, Leach Lake, Calif. quadrangle.

C–204 Gray biotite granite, outcrop on hill 3342, Owlshead Mountains, Leach Lake, Calif. quadrangle.

C–201 Trachyandesite, outcrop on south edge near west corner of sec. 32, T. 19 N., R. 3 E., Leach Lake, Calif. quadrangle.

REFERENCES CITED

Anderson, D., 1971, The San Andreas fault: Scientific Am., v. 225, p. 51–67.

Armstrong, R.L., Taubeneck, W.H., and Hales, P.O., 1977, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition, Oregon, Washington, and Idaho: Geol. Soc. America Bull., v. 88, p. 397–411.

Armstrong, R.L., and Suppe, J., 1973, Potassium-argon geochronometry of Mesozoic igneous rocks in Nevada, Utah, and southern California: Geol. Soc. America Bull., v. 84, p. 1375–1392.

Baird, A.A., 1962, Superposed deformation in the central Sierra Nevada foothills east of the Mother Lode: California Univ. Pubs. Geol. Sci., v. 42, p. 1–70.

Burke, Kevin, and Dewey, J.F., 1973, Plume-generated triple junctions: Key indicators in applying plate tectonics to old rocks: Jour. Geology, v. 81, p. 406–433.

Cebull, S.E., 1972, Sense of displacement along foothills fault system: New evidence from the Melones fault zone, western Sierra Nevada, California: Geol. Soc. America Bull., v. 83, p. 1185–1190.

Churkin, Michael, Jr., 1974, Paleozoic marginal ocean basin-volcanic arc systems in the Cordilleran foldbelt, *in* Dott, R.H., Jr., and Shaver, R.H., eds., Modern and ancient geosynclinal sedimentation: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. no. 19, p. 174–192.

Clark, L.D., 1960, The foothills fault system, western Sierra Nevada metamorphic belt, California: Geol. Soc. America Bull., v. 71, p. 483–496.

Crowell, J.C., 1952, Probable large lateral displacement on the San Gabriel fault, southern California: Am. Assoc. Petroleum Geologists Bull., v. 36, p. 2026–2035.

______1968, Movement histories of faults in the Transverse Ranges and speculations of the tectonic history of California, *in* Dickinson, W.R., and Grantz, A., eds., Proceedings of the conference on geologic problems of the San Andreas fault system: Stanford Univ. Pubs. Geol. Sci., v. 11, p. 323–341.

Davis, G.A., and Burchfiel, B.C., 1973, Garlock fault: An intracontinental transform structure, southern California: Geol. Soc. America Bull., v. 84, p. 1407–1422.

Dibblee, T.W., Jr., 1960, Geology of the Rogers Lake and Kramer quadrangles, California: U.S. Geol. Survey Bull. 1089–B, p. 73–137.

______ 1968, Displacement of the San Andreas fault system in the San Gabriel, San Bernardino, and San Jacinto Mountains, southern California, *in* Dickinson, W.R., and Grantz, A., eds., Proceedings of the conference on geologic problems of the San Andreas fault system: Stanford Univ. Pubs. Geol. Sci., v. 11, p. 260–278.

______ 1972, Rinconada fault in southern Coast Ranges, California and its significance [abs.]: Am. Assoc. Petroleum Geologists Bull., v. 57, p. 432.

______ 1976, The Rinconada and related faults in the southern Coast Ranges, California, and their tectonic significance: U.S. Geol. Survey Prof. Paper 981, 55 p.

Duffield, W.A., and Sharp, R.V., 1975, Geology of the Sierra Foothills melange and adjacent areas, Amador County, California: U.S. Geol. Survey Prof. Paper 827, 30 p.

Early, T.O., and Silver, L.T., 1973, Rb-Sr isotopic systematics in the Peninsular ranges batholith of southern and Baja California [abs.]: EOS (Am. Geophys. Union Trans.), v. 54, p. 494.

Eaton, G.P., 1976, Fundamental bilateral symmetry of the western Basin and Range province: Geol. Soc. America Abs. with Progs., v. 8, p. 583–584.

Evernden, J.F., and Kistler, R.W., 1970, Chronology of emplacement of Mesozoic batholithic complexes in California and western Nevada: U.S. Geol. Survey Prof. Paper 623, 42 p.

Garfunkel, Zvi, 1974, Model for the late Cenozoic tectonic history of the Mojave Desert, California, and for its relation to adjacent regions: Geol. Soc. America Bull., v. 85, p. 1931–1944.

Garson, M.S., and Krs, M., 1976, Geophysical and geological evidence of the relationship of Red Sea transverse tectonics to ancient fractures: Geol. Soc. America Bull., v. 87, p. 169–181.

Gilluly, James, and Gates, Olcott, 1965, Tectonic and igneous geology of the northern Shoshone Range, Nevada: U.S. Geol. Survey Prof. Paper 465, 153 p.

Graham, S.A., 1975, Tertiary sedimentary tectonics of the central Salinian block of California [abs.]: Geol. Soc. America Abs. with Progs., v. 7, p. 1089.

Hamilton, Warren, 1969, Mesozoic California and the underflow of Pacific mantle: Geol. Soc. America Bull., v. 80, p. 2409–2430.

Hart, S.R., Brooks, C., Krogh, T.E., Davis, G.L., and Nava, D., 1970, Ancient and modern volcanic rocks—A trace element model: Earth and Planetary Sci. Letters, v. 10, p. 17–28.

Hoffman, Paul, Dewey, J.F., and Burke, Kevin, 1974, Aulacogens and their genetic relation to geosynclines, with a Proterozoic example from Great Slave Lake, Canada, *in* Dott, R.H., Jr., and Shaver, R.H., eds., Modern and ancient geosynclinal sedimentation: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. no. 19, p. 38–55.

Jennings, C.W., Burnett, J.L., and Troxel, B.W. (compilers), 1962, Trona sheet: Geologic map of California, O.P. Jenkins edition, California Div. Mines and Geology, scale 1:250,000.

Ketner, K.B., 1966, Comparison of Ordovician eugeosynclinal and miogeosynclinal quartzites of the Cordilleran geosyncline: U.S. Geol. Survey Prof. Paper 550–C, p. C54–C60.

Kistler, R.W., 1968, Potassium-argon ages of volcanic rocks in Nye and Esmeralda Counties, Nevada: Geol. Soc. America Mem. 110, p. 251–262.

——— 1974, Phanerozoic batholiths in western North America: A summary of some recent work on variations in time, space, chemistry and isotopic compositions: Earth and Planetary Sci. Letters Ann. Rev., v. 2, p. 403–418.

Kistler, R.W., Evernden, J.F., and Shaw, H.R., 1971, Sierra Nevada plutonic cycle—Part 1, Origin of composite granitic batholiths: Geol. Soc. America Bull., v. 82, p. 853–868.

Kistler, R.W., and Peterman, Z.E., 1973, Variations in Sr, Rb, K, Na, and initial Sr^{87}/Sr^{86} in Mesozoic granitic rocks and intruded wall rocks in central California: Geol. Soc. America Bull., v. 84, p. 3489–3512.

Kistler, R.W., Peterman, Z.E., Ross, D.C., and Gottfried, D., 1973, Strontium isotopes and the San Andreas fault, *in* Kovach, R.L., and Nur, Amos, eds., Proceedings of the conference on tectonic problems of the San Andreas fault system: Stanford Univ. Pubs. Geol. Sci., v. XIII, p. 339–347.

Le Conteur, P.C., and Templeman-Kluit, D.J., 1976, Rb-Sr ages and a profile of initial Sr^{87}/Sr^{86} ratios for plutonic rocks across the Yukon crystalline terrane: Canadian Jour. Earth Sci., v. 13, p. 319–330.

Mattinson, J. M., Hopson, C. A., and Davis, T. E., 1972, U-Pb studies of plutonic rocks of the Salinian block, California: Carnegie Inst. Washington Pub. Ann. Rept. 1972, p. 571–576.

McConnell, R. B., 1972, Geological development of the rift systems of Eastern Africa: Geol. Soc. America Bull., v. 83, p. 2549–2572.

Nilsen, T. H., and Clarke, S. H., Jr., 1975, Sedimentation and tectonics in the early Tertiary continental borderland of central California: U.S. Geol. Survey Prof. Paper 925, 64 p.

Obradovich, J. D., and Peterman, Z. E., 1968, Geochronology of the Belt Series, Montana: Canadian Jour. Earth Sci., v. 5, pt. 2, p. 737–747.

Oliver, H. W., 1977, Gravity and magnetic investigations of the Sierra Nevada batholith, California: Geol. Soc. America Bull., v. 88, p. 445–461.

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

Petö, P., and Armstrong, R. L., 1976, Strontium isotope study of the composite batholith between Princeton and Okanagan Lake: Canadian Jour. Earth Sci., v. 13, p. 1577–1583.

Poole, F. C., 1974, Flysch deposits of Antler foreland basin, western United States, *in* Dickinson, W. R., ed., Tectonics and sedimentation: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. no. 22, p. 58–82.

Prostka, H. J., and Oriel, S. S., 1975, Genetic models for Snake River Plain, Idaho [abs.]: Geol. Soc. America Abs. with Progs., v. 7, p. 1236.

Ross, D. C., 1976, Reconnaissance geologic map of pre-Cenozoic basement rocks, northern Santa Lucia Range, Monterey County, California: U.S. Geol. Survey Misc. Field Studies Map MF–750, scale 1:62,500.

Ross, D. C., and Brabb, E. E., 1973, Petrography and structural relations of granitic basement rocks in the Monterey Bay area, California: U.S. Geol. Survey Jour. Research, v. 1, p. 273–282.

Saleeby, J. B., 1975, Structure, petrology, and geochronology of the Kings-Kaweah mafic-ultramafic belt, southwestern Sierra Nevada foothills, California: California Univ., Santa Barbara, Ph.D, Thesis, 200 p.

Schweikert, R. A., and Cowan, D. S., 1975, Early Mesozoic tectonic evolution of the western Sierra Nevada, California: Geol. Soc. America Bull., v. 86, p. 1329–1336.

Silver, E. A., 1975, Geophysical studies and tectonic development of the continental margin of the western United States [abs.]: Geol. Soc. America Abs. with Progs., v. 7, p. 1273.

Silver, L. T., and Anderson, T. H., 1974, Possible left-lateral early to middle Mesozoic disruption of the southwestern North America craton margin [abs.]: Geol. Soc. America Abs. with Progs., v. 6, p. 955–956.

Smith, G. I., 1962, Large lateral displacement of Garlock fault, California, as measured from offset dike swarm: Am. Assoc. Petroleum Geologists Bull., v. 46, p. 85–104.

Stanley, K. O., Jordan, W. M., and Dott, R. H., Jr., 1971, New hypothesis of Early Jurassic paleogeography and sediment dispersal for western United States: Am. Assoc. Petroleum Geologists Bull., v. 55, p. 10–19.

Stewart, J. H., 1972, Initial deposits in the Cordilleran geosyncline: Evidence of a late Precambrian (850 m.y.) continental separation: Geol. Soc. America Bull., v. 83, p. 1345–1360.

Stewart, J. H., and Poole, F. G., 1975, Extension of the Cordilleran miogeosynclinal belt to the San Andreas fault, southern California: Geol. Soc. America Bull., v. 86, p. 205–212.

Troxel, B. W., Wright, L. A., and Jahns, R. H., 1972, Evidence for differential displacement along the Garlock fault zone, California [abs.]: Geol. Soc. America Abs. with Progs., v. 4, p. 250.

Wentworth, C. M., 1966, The Upper Cretaceous and lower Tertiary rocks of the Gualala area, northern Coast Ranges, California: Stanford, Calif., Stanford Univ., Ph.D. thesis, 197 p.

Wright, L. A., Troxel, B. W., Williams, E. G., Roberts, M. T., and Diehl, P. E., 1974, Precambrian sedimentary environments of the Death Valley region, eastern California, *in* Guidebook—Death Valley region, California and Nevada: Geol. Soc. America Cordilleran Sec. Mtg., p. 27–36.

Wylie, P. J., Huang, W.-L., Stern, C. R., and Maaløe, S., 1976, Granitic magmas: Possible and impossible sources, water contents, and crystallization sequences: Canadian Jour. Earth Sci., v. 13, p. 1007–1019.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1978-789-107/24