49. PETROLOGY AND GEOCHEMISTRY OF GRANITE RECOVERED AT SITE 476, DEEP SEA DRILLING PROJECT LEG 64, GULF OF CALIFORNIA[1]

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ABSTRACT

Drilling at Site 476, the most landward of the three-site transect at the tip of Baja California Sur, recovered approximately one meter of partially weathered granite. Certain portions of the granite show severe cataclastic deformation, possibly mylonitic in part. The fresher portions have a typical granite mineralogy with abundant quartz; potassium feldspar predominant over plagioclase; and minor hornblende, biotite, and muscovite. X-ray fluorescence and instrumental neutron activation analysis of the granite show a high normative Or content and high K_2O/Na_2O (>1.5), Ce_N/Yb_N (10.8), Rb/Sr (1-1.5), and Ba/Sr (9-12) ratios. The chemistry of Site 476 granite is typical of a calc-alkaline granite, albeit one that perhaps has been emplaced some distance away from the original trench/subduction zone system. The granite is probably an extension of the Mesozoic arc terrain exposed on Cabo San Lucas and north of Bahía Sebastián Viscaíno.

INTRODUCTION

Site 476 (23°02.43′N, 109°05.35′W. 2403 m) is the third and most landward of the three-site transect (474; 475; 476) across the continental margin at the tip of Baja California (Fig. 1). Two of the main objectives were to confirm that continental crust is indeed present in this region and to assess the composition and, if possible, the age of any basement rocks. This chapter will present petrographical and geochemical data on the small quantity of granitic rocks recoverd at Site 476 and will attempt to compare these data with information on granitic rocks from similar tectonic settings.

RECOVERY

Drilling at Site 476 penetrated approximately 200 meters of Pleistocene-to-late-Miocene hemipelagic slope deposits comprising turbidites, occasional lenses of glauconitic sands, and a rhyolitic ash band. Beneath this sequence were 57 meters of poorly consolidated conglomerate consisting of low-grade metasedimentary and metavolcanic cobbles. The conglomerate contained no cobbles of the underlying granite.

We encountered granite at 256 meters sub-bottom and, although drilling continued for a further 29 meters, we recovered only 1.14 meters of consolidated rock. We also recovered several kilograms of granitic drilling breccia, particularly in the last cores, testifying to the rather weathered, friable nature of the rock.

PETROGRAPHY

The rock recovered in Cores 28 through 31 is a biotite- and hornblende-bearing granite—medium-grained, inequigranular, texturally heterogeneous, and light gray (5B 7/1). In thin section, the granite consists primarily

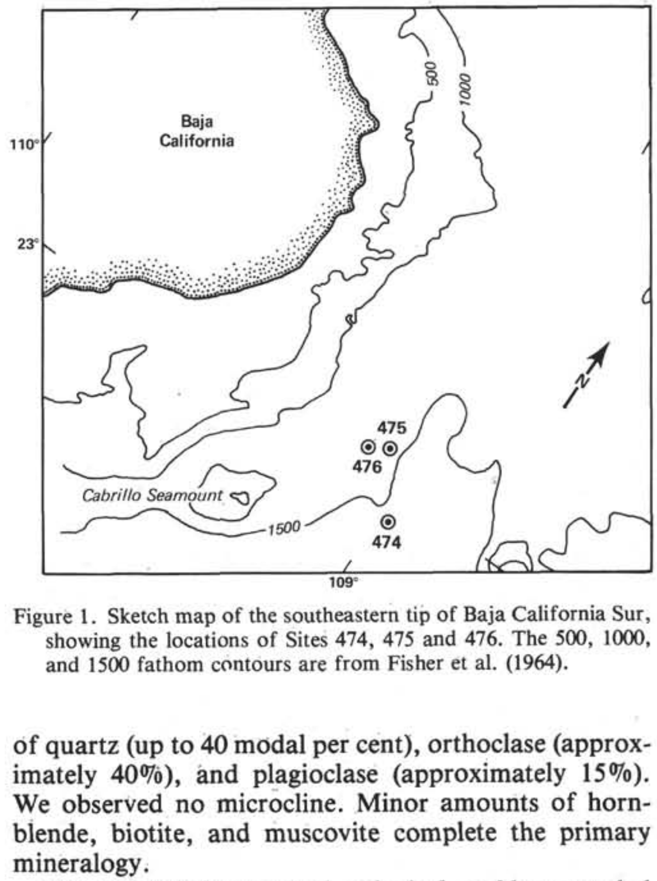

Figure 1. Sketch map of the southeastern tip of Baja California Sur, showing the locations of Sites 474, 475 and 476. The 500, 1000, and 1500 fathom contours are from Fisher et al. (1964).

of quartz (up to 40 modal per cent), orthoclase (approximately 40%), and plagioclase (approximately 15%). We observed no microcline. Minor amounts of hornblende, biotite, and muscovite complete the primary mineralogy.

The quartz is fragmented, anhedral, and has rounded grains, often with shadowy extinction. Severely sericitized plagioclase (?albite-oligoclase) is present as subhedral crystals up to 2 mm long. The potassium feldspar has crystal dimensions similar to the plagioclase but tends to be more anhedral, is less altered, and contains abundant perthite rods. Textural evidence suggests that the orthoclase crystallized after the plagioclase.

[1] Curray, J. R., Moore, D. G., et al., *Init. Repts. DSDP*, 64: Washington (U.S. Govt. Printing Office).

The thin sections revealed that all of the biotite and hornblende had been pseudomorphed by chlorite, and several of the pseudomorphs after biotite contain a small, dark, translucent mineral, possibly zircon.

As stated above, the granite is texturally heterogeneous. Pieces 5 and 12 of Section 476-29-1 are the freshest, exhibiting hypidiomorphic textures and only minor alteration of the biotite and hornblende. Several of the remaining pieces exhibit textures suggesting severe postemplacement cataclastic deformation; the constituent minerals of the granite form isolated aggregates within a streaky, aphanitic matrix in the more deformed samples. In thin section, this matrix comprises small angular fragments of quartz and feldspar embedded in a very fine-grained, opaque-rich groundmass. We believe that the matrix is a mylonitic or cataclastic component indicating intense deformation and shattering of the granite.

The degree of alteration of the granite appears to be as large as, and probably corresponds with, the degree of deformation. In hand specimen, the mafic minerals grade from fresh to completely chloritized, although most of the plagioclase is severely sericitized. Minor amounts of pyrite occur in veins and clusters, and epidote fills a few small cavities.

The predominance of alkali feldspar over plagioclase supports the original nomenclature of this rock as a granite (Carmichael et al., 1974), rather than as an adamellite or quartz monzonite.

GEOCHEMISTRY

We took two 50-gram samples from the freshest portion of Core 29, Section 1, crushed them to less than 250 mesh in an agate swing mill, and analyzed them by X-ray fluorescence at Birmingham University (Table 1). We also analyzed one of the samples (476-29-1, 30–40 cm) by instrumental neutron activation at Bedford College (Table 2). Full details of the analytical methods are given in Saunders et al. (this volume, Pt. 2). Where applicable, there is good agreement between the two methods of analysis.

The slight differences in composition between the two samples are to be expected, since the sample size is still too small to ensure representative analysis, particularly with such texturally heterogeneous material. But the similarity of the analyses is encouraging.

The major element data amplify the petrographic observations. The high SiO_2 and K_2O contents and high K_2O/Na_2O ratios reflect the high quartz and feldspar content. Feldspar is also indicated by the high normative Or content; the rock plots well inside the granite field on the Or–Ab–An diagram (Fig. 2). Although it contains over 8 wt.% alkalies, the granite is certainly not peralkaline and on major element grounds may be closely compared to calc-alkaline granites and quartz monzonites from the Sierra Nevada batholith and from other destructive plate margin regions (e.g., the Antarctic Peninsula) (Table 1).

The trace element data facilitate further comparative studies. There are high abundances of Rb and Ba, which correlate with the high K_2O content. Moderate Sr content (116–168 ppm) indicates that plagioclase fractionation (Philpotts and Schnetzler, 1970) occurred during the formation of the granite, although the absence of any consanguineous basic and intermediate material makes this speculative. Nevertheless, the Rb/Sr and Ba/Sr ratios are high (0.98–1.55 and 8.6–11.5, respectively).

Table 1. Analyses of granite from Site 476 and of granites and related rocks from Sierra Nevada and Antarctic Peninsula.

	1	2	3	4	5
SiO_2	71.56	74.10	71.42	75.4	76.04
TiO_2	0.31	0.28	0.36	0.1	0.16
Al_2O_3	14.12	13.52	14.03	13.3	12.70
tFe_2O_3	2.50	2.24	2.70	1.12	1.09
MnO	0.03	0.02	0.05	0.08	0.03
MgO	0.88	0.59	0.70	0.12	0.12
CaO	1.10	0.37	1.91	0.48	0.57
Na_2O	3.36	2.95	2.86	4.1	4.32
K_2O	5.12	5.60	5.35	4.5	4.53
P_2O_5	0.09	0.08	0.09	0.01	0.04
L.O.I.	1.15	0.54	0.43	0.46	—
Total	100.22	100.29	99.90	99.67	99.60
Trace Elements (ppm)					
Ni	<1	<1	3	—	<1
Cr	9	10	6	—	5
Zn	27	25	—	—	21
Ga	20	17	—	—	—
Rb	164	180	—	—	173
Sr	168	116	300	—	24
Y	13	13	—	—	19
Zr	130	119	500	—	92
Nb	6	5	—	—	11
Ba	1448	1373	1000	—	167
La	34	37	—	—	19
Ce	55	61	—	—	49
Nd	21	22	—	—	22
Pb	14	14	20	—	22
Th	16	13	—	—	26
C.I.P.W. Norms					
Q	27.4	32.6	28.38	32.58	32.52
Or	30.2	33.1	31.68	26.69	26.92
Ab	28.4	24.9	24.11	34.58	36.69
An	5.2	1.6	9.46	2.50	1.86
Di	0.0	0.0	0.0	0.0	0.24
Hy	5.1	4.1	3.55	1.36	0.19
Mt	0.4	0.4	1.39	0.46	0.0
Il	0.6	0.5	0.65	0.0	0.06
Ap	0.2	0.2	0.0	0.0	0.10
C	0.0	0.0	0.10	0.71	0.0
Selected Ratios					
K_2O/Na_2O	1.52	1.90	1.87	1.10	1.05
$(Ce/Y)_N$	10.4	11.5	—	—	5.3
K/Rb	259	258	—	—	217
Zr/Nb	22	24	—	—	8

Note: 1 = Sample 476-29-1, 23–29 cm; 2 = Sample 476-29-1, 30–40 cm; 3 = Tungsten Hills quartz monzonite, east central Sierra Nevada (Bateman et al., 1963); 4 = Quartz monzonite, Cathedral Peaks type, east central Sierra Nevada (Bateman et al., 1963); 5 = Granite, Andean Intrusive Suite, Oscar II Coast, Graham Land (Saunders et al., 1980). Analyses 1, 2, and 5 were determined by XRF techniques at Birmingham University; tFe_2O_3 = total iron as Fe_2O_3; L.O.I. = loss on ignition.

Table 2. Neutron activation analysis of granite, Sample 476-29-1, 30–40 cm.

La	36.9
Ce	57.5
Nd	21.0
Sm	3.50
Eu	0.54
Tb	0.37
Tm	0.19
Yb	1.36
Lu	0.18
Ta	0.47
Th	12.5
Hf	3.5

Note: All values in ppm.

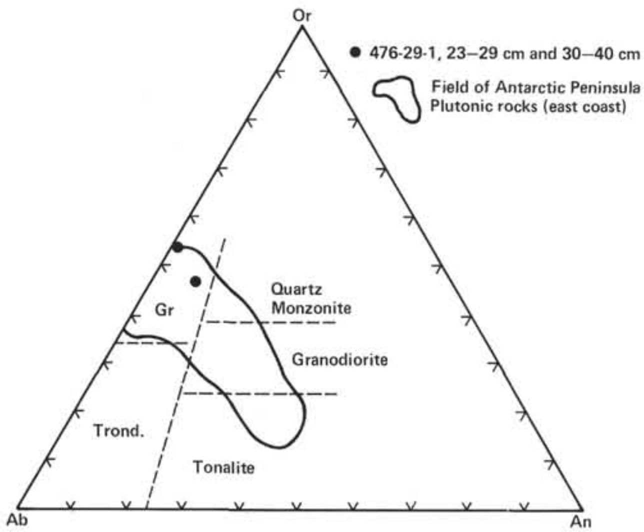

Figure 2. Site 476 granite plotted on a normative albite (Ab)–orthoclase (Or)–anorthite (An) diagram. The field boundaries have been modified slightly after O'Conner (1965). Data for the calc-alkaline plutonic rocks from the east coast of the Antarctic Peninsula are taken from Saunders et al. (in press).

The rare earth element (REE) data (Table 2; Fig. 3) show that the granite has a high Ce_N/Yb_N ratio (10.8; calc-alkaline granites typically have Ce_N/Yb_N ratios between 4 and 8; Atherton et al., 1979; Saunders et al., 1980). A small negative europium anomaly (Eu/Eu* ~0.5) supports the previous suggestion of plagioclase removal from the parental melt (Schnetzler and Philpotts, 1970).

DISCUSSION

The geology of the western margins of North America, including Baja California, is dominated by extensive Mesozoic calc-alkaline cordilleran batholiths and associated volcanic rocks (Hamilton, 1969a, b). In northern Baja alone, for example, there are almost 400 individual plutons, ranging in composition from gabbro to granite and covering an area of approximately 28,000 km^3 (Gastil et al., 1975). This region of northern Baja California, part of the Peninsular Ranges batholith, exhibits a distribution and compositional range of plutons

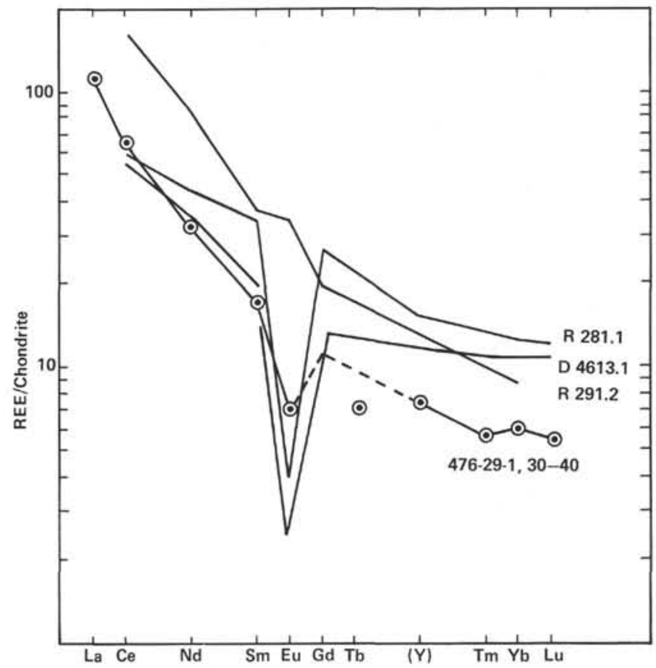

Figure 3. Chondrite-normalized rare earth element data for the granite recovered at Site 476 and for two granites (R281.1 and D4613.1) and a quartz-feldspar porphyry (R291.2) from the Antarctic Peninsula (Saunders et al., 1980; Saunders, unpublished).

resembling the Sierra Nevada batholith to the north (Gastil et al., 1971).

Unfortunately, there are few data available for the southern half of Baja California (Baja California Sur). On a regional scale, the Peninsular Ranges plutonic complex swings eastward at about 27°S and parallels the eastern side of the Baja Peninsula. In the extreme south, a narrow remnant of the complex re-enters the peninsula near La Paz and cuts southward across the tip of the peninsula. To the east of this now much-reduced belt is an area, near Cabo San Lucas, of Triassic and Jurassic eugeosynclinal deposits, deformed during the Nevadan Orogeny and intruded by relatively potassium-rich, Late Jurassic and mid Cretaceous plutons (Gastil et al., 1975). This relation of calc-alkaline plutonic rocks becoming increasingly potassic toward the continent is seen more clearly in northern California—in the Sierra Nevada batholith and in the Basin and Range Province (Moore, 1969). Not only do the K_2O/SiO_2 and K/Na ratios increase when passing from the Sierra Nevada batholith into the Basin and Range Province, but the ratios also increase within the Sierra Nevada batholith itself (Bateman et al., 1963). Similarly, Hirschi and de Quervain (1933) and Larsen (1948) suggested that the Mesozoic Peninsular Ranges batholith becomes increasingly alkalic to the east. On the basis of a limited sample population, however, Gastil et al. (1975) were unable to verify these conclusions; more data on the plutonic rocks of Baja are required.

The granite recovered at Site 476 is similar to granites exposed in other calc-alkaline complexes. This is demonstrated by the data in Table 1, where we compare the Site 476 granites to granites and quartz monzonites from the Sierra Nevada batholith and Graham Land (Antarctic Peninsula). Samples from the latter were analyzed at Birmingham (England) to avoid interlaboratory error. Although some differences do exist—which are to be expected in view of the complex processes involved in the formation of evolved calc-alkaline rocks—several similarities are striking, particularly in K_2O, Rb, Th, Pb, and Zr contents and K/Rb ratios. The content of Sr varies between the different rocks, but this is probably a function of the degree of feldspar fractionation. The high Ce/Yb and Ba/Yb ratios of the Site 476 granite are not "typical" of most calc-alkaline granites (Sample D4613.1 in Fig. 3 has a "typical" Ce_N/Yb_N ratio of 4.2), although a comparable REE pattern (Sample R291.2, a quartz-feldspar porphyry from the east coast of the Antarctic Peninsula) is shown in Figure 3. The high Ce/Yb and Ba/Yb ratios of the Site 476 granite are consistent with the high K/Na, Rb/Sr, and Ba/Sr ratios; Ba, the light REE, K, and Rb behave as a coherent group in calc-alkaline suites (Saunders et al., 1980).

The high Ce/Yb, Ba/Yb, Ba/Sr, and K/Na ratios also may be consistent with emplacement of the Site 476 granite relatively distant from the trench/subduction zone system, since in calc-alkaline suites these ratios tend to increase systematically away from the trench (Dickinson and Hatherton, 1967; Ringwood, 1974; Dickinson, 1975; Saunders et al., 1980). Again, this corroborates previous observations that the plutonic rocks of the Cabo San Lucas region are relatively potassic and may be grouped with calc-alkaline rocks found in the Basin and Range Province (Gastil et al., 1975). This must remain as speculation, however, until trace element data are available for plutonic rocks from the adjacent Baja California Peninsula.

The granite sampled at Site 476 is also similar to dredged granites recovered from the Cabrillo Seamount (Fig. 1) (J. Hawkins, personal communication), that may be a remnant sliver of the prerift batholithic foundation now exposed on Cabo San Lucas (Fornari et al., this volume, Pt. 2). Otherwise described, the Cabrillo Seamount is a rigid or semirigid crustal block, too small or too nonrigid to be termed a plate, and bounded by reverse, normal or strike-slip faults (a *scholle*) (Sengor and Dewey, 1979). In fact, the entire southern tip of Baja could be considered the Cabo San Lucas *scholle* (CSLS). The exposure of Mesozoic arc terrain (granitic plutons) in the Cabo San Lucas region is enigmatic, considering that the next exposure of this lithology is 550 km to the north, east of Bahía Sebastián Viscaíno. The northeast-trending lineaments (Normark and Curray, 1968) outlining the CSLS juxtapose the lineaments that trend northwest, outlining the northern two *scholles*. These two northern *scholles* probably moved to their present positions from the adjacent Mexican landmass in mid-Tertiary time (R. F. Livacarri, pers. comm.). Livacarri suggests that the CSLS moved southwestward 15- to 10 Ma (after the movement of the northern *scholles*) from an area north of Topolobampo, where a medium sized bay now exists. This movement took place along the northeast-trending transcurrent faults that now bound the CSLS and can be correlated to similar lineaments north-northeast of Topolobampo in the Sonora Basin and Range province. But the cause of the migration of the Cabo San Lucas is unclear, especially because the direction of movement is rotated 90° to the northwest-striking paths travelled by the northern *scholles*.

CONCLUSIONS

The basement rock recovered at Site 476 is mineralogically and chemically a true granite that has been, in part, cataclastically deformed. Its composition falls in the range observed for calc-alkaline granites found in many other cordilleran belts. Nonetheless, the granite does have high K/Na, Ce/Yb, and Ba/Sr ratios, which perhaps are consistent with emplacement farther from the original trench system than, for example, many of the plutonic suites of the Peninsular Ranges and the Sierra Nevada batholith. This granite and the Cabrillo Seamount are the southern exposure of the Mesozoic arc terrain, exposed both on Cabo San Lucas and north of Bahía Sebastián Viscaíno, that has been disrupted by transcurrent faults which accommodated the opening of the Gulf of California.

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