GRANITIC AND METAMORPHIC ROCKS OF THE SALINIAN BLOCK, CALIFORNIA COAST RANGES

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The Salinian block is an elongate segment of the Coast Ranges, characterized by a basement of granitic and high-grade metamorphic rocks. The granitic rocks have been dated as Cretaceous in a number of places (fig. 1), yet they nowhere intrude nor metamorphose older Franciscan rocks that lie against the block along the San Andreas and Sur faults. This interesting situation has led to several important hypotheses involving large-scale displacements on the east side of the block (Curtis, Evernden, and Lipson, 1958; Bailey, Irwin, and Jones, 1964). The west side, however, has remained a puzzle. Moreover, almost nothing has been written about the overall nature and history of the Salinian rocks themselves. Do the scattered basement exposures constitute one closely related suite of rocks? What tectonic histories do their structures suggest? How do the various absolute ages fit into this history? This paper presents a brief summary of data and ideas pertaining to these and related questions.

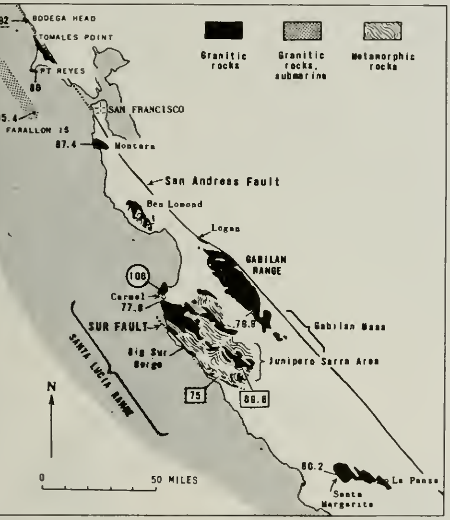

Figure 1. Index map of a central part of the Coast Ranges showing principal exposures of Salinian granitic and metamorphic rocks. Numbers are absolute ages in millions of years; those unmarked are from Curtis, Evernden, and Lipson (1958) recalculated to 1965 values of decay rates; the circled 106 is a nonisotopic Th-Pb age for monazite from Pacific Grove (Hutton, 1959, p. 20); the numbers in rectangles are unpublished K-Ar ages determined by John Obradovich (see table 1), and the underlined 92 is an unpublished K-Ar age determined by R. W. Kistler (see table 1). Submarine outcrop from Uchupi and Emery, 1963.

The writer's knowledge of the region is based on a fairly thorough study of the Junipero Serra area of the Santa Lucia Range, on far briefer studies in the Lucia quadrangle, the Santa Margarita-La Panza area, the north end of Gabilan Range, and the Ben Lomond area, and on reconnaissance of the other major exposures. Several geologists have kindly discussed areas and contributed data and thin sections from work in progress: Fred Berry and Edward Gribi (Gabilan Mesa), Oliver Bowen (Monterey quadrangle and northern Gabilan Range), Allan Galloway (Point Reyes-Tomales Bay area), Olaf Jenkins (Monterey-Gabilan Range area), G. W. Leo (Ben Lomond), Julius Schlocker (Bodega Head), and Robert Wiebe (northern Santa Lucia Range). John Obradovich, then at the University of California at Berkeley K-Ar laboratory, generously determined the ages of two biotites from the Junipero Serra area, and Garniss Curtis was helpful in providing these data for publication. Julius Schlocker also contributed a K-Ar age determined for him by R. W. Kistler of the U.S. Geological Survey. John Spotts' thin sections in the Stanford Mineralogy Collection proved invaluable, as did a number of thin sections borrowed from the collections of the University of California at Berkeley. The U.S. Forest Service and many private land owners were helpful with the field studies, and funds from the Shell Grant for Fundamental Research financed part of the field work as well as six new chemical analyses.

SANTA MARGARITA TO LA PANZA AREA

The most southerly major exposure of Salinian basement consists of adamellite that probably extends considerably beyond the 10- by 30-mile exposed tract. Samples from ten widely separated localities, studied in thin section and on large, stained slabs, have compositions close to: quartz, 30 percent; K-feldspar, 25 percent; calcic oligoclase, 35 percent; and biotite, 10 percent. K-feldspar phenocrysts are generally present and commonly are zoned and elongate parallel to the *a*-axis like those described by Lawson (1893) from the Carmel area. Small inclusions of fine-grained diorite occur widely, and in a few places adamellite

Table 1. Data for unpublished K-Ar age determinations on Salinian rocks.

Lab number	Field number	Mineral	Weight in grams	Percent K	Radiogenic Ar^{40} moles $\times 10^{-11}$	Percent atmospheric Ar^{40}	Age* (10^6 yr)
KA-585-I[1]	58-7[3]	biotite	0.5355	7.30	49.70	27	70.2
KA-585-II[1]	" [3]	biotite	0.4934	7.30	45.01	17	69.0
KA-586[1]	Cone Pk[4]	biotite	0.5754	7.14	55.90	21	75.0
KA-399[2]	JS-145BD[5]	hornblende	2.1515	0.83	30.30	13	92

* The constants used in calculations: $\lambda\xi = 0.584 \times 10^{-10} yr^{-1}$; $\lambda\beta = 4.72 \times 10^{-9} yr^{-1}$; moles K^{40}/moles K = 1.19×10^{-4}.
[1] Analyses by John Obradovich at University of California, Berkeley.
[2] Analysis by R. W. Kistler, U. S. Geological Survey.
[3] Quartz diorite near south border Junipero Serra pluton; Cone Peak quadrangle, T. 21 S., R. 5 E., 2,500 ft north and 400 ft east of SW corner sec. 12.
[4] Pyroxene-biotite-plagioclase granofels; summit of Cone Peak; for description and rock analysis see Compton (1960).
[5] Granodiorite collected by Julius Schlocker, U. S. Geological Survey, at Pacific Gas and Electric Co. atomic reactor site, Bodega Head, Sonoma County.

grades to quartz diorite around large gabbroic inclusions. Marbles, diaphthoritic schists, and biotite-orthoclase-andesine quartzites closely similar to Sur series relics in the Gabilan Range form inclusions as much as a mile long in the northeast part of the area. The inclusions have vague early lineations and distinct later folds that plunge at low angles to the northwest in some places and to the south or southeast in others. In the adamellite, these same trends are defined by complexly folded fabrics and by folded swarms of diorite inclusions which are themselves locally elongated parallel to the fold axes. Some granitic dikes have been recrystallized to give the same tectonite pattern (fig. 2).

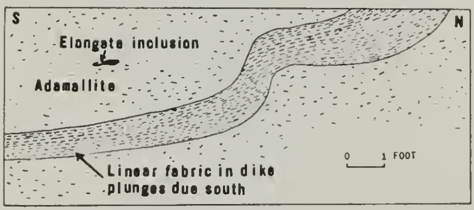

Figure 2. Granitic dike with strongly linear fabric as exposed in vertical cut on Black Mountain road, 1½ miles northwest of Navaja Road summit. The dike strikes due west.

Petrofabric diagrams of biotite from two localities in adamellite show two fabric axes: One parallel to the northwest-plunging fold axes and an earlier one at about right angles to them (fig. 3). Under the microscope, the biotites form complex groups, some of which are folded; yet textures are not protoclastic and plagioclase grains are subhedral and show oscillatory zoning. These various relationships suggest the adamellite was deformed at a very late magmatic stage but under highly insulated conditions. If it was deformed in two episodes, they must have succeeded each other closely, or else the rock body remained hot for a long time.

JUNIPERO SERRA AREA

This sector of Santa Lucia Range is underlain largely by high-grade metamorphic rocks that can be traced northwest to the type area of the Sur series designated by Trask (1926). In the area the writer has mapped in detail (fig. 4) they are mainly biotite-feldspar quartzites and quartzo-feldspathic granofelses and gneisses, with many layers of calc-silicate granofelses, amphibolites, aluminous schists, calcite marbles, and metadolomites. Judged from their present associations and bulk compositions, roughly 70 percent of the original sedimentary rocks were feldspathic or argillaceous sandstones and siltstones; 10 percent were silty, argillaceous limestones and dolomites; 10 percent were Ca-poor claystones; 5 percent were nearly pure limestones and dolomites, and 5 percent were very quartzose sandstones. That many of the quartzo-feldspathic rocks were originally calcareous or dolomitic is indicated by their abundant calcic to intermediate plagioclase, as well as by the intricately interlayered calc-silicate rocks. Some associations of the quartzites and

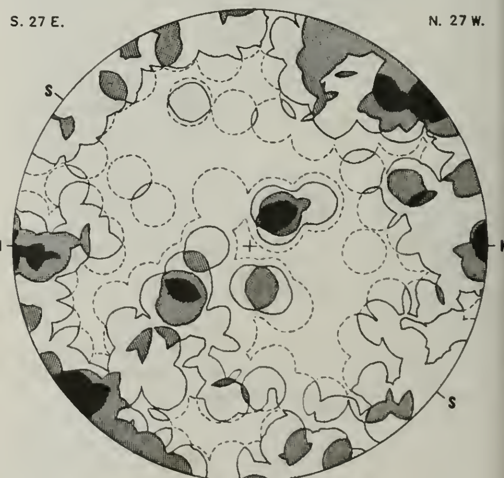

Figure 3. Petrofabric diagram of poles to cleavage in 200 biotite grains, corrected for *Schnitteffekt*. Contours at 3, 2, 1, and 0.5 percent per 1 percent of area. Thin section cut perpendicular to one lineation and parallel to second. *HH*, horizontal; *SS*, principal foliation. Adamellite on Highway 178, ½ mile west of La Panza.

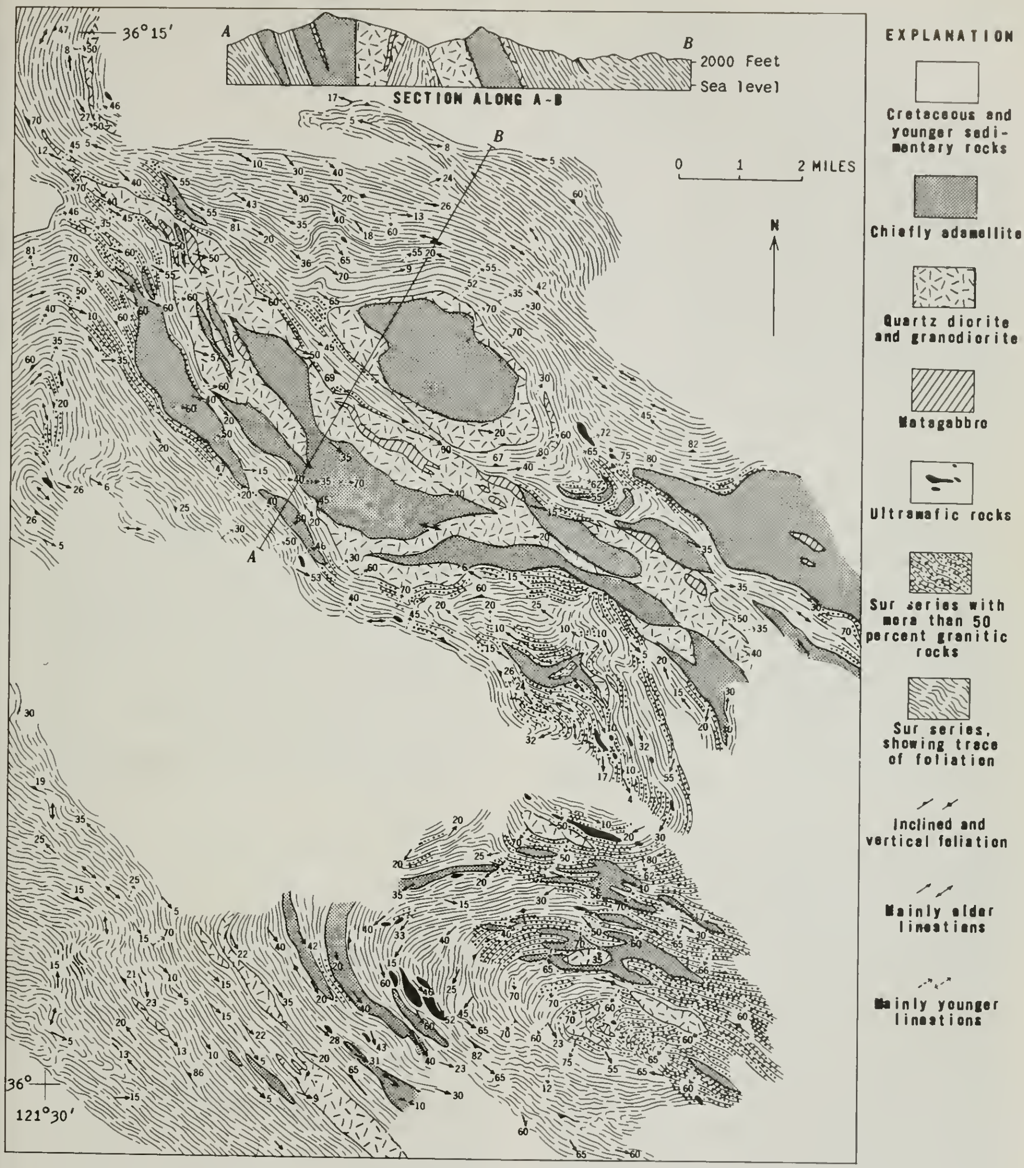

Figure 4. Basement rocks and structures of the Junipero Serro 15′ quadrangle and surroundings. The main figure is a horizontal section at 2,000 feet altitude.

Table 2. Chemical analyses of Salinian plutonic rocks.

	1 Pyroxe-nite	2 Horn-blendite	3 Quartz diorite	4 Grano-diorite	5 Adamel-lite	6 Granite	7 Gabbro	8 Gabbro	9 Biotite diorite	10 Quartz diorite
SiO_2	47.82	53.04	55.85	71.74	71.90	73.65	46.23	49 26	58.44	63.12
TiO_2	0.56	0.61	1.19	0.42	0.45	0.16	tr	tr	0.15	tr
Al_2O_3	5.10	9.98	19.64	13.46	14.76	13.86	18.29	16.88	17.06	16.13
Fe_2O_3	1.03	1.20	1.70	1.52	0.06	0.35	6.55	6.49	1.36	3.53
FeO	8.45	7.30	5.59	2.03	1.55	0.79	7.07	6.94	5.06	3.65
MnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.12	0.61	0.50	0.38
MgO	20.43	13.58	2.38	0.94	0.63	0.43	7.04	4.80	2.96	1.86
CaO	14.57	10.53	6.29	2.22	2.11	0.82	9.99	7.58	5.82	5.04
BaO	n.d.	n.d.	0.026	0.016	0.053	0.10	n.d.	0	n.d.	n.d.
Na_2O	0.53	1.08	4.64	3.35	3.10	1.92	3.07	3.41	3.40	2.78
K_2O	0.11	0.36	1.32	3.30	4.50	6.79	0.79	0.72	2.84	1.08
H_2O^+	1.12	1.04	1.01	0.69	0.43	0.26	1.02	2.90	2.12	0.93
H_2O^-	0.26	0.46	0.31	0.33	0.16	0.25	0.05	0.41	0.38	0.97
Cr_2O_3	0.22	0.19	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
$NiO+CoO$	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	tr	0.05	n.d.	n.d.
SrO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	tr	tr	n.d.	0.03
P_2O_5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.21	0.34	1.41	0.39
S	0.11	0.32	n.d.	n.d.	n.d.	n.d.	tr	tr	n.d.	n.d.
F	tr	0.050	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cl	0.007	0.007	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.317	99.747	99.946	100.016	99.703	99.38	100.43	100.39	101.50	99.89

1. Olivine-hornblende pyroxenite (CP-8-68A). Cone Peak quadrangle; T. 22 S., R. 5 E.; 930 ft south and 1,920 ft east of NE cor. sec. 14. Analysis by Morito Chiba. Mode, in percent by volume: augite, 45; hornblende, 21; olivine, 15; hypersthene, 14.5; plagioclase, 4; calcite, 0.2.
2. Plagioclase-pyroxene-hornblende rock (BC-3-32B). Bear Canyon quadrangle; T. 21 S., R. 6 E., 3,600 ft north and 1,930 ft east of SW cor. sec. 32. Analysis by Morito Chiba. Mode, in percent by volume: hornblende, 51; plagioclase, 15.5; augite, 11.5; quartz, 8.5; hypersthene, 6; biotite, 6; pyrrhotite, 1; apatite, 0.3; rutile, 0.1.
3. Quartz diorite (CP-2-1). Cone Peak quadrangle; T. 21 S., R. 5 E., 3,900 ft north and 600 ft west of SE cor. sec. 11. Analysis by Morito Chiba. Mode, in percent by volume: plagioclase, 64; biotite, 16; quartz, 10; hornblende, 9; sphene, 0.5; apatite, 0.3; pyrite, 0.2.
4. Granodiorite (JSP-6-2). Junipero Serra Peak quadrangle; 700 ft south and 860 ft west of NE cor. sec. 11. Analysis by Morito Chiba. Mode, in percent by volume: plagioclase, 42.5; quartz, 29.2; K-feldspar, 19.2; biotite, 9.
5. Adamellite (JS-1). Junipero Serra Peak quadrangle; T. 20 S., R. 5 E., 950 ft north and 1,580 ft east of SE cor. sec. 34. Analysis by Morito Chiba. Mode, in percent by volume: K-feldspar, 38; plagioclase, 31; quartz, 26; biotite, 4; ilmenite, 1.
6. Granite (BC-1-4C). Bear Canyon quadrangle; T. 21 S., R. 6 E.; 3,320 ft south and 320 ft east of NE cor. sec. 16. Analysis by Morito Chiba. Mode, in percent by volume: K-feldspar, 49; quartz, 28.5; plagioclase, 17; biotite, 5.4.
7. Hornblende gabbro ("diorite") occurring as fine-grained inclusions in coarser quartz-bearing rocks, Pajaro (Logan) quarry. Analysis by J. A. Reid. Mode: roughly equal amounts of labradorite and hornblende, with accessory opaques and apatite (Reid, 1902).
8. Hornblende gabbro ("diorite"); same locality and analyst as 7. Mode: chiefly labradorite and hornblende, with accessory opaques, apatite, biotite, and quartz (Reid, 1902).
9. Biotite diorite from south end of Bodega peninsula. Analysis by V. C. Osmont. Mode: roughly equal amounts of biotite and andesine, with accessory apatite, opaques, sphene, and appreciable "decomposition products" (Osmont, 1905).
10. Quartz-biotite diorite; same locality and analyst as 9. Mode: chiefly andesine and biotite, with quartz, hornblende, and orthoclase, and accessory apatite and sphene (plus "decomposition products") (Osmont, 1905).

marbles suggest metamorphosed platform-type sediments, for the marbles are locally phosphatic, the quartzites contain abundant rounded zircon grains, and the contacts between quartzites and marbles are sharp. The bulk compositions of the quartzo-feldspathic rocks, and their large detrital zircons, suggest a granitic source for a large share of the sediments.

Only one marble and one quartzite unit proved thick and distinctive enough to be mapped readily across the brushy terrain; they are shown by sets of parallel lines in the northern part of figure 4. In all distinctly layered rocks, metamorphic foliations are generally parallel to compositional layers that may be relict sedimentary beds. Outside of the rounded zircon grains, however, there are no convincing relics of sedimentary grains or structures, so that stratigraphic sequence is as yet undetermined.

Grain sizes average 1–2 mm in quartzo-feldspathic rocks and 4–8 mm in marbles (except for those affected by late granulation and recrystallization). Locally, quartzites have grains 1–2 cm in diameter and marbles are as coarse as 4–8 cm—attesting to prolonged crystallization or to unusually mobile conditions of crystallization.

The abundant biotitic quartzites and gneisses give a misleading impression of moderate metamorphic grade, but aluminous rocks are sillimanite-garnet-cordierite-orthoclase schists and gneisses; basic rocks are hornblende-andesine granofelses, locally with clinopyroxene and hypersthene; most calc-silicate rocks contain abundant clinopyroxene and meionitic scapolite as well as accessory orthoclase, and wollastonitic schists occur in several places. These mineral assemblages are of highest grade amphibolite facies and locally granulite facies. The granulite facies rocks define a broad, crude metamorphic zoning: they are most abundant in the southwest part of the area, occur here and there in the central part, and are wholly missing in the northern part. The granulite facies rocks commonly form irregular to tabular, coarse veins cutting through amphibolite facies rocks—suggesting they formed where water was lost along fracture systems (Compton, 1960). In the southwest part of the area, the rather common occurrence of dolomitic marbles without periclase and of meionitic scapolite rather than calcic plagioclase indicate that pressures outside of the fracture systems were so high as to inhibit reactions producing free CO_2.

Granitic veins and dikes make up 5 to 15 percent of most outcrops and average over 50 percent throughout large areas. The granitic bodies range from nebulous spots to dikes and lenses 100 ft thick. Their compositions are closely correlative with the rocks in which they occur. Diorite veins and dikes occur only in mafic metagabbro and ultramafic bodies, while quartz diorite and calcic granodiorite veins occur only in quartzo-feldspathic rocks containing little if any K-feldspar. Small adamellite bodies occur in rocks containing both feldspars, but coarse-grained dikes and dilative lenses of adamellite may cut through all kinds of metamorphic rocks. Potassic granite veins and dikes, some coarse-grained and intrusive, occur only in and near Ca-poor schists (no. 6, table 2). Significantly, the specific gravities of ten samples of schists associated with these granites range from 2.81 to 3.16 and average 2.95. In three samples, spinel or corundum grains lie only a few millimeters from granitic veins. Considered along with the correlation of vein and host-rock compositions, these data indicate the various veins were segregated from their hosts. The intrusive adamellite and granite dikes are probably partial melts from the Sur series, for they may occur far from any of the major intrusive bodies and are texturally and mineralogically different from rocks of these major bodies.

The rocks were folded strongly twice. The earlier folds generally have subhorizontal axes and are commonly isoclinal (fig. 5). Coarse adamellite and granite were locally emplaced during the folding (fig. 6), and high-temperature minerals such as sillimanite lie roughly parallel to fold axes. Lineations tend to steepen near the main granitic bodies, for example in the northwest part of figure 4. Possibly this resulted from solid flowage consequent on intrusion of the plutonic bodies.

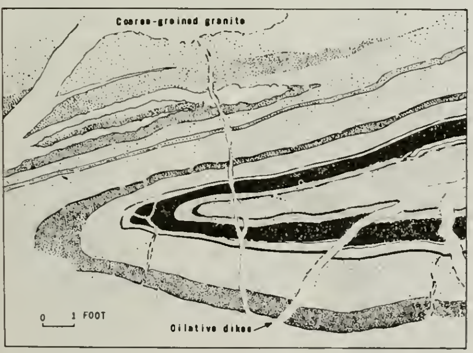

Figure 5. Recumbent folds and granite dikes in layered granofelses consisting of various proportions of hornblende, plagioclase, and clinopyroxene. Sketched from exposure in vertical roadcut near Escondido Camp, 5 miles west of Junipero Serra Peak.

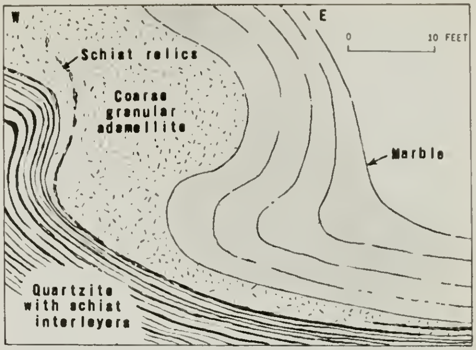

Figure 6. Coarse-grained adamellite intruded between marble and quartzite layers during first folding of Sur series. View is approximately along fold axes. Sketched from exposure on vertical canyon wall, 5½ miles west-northwest of Junipero Serra Peak.

The second folding repeated the stratiform rocks across the southern part of the area in a series of broad loops which have steeply plunging axes. The earlier lineations were rotated around these folds. New mineral lineations were formed but are restricted to sectors near plutonic bodies, indicating that the plutons supplied the heat required for pronounced recrystallization during this folding. Because lineations of the first folding are imprinted in several of the plutonic bodies, the two deformations were closely spaced in time or else the plutons were emplaced and crystallized over a long period.

The plutonic bodies themselves are three-fourths granitic rocks but may include rocks ranging from peridotite to granite. The largest and most complexly composite is 2½ miles wide and more than 16 miles long. All the bodies have curving contacts that tend to parallel the second folds in the Sur series, and many of the quartz diorites are lineated parallel to the earlier lineations in adjoining metamorphic rocks. Where distinct, the lineations consist of elongate biotite flakes and linear clusters of biotite grains. Petrofabric diagrams show parallel plagioclase lineations (fig. 7). Because these fabrics are far more distinct in the outer parts of the plutons, they are judged to have formed when the plutons were still partly molten. Even the last emplaced and most massive of the plutonic units, the adamellite that forms the central part of the main pluton, has vague elongate biotite clusters with tectonite fabrics.

The numerous ultramafic bodies are especially interesting because they were emplaced at various times during plutonism. Those with granoblastic textures, granulite facies mineral assemblages, and lineations parallel to the older fold axes are judged to be the oldest plutonic rocks in the area. At the other extreme,

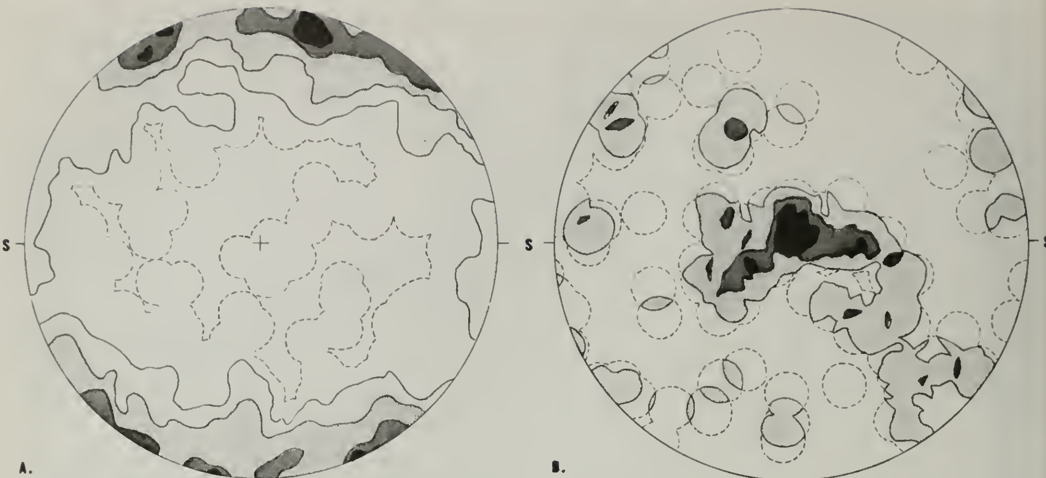

Figure 7. Petrofabric diagrams of quartz diorite sectioned approximately at right angles to megascopic lineation that is parallel to first fold axes of Sur series. A, Poles to cleavage in 500 biotite grains, corrected for *Schnitteffekt;* contours at 4, 3, 2, 1, and 0.2 percent per 1 percent of area. B, X optic axes (approximately parallel to a crystallographic axes) of 100 andesine grains in same thin section as A; contours at 6, 4, 2, and 1 percent per 1 percent of area. SS, biotite foliation. Sample from San Antonio River narrows, 7½ miles southeast of Junipero Serra Peak.

several bodies in the northeast part of the area are serpentinized peridotites similar to other Coast Range serpentinites except for containing appreciable amphiboles, chlorite, and talc. These bodies were presumably emplaced during the waning stages of the metamorphism. Bodies of intermediate age are most abundant and consist of coarse to very coarse inner zones of olivine-hornblende-pyroxene rocks (no. 1, table 2) and outer zones of amphibolites or pyroxene-hornblende rocks bearing appreciable plagioclase, biotite, and quartz (no. 2, table 2). The zonal arrangements, the unusual compositions, and the appreciable content of Cr_2O_3 indicate the bodies originated by mixing of peridotite with materials from the metamorphic rocks, possibly anatectic magma.

Gabbros, recrystallized almost totally to plagioclase-hornblende rocks, probably once formed sizable bodies but are now reduced to a few large relics and to hosts of dark inclusions in subsequent quartz diorite intrusions. The earlier granitic rocks are typically heterogeneous and range from rather basic quartz diorite (no. 3, table 2) to granodiorite with only 10 percent of biotite. All are allotriomorphic, have plagioclase (andesine) that is unzoned and commonly antiperthitic, and carry mafic minerals in clusters rather than simple grains (photo 1). A complex history of recrystallization is further indicated by the tectonite fabrics already mentioned and by a small relic of charnockitic (hypersthene-garnet) quartz diorite in normal quartz diorite near the southern contact of the main pluton.

Most of the adamellite was intruded subsequently, for it forms dilative dikes in the more basic rocks in many places. The youngest and most massive of the adamellites is rather fine-grained and porphyritic (no. 5, table 2). Heterogeneous gneissoid adamellites, locally garnetiferous, occur in mixed zones with granodiorite near the borders of the main pluton (no. 4, table 2).

That the larger plutons are intrusive is indicated by the diking effects of their constituent rocks and by their fairly distinct outer contacts. The northeast and southwest contacts of the main pluton dip distinctly toward one another (sec. A-B, fig. 4), and the con-

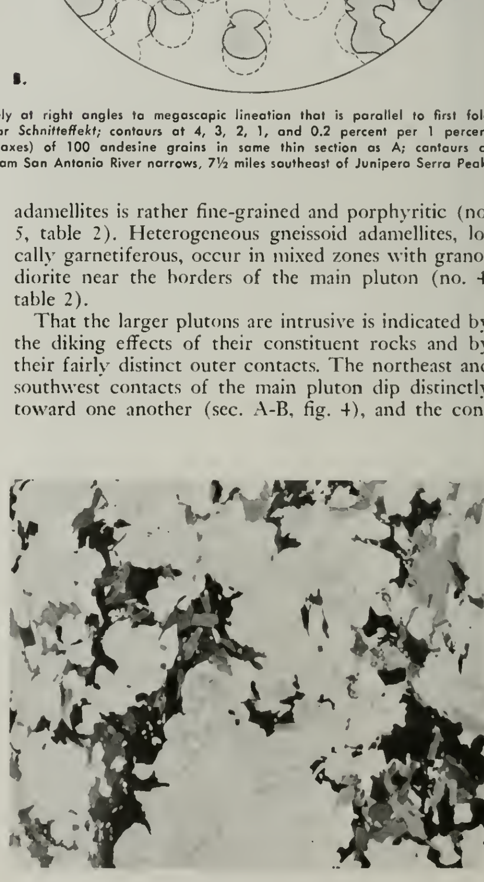

Photo 1. Photomicrograph of typical allotriomorphic quartz diorite of Junipero Serra area, showing clustered biotite grains. View is 12 mm across. Plane polarized light.

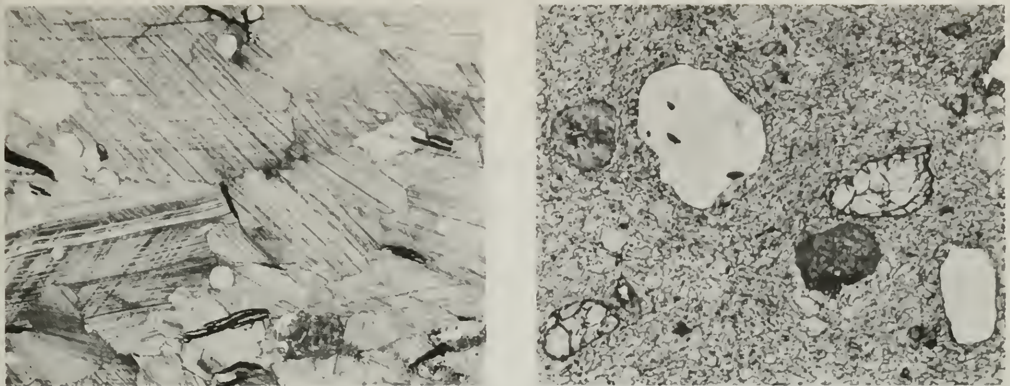

Photo 2. Photomicrographs of Sur marble. *Left,* strongly twinned calcite grains with black graphite tablets and equidimensional, white grains of apatite and K-feldspar. *Right,* recrystallized fine-grained calcite with large relics of K-feldspar (white), clinopyroxene (lined), and altered meionitic scapolite (dark gray). Views are 6 mm across. Plane polarized light.

tacts of the other mapped bodies either converge downward or are parallel. This geometric relationship suggests the exposed level was once in the deep root-zone of one or more plutons—a view supported by the high-grade metamorphism of the Sur series and the abundance of segregated granitic dikes and veins. Possibly, the plutons themselves arose in part as melts from underlying metamorphic rocks.

Following the second folding and the last of the plutonic intrusions, the rocks were uplifted and eroded, and by Late Cretaceous (Campanian) time fossiliferous marine strata were deposited on them. Considering the magnitude of this uplift, post-granite deformational structures are surprizingly localized. The marbles appear to have taken up most of the movement within the rock mass, for they are rather commonly crushed or recrystallized, with abundant $\{01\bar{1}2\}$ twin lamellae (photo 2). Stress analyses of strongly twinned calcite grains, based on methods described by Turner and Weiss (1963), suggest that maximum compressive stresses were aligned so as to plunge steeply to moderately toward the southwest quadrant. Quartz deformation lamellae in a quartzo-feldspathic blastomylonite indicate a similar stress orientation. Minor folds in this blastomylonite are subhorizontal and trend northwest.

NORTHERN SANTA LUCIA RANGE

The Sur series metamorphic rocks that occur widely in the northern part of Santa Lucia Range show a fairly pronounced geographic variation from the coast inland. Marbles and calc-silicate rocks are abundant along the coastal ridge but fall off toward the east, so that the northeast ridge of the range consists almost entirely of quartz-rich metasediments (Fiedler, 1944, p. 182). The scarce marble lenses in the northeast half of the range are relatively pure and in sharp contact with quartzose rocks, much as in the Junipero Serra area. Graphitic quartzites and schists, which occur only locally in the Junipero Serra area, are more common in the northern part of the range (Trask, 1926; Reiche, 1937).

Metamorphic mineral assemblages of the coastal ridge as far north as Big Sur gorge are of highest grade amphibolite facies and locally of granulite facies. To the north and northeast, the rocks tend to be finer grained and are probably entirely of amphibolite facies. The distribution of veins and dikes emphasizes this pattern: to the west, minor granitic bodies are abundant and are much like those of the Junipero Serra area (Trask, 1926, p. 129), whereas the northeast ridge of the range exposes few of them (Fiedler, 1944, p. 185).

All earlier workers noted folds in the Sur series but apparently considered them unimportant. The writer has observed northwest-trending minor folds and mineral lineations along the coastal ridge as far north as Big Sur gorge, and Robert Wiebe (oral communication, 1965) has mapped well-developed subhorizontal lineations that have been refolded in the area northeast of Big Sur gorge. Judged from Wiebe's work and rather scant data on published maps, metamorphic foliations generally strike northwest, parallel to the range, but are folded sharply around some plutons. Major steep-axis convolutions like those of the Junipero Serra area are apparently absent, except possibly at the north end of the range, where Bowen (oral communication, 1965) has mapped a broad northeast trend in the Sur rocks.

Granitic rocks form about half the basement in the north part of the Santa Lucia Range. The individual bodies continue elongate and narrow for 10 to 15 miles north of the Junipero Serra area but then gradually merge so as to form a single mass at least 10 miles wide at the north end of the range. Textures change

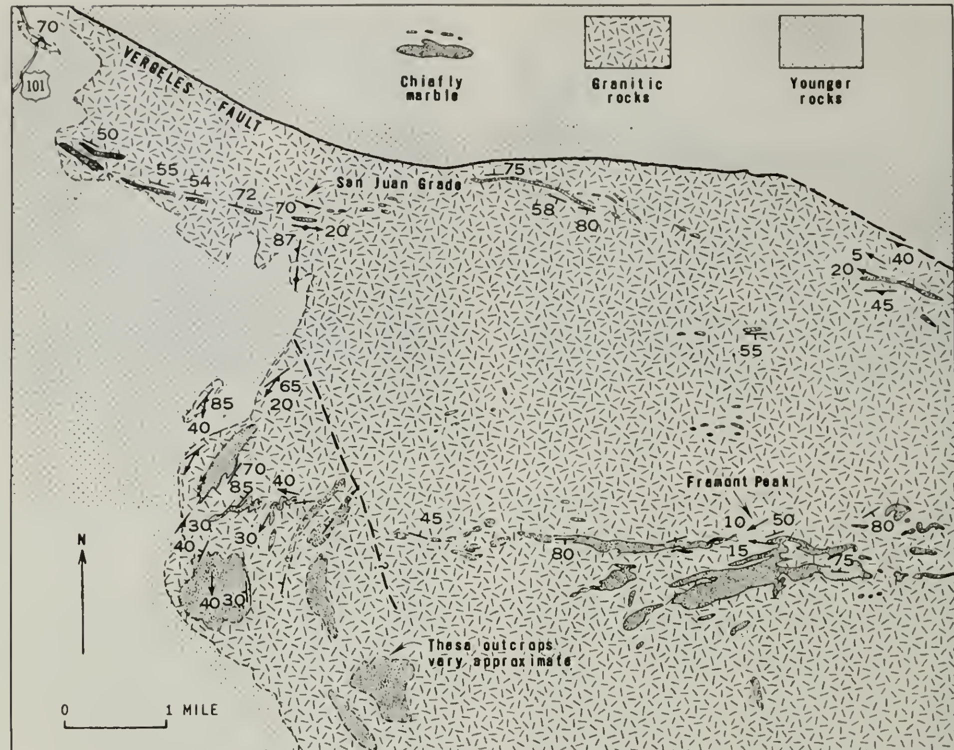

Figure 8. Map of north end of Gabilan Range, with marble relics suggesting a large fold around which earlier lineations have been rotated. Chiefly from maps of Allen (1946), Bowen and Gray (1959), and Santa Cruz sheet of the Geologic Map of California (Jennings and Strand, 1958), with additions by the writer.

significantly toward the north and east. Along the coastal ridge south of Big Sur gorge, quartz diorites are allotriomorphic and locally charnockitic (Compton, 1960). North and east of these bodies, granitic rocks become increasingly hypidiomorphic granular, with plagioclase subhedra showing oscillatory zoning. Ultramafic rocks form numerous small bodies for 15 miles northwest of the Junipero Serra area and then fall off markedly. Most of them are like the least metamorphosed peridotites of the Junipero Serro area rather than the strongly metamorphosed hybrid types. Finally, the number of metamorphosed basic intrusions (amphibolites) decreases toward the northeast side of the range (Fiedler, 1944, p. 183).

GABILAN RANGE

Basement rocks are not well exposed in this range but appear to form a broad granitic complex enclosing numerous large metamorphic relics. The metamorphic rocks are marbles, quartzites, schists, and calc-silicate rocks, many originally dolomitic and graphitic. Their gross interlayering and petrographic features suggest a direct correlation with the Sur series of the adjoining northern Santa Lucia Range. The correlation is important because Bowen and Gray (1959) noted occurrences of possible crinoid and cup coral remains in marbles on Fremont Peak. These are the only known fossils from the Salinian basement.

Except for the medium- to coarse-grained calcite and dolomite marbles, the rocks are rather fine-grained schists and quartzites, some of which are nearly black because of their large graphite content. Metamorphic minerals reported by Bowen and Gray (1959), and those studied by the writer, are mainly indicative of amphibolite facies, but transitions to lower grade rocks are suggested by widespread occurrences of tremolite-actinolite and muscovite. Local occurrences of sillimanite and wollastonite may reflect contact metamorphism, though the syntectonic nature of some of the granitic bodies makes it difficult to distinguish between pregranitic and contact-metamorphic effects.

Dikes from the plutonic bodies cut the metamorphic rocks in many places, but intricately veined rocks like those of the Junipero Serra area occur only locally near pluton contacts.

Folds in the Sur series were examined only in the northern part of the range, where structurally aligned marble relics that trend east-west through Fremont Peak swing N. 60° E. to N. 30° W. near the west side of the range—thereby defining a large steeply plunging fold (fig. 8). Subhorizontal mineral lineations and axes of small-scale folds trend around this major fold form, and subhorizontal lineations have clearly been refolded on steeply plunging small-scale folds. A third deformation is recorded by zones of fine-grained porphyroclastic marble that cut through coarser rock here and there. The sequence of structures is thus the same as that in the Junipero Serra area.

Granitic rocks form the great bulk of the range, and drill-hole data compiled by Fred Berry and Edward Gribi (oral communication, 1965) suggest that granitic rocks and gneisses underlie much of the Gabilan Mesa—the upland extending southeast from the Gabilan Range. The exposed plutonic rocks are dominantly silicic, ranging from biotite granodiorite to adamellite and granite (Wilson, 1943; Bowen, oral communication, 1965). Quartz diorite forms a considerable body extending from the south end of the range southeast under the Gabilan Mesa (Andrews, 1936). Quartz diorites and hornblende-biotite granodiorites examined by the writer at the north end of the range are lineated in parallel with subhorizontal folds in nearby marbles (fig. 8).

Quartz diorite is the principal rock in scattered outcrops extending for 10 miles northwest of the range. Metagabbro inclusions are locally abundant in these quartz diorites, which grade to more basic rocks in some places (nos. 7 and 8, table 2). Basic rocks also intruded the quartz diorites, and half a mile south of where U.S. Highway 101 crosses the San Andreas fault an irregular dike of amphibole-bearing peridotite cuts quartz diorite and metagabbro (Olaf Jenkins, oral communication, 1965). This rock is petrographically identical to some of the younger peridotites of Santa Lucia Range and is the most northerly ultramafic Salinian rock known to the writer.

BEN LOMOND AREA

Basement outcrops extending for 15 miles northwest of Santa Cruz have been studied extensively by Leo (1961) and locally by the writer. Leo estimated that the metamorphic rocks are 90 percent pelitic schists, quartzites, and gneisses, and 10 percent marbles and calc-silicate rocks. The marbles form thick lenses and layers in quartzose metasediments. Locally, as at Spring Street quarry in Santa Cruz, the writer found them interlayered with graphitic schists, exactly as in the Gabilan, La Panza, and northern Santa Lucia areas.

The mica-quartz schists and granofelses are rather fine grained and are only very locally injected by small granitic dikes. Muscovite is a common constituent of the schists, and tremolite is widespread in the marbles and calc-silicate rocks. Locally near intrusions, Leo found wollastonite in calc-silicate rocks and K-feldspar, cordierite, and sillimanite in coarse-grained schists, suggesting high-temperature metamorphism by the granitic bodies.

Foliations in the metamorphic rocks strike east-west on the average, and distinct mineral lineations and small-scale folds plunge at low angles, generally to the east-southeast in the eastern part of the area and to the west-southwest in the western part. Foliations and lineations swing concordantly with the contacts of the larger (quartz diorite) plutonic bodies, indicating they were refolded on steep axes before or during emplacement of the intrusions.

Apparently, the oldest of the plutonic rocks is a granodiorite that is distinctly gneissose parallel to the schistosity of adjoining schists but oblique to the granodiorite-schist contact. Another rock that appears to have been emplaced at an early tectonic stage is a garnetiferous biotite adamellite (Leo's Smith Grade pluton) which has vaguely to distinctly lineated biotite clusters that are subhorizontal and trend N. 70° E. to east-west, parallel to mineral and fold lineations in nearby schists and quartzites. Plagioclase in this rock is subhedral and zoned, suggesting a crystallization relationship very much as in the lineated adamellites of La Panza Range.

Small bodies of hornblende-cummingtonite gabbro, studied in detail by Leo, were emplaced before voluminous quartz diorite which crops out over areas as large as 6 by 10 miles. The quartz diorite is typically heterogeneous, orthoclase-bearing, and carries about 10 percent biotite and 5 percent hornblende; locally, it grades to more basic rocks as well as to granodiorite. Textures are consistently medium-grained hypidiomorphic granular and plagioclase is commonly zoned. Tectonic lineations like those of the Junipero Serra quartz diorites appear to be absent. Spotts (1962) reported that accessory epidote, chlorite, and sphene are common and that magnetite is scarce. Fine-grained mafic inclusions are widespread, some apparently having formed by disruption of mafic dikes emplaced into the granitic rocks at a late magmatic stage.

MONTARA MOUNTAIN AND THE FARALLON ISLANDS

As nearly as the writer could determine, granitic rocks form the entire exposures of these two areas. The Montara exposure, measuring about 4 by 10 miles, is mainly coarse-grained quartz diorite mineralogically like that of Ben Lomond. Quartz-bearing diorite inclusions are common and are locally associated with markedly mafic granitic rock. Along the sea cliff and Highway 1 (the only exposures the writer could examine in detail) strikingly planar inclusions lie parallel to a crudely gneissoid fabric that strikes N. 70° W. to E-W and dips steeply. The inclusions are locally elongate, but the writer could detect no consistent linear pattern nor any linear fabric in the granitic rocks themselves. In the southeast part of the area, quartz diorite appears to grade to ferrohastingsite-biotite granodiorite. Textures of all the granitic rocks range from allotriomorphic to hypidiomorphic, with plagioclase commonly showing oscillatory zoning. The accessory minerals are closely similar to those of the Ben Lomond rocks (Spotts, 1962).

The rocks of the Farallon Islands apparently range from quartz diorite to granodiorite which contains only a few percent of biotite and ferrohastingsite. Texturally and mineralogically they are closely similar to the rocks of Ben Lomond and Montara. Dredged samples indicate the same body of quartz diorite forms a 6-mile wide strip along the edge of the continental shelf, extending for 30 miles northwest of the islands (Uchupi and Emery, 1963). Samples described by Chesterman (1952) from the same submarine outcrop are like quartz diorites from Montara and Ben Lomond.

BODEGA HEAD, TOMALES-INVERNESS RIDGE, AND POINT REYES

The granitic rocks of these areas apparently represent a closely related group of intrusions, each bearing evidence of a complex emplacement history. The rocks on Bodega Head are mainly hornblende-biotite quartz diorite (no. 10, table 2) and somewhat less mafic granodiorite, grading locally to schlieren and large inclusions of mafic biotite diorite (no. 9, table 2) and also to schlieren of adamellite. Dikes of adamellite and potassic granite pegmatite locally cut the other rocks. Texturally and mineralogically, the quartz diorites and granodiorites are nearly identical to those of Montara Mountain; even their accessories are similar (Spotts, 1962). The schlieren and crudely gneissoid fabrics, which are generally steeply inclined and strike due north to N. 20° W., are locally folded on steeply plunging axes. Some granite pegmatites are folded on moderately inclined axes. Lineate biotite fabrics, however, were not noted by the writer.

The plutonic body underlying Tomales Point and Inverness Ridge is at least 18 miles long and consists of granodiorite and adamellite, with quartz diorite occurring locally at its north end. Large relics of metamorphic rocks are abundant along the northeast (Tomales Bay) side of the body and occur here and there elsewhere. They are mainly biotitic quartzites, calc-silicate rocks, and aluminous schists. Graphitic marbles, which form several small bodies 3 miles southeast of Inverness, carry orthoclase and meionitic scapolite, and are cut by foliated porphyroclastic bands like those occurring elsewhere in the Salinian block. The various rocks are rather fine grained, but sillimanite occurs in schists at several outcrops.

All of the Tomales Point outcrops examined show at least minor lineations, and several of the larger ones display tight folds formed during metamorphism. An excellent exposure at the south end of McClures Beach, on the west side of Tomales Point, shows thin-layered metamorphic rocks folded on nearly vertical axes. An adamellite on the south side of these rocks has strongly lineated biotite clusters oriented parallel to the metamorphic fold axes, indicating that at least this part of the plutonic body was emplaced before or during folding. Granodiorite and quartz diorite just north of the metamorphic outcrop appear to be younger for they are massive and contain unusually large, undeformed biotite subhedra. Half a mile to the north, however, these large biotites are crenulated, and rock foliations are locally folded on subhorizontal axes. Other granitic outcrops on the Tomales-Inverness Ridge show no compelling evidence of paracrystalline deformation, but few are suitable for detailed structural study.

Complex age relationships are also indicated by the excellent outcrops at the east end of Point Reyes. The silicic granodiorite and adamellite that extend for half a mile east and west of the Coast Guard lifeboat station range from massive to gneissoid and from fine gained to coarse grained. Some contacts between textural varieties are sharp and some are gradational, yet steeply dipping foliations swing gradually from northeast to northwest as one proceeds east from the lifeboat station to the point, suggesting that the entire mass was deformed after its emplacement. Unfortunately, the writer could not observe the relationships between these adamellites and the rocks exposed at the west end of the point. These appear to be mainly hornblende-biotite granodiorite and quartz diorite, locally with mafic inclusions and schlieren.

INTERPRETATION

This survey of the principal basement exposures indicates a complex but reasonably consistent plutonic history for the Salinian rocks. The metamorphic rocks apparently represent one heterogeneous sedimentary assemblage of Paleozoic or Mesozoic age. Their platform-type sandstones and limestones and the abundance of dolomitic rocks prove they are not metamorphosed Franciscan rocks. All were folded and metamorphosed more than once; in most areas, folding on subhorizontal axes was followed by folding on steeply inclined axes. Plutonic rocks ranging from peridotite to potassic granite were emplaced before or during the first folding as well as later. The granitic textures and the distribution of the second mineral lineations indicate these events constitute one prolonged period of plutonism. Local recrystallization and cataclasis recorded a final tectonic episode that may well have been synchronous with uplift of the entire Salinian mass.

Increase in metamorphic grade and increasing abundance of granitic veins and dikes toward the southwest edge of the block indicate this part of the terrain was most heated and probably most deeply buried. The narrow, lens-shaped granitic bodies of this sector appear to represent the lower (catazonal) parts of one or more plutons, while the broad granitic bodies exposed to the north and east represent higher (mesozonal) sections through related plutons. This geometric scheme is based mainly on geographic variations in the shapes of granitic bodies in Santa Lucia Range; it is supported by regional variations in granitic textures and mineralogy as well as by the degree to which the terrain yielded during the second folding. If the scheme is correct, the plutonic suite could not have originated by gravitative differentiation in place, for the lower parts of the plutons are at least as silicic as the higher parts. The heterogeneity of the quartz diorites and granodiorites suggests they might have arisen by mixing of gabbroic melt with anatectic materials from underlying metamorphic rocks. The numerous zoned ultramafic bodies are almost certainly hybrid.

In spite of the excellent K-Ar determinations available, it is difficult to assign dates to the various plutonic events. The difficulty is epitomized by the Junipero Serra rocks, which have given the youngest ages (69.6 and 75 m.y.) yet are overlain by Upper Cretaceous beds containing Campanian fossils. This relationship suggests that the K-Ar ages represent a postgranite event, for example the deformation that produced the fine-grained recrystallized marbles. In this light, it is interesting to note that the other K-Ar ages tend to increase away from the Junipero Serra area, in a rough correlation with the broad depth zoning just described. It is thereby suggested that the higher parts of the plutons crystallized during mid-Cretaceous time, yielding the oldest K-Ar ages (around 90 m.y.). The more deeply buried rocks continued to recrystallize during this time and began to accumulate argon only when lifted and cooled as the Salinian block was uplifted and eroded. The possibility that the plutonic suite is much older than Cretaceous tends to be disallowed by Hutton's Th-Pb determination (fig. 1) and by Pb isotope ratios (of rocks 5 and 6, table 1) which are closely similar to ratios of Cretaceous to Recent silicic igneous rocks from other parts of the western United States (Doe, in press).

If the granulite facies rocks were in fact generated during the Cretaceous, the Salinian block was uplifted many miles during Late Cretaceous time. The metamorphic zoning indicates the west side was uplifted farther than the east. A suggestion of early movement with a strike-slip sense (such as might be related to an ancestral San Andreas fault) is found in the steep-axis folds in the Sur rocks; however, not enough folds have been mapped to test for sense of shear or asymmetry. The latest set of metamorphic structures (those of the fine-grained recrystallized marbles) suggests maximum compressive stresses aligned roughly normal to the length of the block.

Not the least perplexing problem is the apparent disappearance of the great mass of sediments eroded from the rising block. Because the Cretaceous sediments east of the block were likely derived from the east (Bailey, Irwin, and Jones, 1964), the Salinian detritus was presumably carried west into the Pacific Ocean. From here, it was conceivably thrust or dragged eastward under the continental edge, generating the deep root required for the continued rise of the Salinian block. This sense of movement is suitable to the youngest metamorphic structures in the Junipero Serra area and also to the general northeastward dip of foliations and axial planes of folds in the Sur series and in the Franciscan rocks of the adjoining coastal strip. Otherwise, the model must be pure conjecture until the ages of the plutonic rocks are fixed more firmly.

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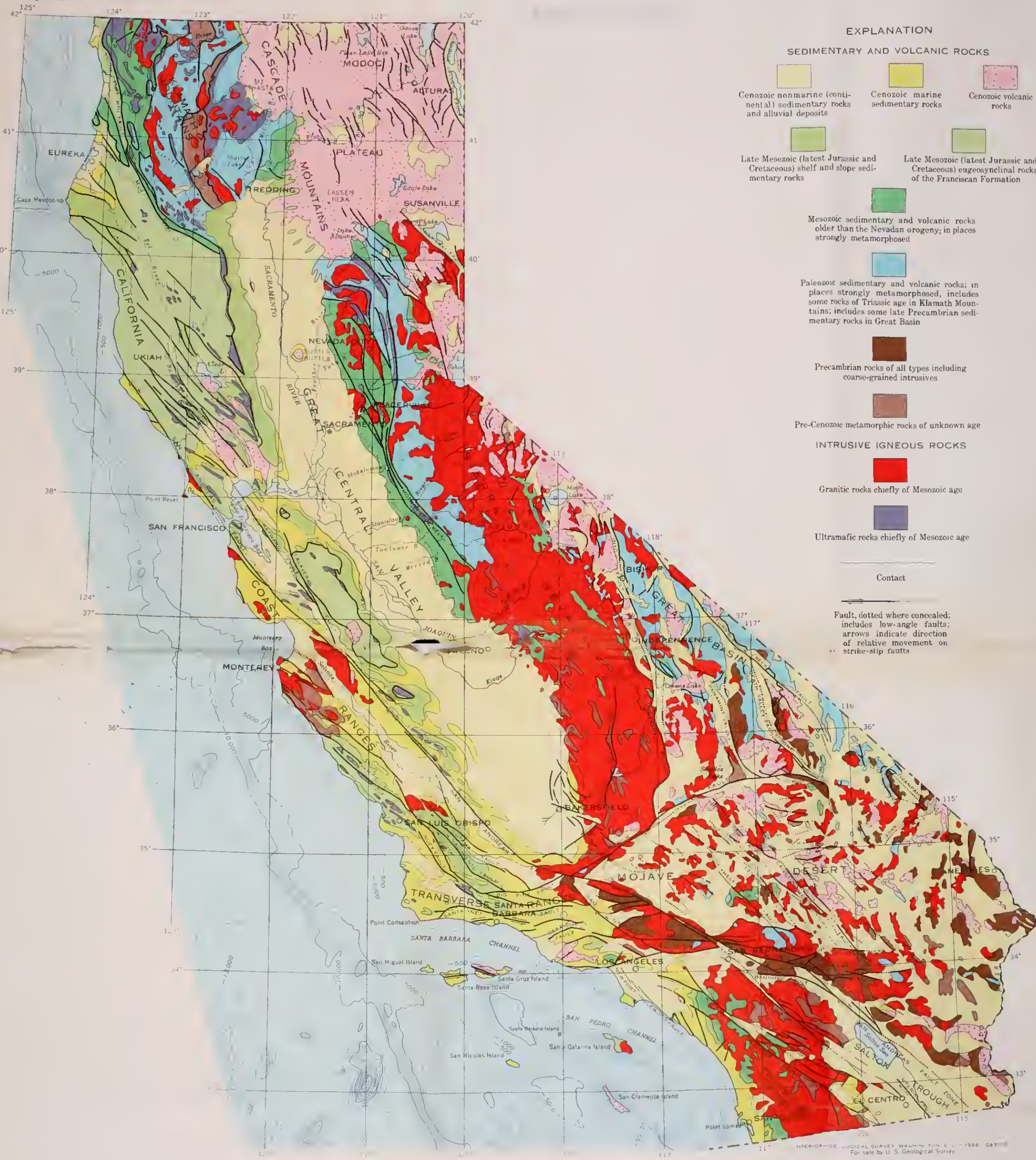
UNITED STATES GEOLOGICAL SURVEY

MISCELLANEOUS GEOLOGICAL INVESTIGATIONS
MAP I-512



EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

Cenozoic nonmarine (continental) sedimentary rocks and alluvial deposits

Cenozoic marine sedimentary rocks

Cenozoic volcanic rocks

Late Mesozoic (latest Jurassic and Cretaceous) shelf and slope sedimentary rocks

Late Mesozoic (latest Jurassic and Cretaceous) eugeosynclinal rocks of the Franciscan Formation

Mesozoic sedimentary and volcanic rocks older than the Nevadan orogeny; in places strongly metamorphosed

Paleozoic sedimentary and volcanic rocks; in places strongly metamorphosed, includes some rocks of Triassic age in Klamath Mountains; includes some late Precambrian sedimentary rocks in Great Basin

Precambrian rocks of all types including coarse-grained intrusives

Pre-Cenozoic metamorphic rocks of unknown age

INTRUSIVE IGNEOUS ROCKS

Granitic rocks chiefly of Mesozoic age

Ultramafic rocks chiefly of Mesozoic age

Contact

Fault, dotted where concealed; includes low-angle faults; arrows indicate direction of relative movement on strike-slip faults

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—1966
For sale by U. S. Geological Survey

GEOLOGIC MAP OF CALIFORNIA

COMPILED BY U.S. GEOLOGICAL SURVEY
AND CALIFORNIA DIVISION OF MINES AND GEOLOGY

SCALE 1:2 500 000

0 50 100 MILES

SUBMARINE CONTOUR INTERVALS 500 AND 1000 FEET DATUM IS SEA LEVEL

1966