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COMPARISON OF RADIOACTIVITY AND GEOCHEMISTRY OF ROCKS FROM PLUTONIC BODIES ADJACENT TO THE SOUTHERN PART OF GOLFO DE CALIFORNIA

J. FIALA*
V. HANUŠ* ***
J. VANĚK** ***
V. VAŇKOVÁ**
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RESUMEN

La comparación de la composición modal y los contenidos de los elementos mayores, radioactivos (U, Th, K) y de elementos de traza seleccionados (Rb, Sr, Ba, Y, Zr, V, Cr, Ni) en las rocas graníticas de los complejos plutónicos de la región de Jalisco y Baja California Sur, apoya la idea de un cuerpo batolítico original separado más tarde por el proceso de abertura del Golfo de California.

ABSTRACT

The comparison of modal composition and contents of major, radioactive (U, Th, K) and selected (Rb, Sr, Ba, Y, Zr, V, Cr, Ni) trace elements of granitic rocks from the Jalisco and Baja California Sur plutonic complexes supports the idea that they were part of a single batholithic body separated later by the process of opening of the Gulf of California.

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* *Institute of Geology and Geotechnics, Czechoslovak Academy of Sciences, Prague.*
** *Geophysical Institute, Czechoslovak Academy of Sciences, Prague.*
*** *Profesores visitantes, Instituto de Geofísica, UNAM, México.*

INTRODUCTION

Numerous oceanographic and geophysical investigations, carried out in the Gulf of California, indicate that this specific feature of the Pacific continental margin of North America was probably created by separating Baja California from the Mexican continent (Larson *et al.*, 1968; Moore and Buffington, 1968). It is supposed that this opening started between 4 and 6 Ma before present (Larson, 1972); several authors assume that a proto-gulf existed here from the Miocene (Karig and Jensky, 1972; Moore, 1973).

In this model, the tip of Baja California should have been contiguous with the Jalisco batholithic complex, as suggested by Hamilton (1961). The Jalisco batholith is a plutonic complex and there is no evidence to suggest that both this and the pluton at the tip of Baja California are other than Late Mesozoic (Karig and Jensky, 1972; Gastil *et al.*, 1974). It seems therefore that the plùtons in Jalisco and at the tip of Baja California (Sierra de la Vìctoria) are parts of the same batholith, separated by the process of opening of the Gulf of California. The aim of this paper is to examine this assumption by investigating radioactivity, petrology and geochemistry of rock samples collected from both plutonic complexes.

GEOLOGICAL SETTING AND SAMPLING OF ROCKS

The rocks under study are representative of typical plutonites in the central part of a linear belt of batholiths ranging from South California to the State of Oaxaca. The batholiths, which are members of the circum-Pacific plutonic chain, form probably the southern continuation of a large coastal Middle Cretaceous batholithic complex bordering the western margin of the North American continent (Hamilton, 1961).

Gastil *et al.*, (1974) divided the batholithic belt into three "sub-belts", which parallel the strike of the belt. The gabbro sub-belt in the west is followed eastward by tonalite and adamellite sub-belts. The oldest plutonic rocks of the batholiths are dated to 145 Ma in the western part, changing the age eastward to 85 Ma. The tendency of plutonic as well as that of volcanic complexes to get younger landward is similar to most other regions overlying convergent plate margins. The above phenomenon was interpreted in the Andean South America and Tonga-Kermadec island arc by Hanuš and Vaněk (1979) as a result of the cyclic character of subduction changing the place of its operation in the direction of the respective ocean-floor spreading.

The occurrence of deep earthquakes underlying the recent Mexican zone of subduction (see cross-sections M 24 and M 32 in Hanuš and Vaněk, 1977-78) might support the idea of cyclicity of the subduction in this region and the above mentioned interpretation of the landward decrease of the age of Mexican plutonic bodies related to the process of paleosubduction of the Pacific plate under the North American plate.

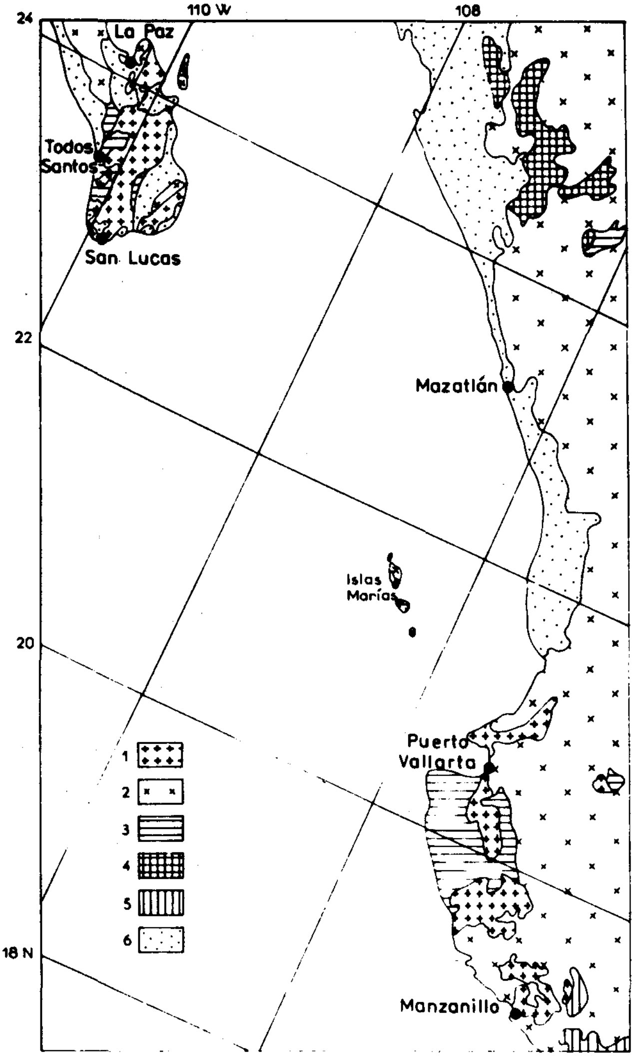

Fig. 1. Schematic geological map showing the distribution of plutonic bodies under study in the region of Baja California Sur and Jalisco. 1-Mesozoic plutonic rocks, 2-Cenozoic volcanic rocks, 3-Paleozoic metamorphic rocks, 4-Mesozoic metamorphic rocks, 5-Mesozoic sediments, 6-Cenozoic sediments.

Most concentrically structured plutonic bodies are emplaced in the Upper Jurassic and mid-Cretaceous volcanic rocks of predominantly andesitic composition (Gastil *et al.*, 1974). It is probable that the shape and chemical composition of plutonic bodies was substantially influenced by the internal structure and chemistry of the surrounding host rocks. Therefore, it can be expected that the individual batholiths, in spite of the similar mechanism of their formation, display specific compositional characteristics, which can help to reconstruct the original tectonic setting.

Schematic geological map based on Carta geológica de la República Mexicana (López Ramón, 1976) shows the distribution of plutonic bodies under study in the region of Baja California Sur and Jalisco (Fig. 1). Localities of sampled rocks are given in Fig. 2a, b and described in Table 1.

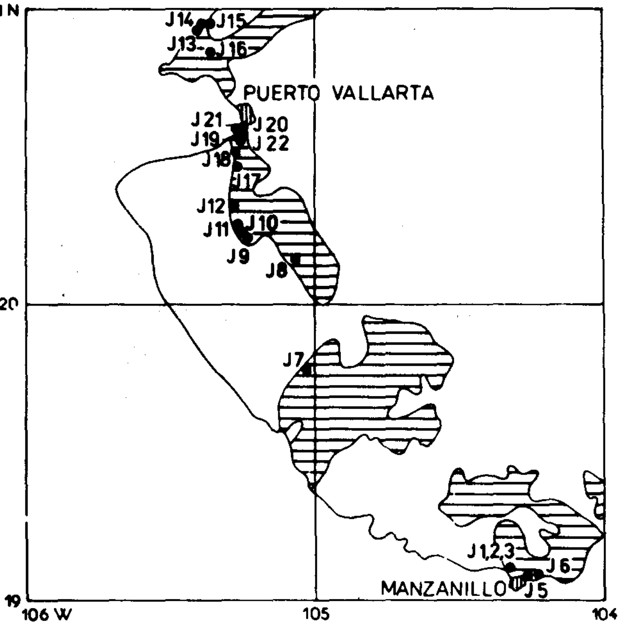

Fig. 2a. Localities of sampled rocks in the Jalisco plutonic complex. Plutonic bodies are denoted by horizontal hatching.

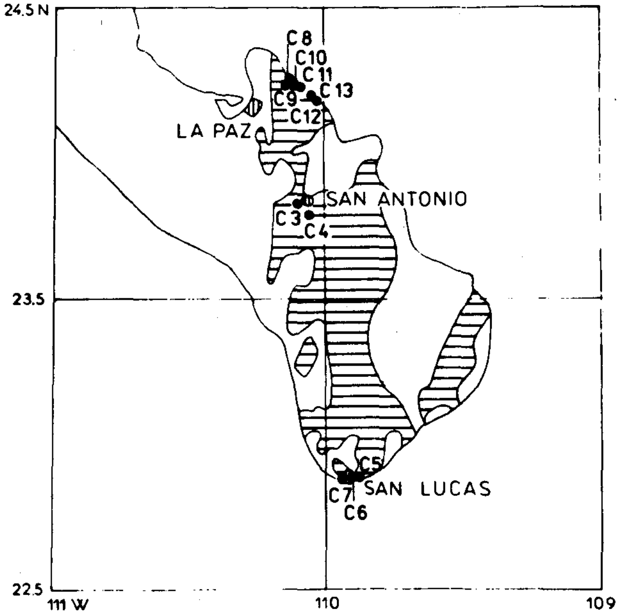

Fig. 2b. Localities of sampled rocks in Sierra de la Victoria (Baja California Sur). Plutonic bodies are denoted by horizontal hatching.

The samples of plutonic rocks were collected either from outcrops along the newly constructed roads or from fresh rocks exposed on the sea coast by V. Hanuš and J. Vaněk during their field trips in 1978. Our sampling was designed to include most occurring rock types in order to study the variability of modal and chemical compositions of the entire plutonic rock series. However, our sampling density per rock type is not necessarily representative of its relative abundance in the field. Samples of about 2 kg weight were taken. Thin sections for petrographic analyses were cut and the remaining samples crushed (-0.5 mm) and used for the gamma-spectrometric measurements of Th, U and K contents. Then representative samples of about 50 g were obtained by quartering and pulverized to -200 mesh with a tungsten-carbide disc mill for measurements of trace and major element contents by an X-ray fluorescence method

Table 1
List of Samples

No.	Rock type	Locality
Jalisco complex:		
J 1	pyroxene-biotite-hornblende diorite	Manzanillo, Las Hadas, fresh outcrop
J 2	biotite granite	Manzanillo, Las Hadas, fresh outcrop
J 3	biotite-hornblende-pyroxene diorite	Manzanillo, Las Hadas, fresh rock from the beach
J 5	hornblende-biotite quartz monzodiorite	Carretera Manzanillo-Colima behind the village El Colomo
J 6	biotite granite	same locality, inside the village El Colomo
J 7	biotite leucogranite	km 114 carretera Barra de Navidad-Puerto Vallarta, in front of La Cumbre
J 8	biotite granodiorite	km 144 of the above carretera
J 9	biotite-hornblende granodiorite	km 155 of the above carretera, near the way to Sta. Cruz
J 10	biotite granite	km 159 of the above carretera
J 11	biotite-hornblende quartz monzodiorite	km 163 of the above carretera
J 13	hornblende-biotite quartz diorite	Sayulita, south tip of the beach
J 14	biotite quartz diorite	Sayulita, north tip of the beach
J 15	biotite granite	Sayulita, north tip of the beach
J 16	biotite-hornblende quartz monzodiorite	km 120 carretera Tepic - Puerto Vallarta
J 17	biotite-hornblende tonalite	km 195 carretera Barra de Navidad-Puerto Vallarta (in the pass)
J 18	biotite granodiorite	km 199 of the above carretera (near the coast)
J 19	biotite granite	km 204 of the above carretera, quarry Piedra
J 20	biotite granite	km 210 of the above carretera, south end of the beach near the hotel Solamar
J 21	biotite leucogranite	same locality as above, north end of the beach
J 22	biotite granite	km 209 of the above carretera, El Cariso
Baja California Sur complex (Sierra de la Victoria):		
C 3	biotite-hornblende granodiorite	km 146 carretera Cabo San Lucas-La Paz (behind San Antonio)
C 4	hornblende-biotite quartz monzodiorite porphyrite	south end of the village San Bartolo, roadcut at carretera Cabo San Lucas - La Paz
C 5	biotite granite	promontory of Cabo San Lucas, behind hotel Solmar
C 6	biotite granodiorite	Cabo San Lucas, near the hotel Finistre
C 7	biotite-hornblende granodiorite	Cabo San Lucas, on the beach below the hotel Finistre
C 8	biotite granite	Punta Rosario
C 9	hornblende-pyroxene gabbro	Punta Rosario, inclusion in granite
C 10	biotite granite	Punta Rosario
C 11	biotite leucogranodiorite	Punta Rosario
C 12	biotite granite	Las Cruces
C 13	biotite-hornblende granodiorite	Las Cruces

METHODS OF MEASUREMENT

The concentrations of Th, U and K were determined by a gamma-spectrometric method in the radiometric laboratory of the Geophysical Institute, Czechoslovak Academy of Sciences (analyst V. Vaňková). The major element contents were estimated by an X-ray fluorescence method in the geochemical laboratory of the Institute of Geology and Geotechnics, Czechoslovak Academy of Sciences (analyst Z. Houdková), and the contents of trace elements Rb, Sr, Ba, Y, Zr, V, Cr, Ni by the same method in the laboratory of the Geological Survey, Brno (analyst M. Janáčková).

Gamma-spectrometric method. The method of measurement and the data processing were described by Krešl and Vaňková (1978, 1982), therefore only a short description is given here. The gamma-ray spectra of the investigated rocks were obtained using a 1024-channel gamma-spectrometer (NTA 1024, EMG-Budapest), equipped with a NaI(T1) ϕ 10 cm x 10 cm scintillation detector (SKG-1 S N 012, Tesla-Liberec) with a reduced background and a resolution of 10.2% for ^{137}Cs. The crushed rocks (1.2 - 1.5 kg) were placed in thin-walled aluminum containers shaped so that the whole active surface of the NaI(T1) crystal was surrounded by a 1 cm thick layer of the measured rock on sides, and by a 1.5 cm thick layer on the top of the crystal. The scintillation probe and the sample were housed in a lead shielding. The apparatus was calibrated with Th, U and K standards prepared in Geofyzika, Brno (Bartošek, 1977). The concentrations of the radioactive elements were computed by the method of energy intervals, using three windows in the low energy region of the gamma-ray spectrum around the energy peaks of 0.239 MeV (Th), 0.352 MeV (U) and 1.46 MeV (K). The counting time was 5 000 s for each sample, each sample being measured three times. The relative error in determining the concentrations is about 3% for Th and U, and about 1.5% for K (Krešl and Vaňková, 1978).

X-ray fluorescence method. The instrument used for determining the contents of major elements was an analyser VRA-2 (Zeiss-Jena), equipped with two Soller collimators (divergence 0.15° and 0.70°), three crystals (ADP, PE, LiF), and radiation detectors (flow and scintillation counters). The initiation was performed by a chromium X-ray lamp (1.3 kW). The pulverized samples were mixed with polyvinyl alcohol (3:1) and after homogenization pressed under pressure of 20MPa to pellets of 40 mm in diameter. International geochemical reference samples GRANIT (GDR) and NIM-G (South Africa) were used as external standards. Every sample was measured 15 times with counting time of 20 s; the reproducibility for individual oxides was characterized by the following average relative errors: 5.7% (SiO_2), 5.3% (TiO_2), 7.0% (Al_2O_3), 2.0% (Fe_2O_3), 1.0% (MnO), 11.7% (MgO), 4.0% (CaO), 14.5% (Na_2O), 11.5% (P_2O_5).

The contents of trace elements were determined with a Phillips PW 1410 X-Ray fluorescence analyser. For the initiation a gold X-ray lamp (2.7 kW) was used. The characteristic radiation was detected by LiF crystal and scintillation or flow counter. The pulverized samples were mixed with PVC (2:1) and with the appropriate internal standard, and pressed under pressure of 30 MPa to pellets of 40 mm in diameter. Synthetic mixtures of a similar bulk composition were used as standards. International standards VAM and ZGI were analyzed for checking the procedure. The reproducibility for individual trace elements was characterized by the following average relative errors: Rb, Sr, Ba, Zr (<10%), Y, V, Cr (10-20%), Ni (~75%, values close to the detection limit).

PETROLOGY AND MAJOR ELEMENT COMPOSITION

The results of modal and chemical analyses are given in Table 2. The rock samples were classified according to the internationally adopted nomenclature of A. Streckeisen (Streckeisen, 1967; IUGS Subcommission on the Systematics of Igneous Rocks, 1973). The respective QAP diagram is given in Fig. 3. The rocks from both regions investigated show a broad variation trend (illustrated by the dashed line in Fig. 3) with the following sequence: granite → granodiorite → tonalite → quartz monzodiorite → quartz diorite → diorite → gabbro. Rocks falling in the granite field of Streckeisen's diagram correspond to adamellite (monzogranite).

As seen from Fig. 3 and Table 1, the majority of the samples studied represents biotite granites and biotite ± hornblende granodiorites. There is no specific difference in the position of J- or C-samples in the QAP diagram, and only one common variation trend can be delimited.

The abundance of granite types in both the Jalisco and Baja California Sur plutonic complexes shows certain differences from other Laramide plutons situated further north to the studied area. For instance, in the Southern California batholith granodiorites and tonalites strongly prevail over granite types (Larsen, 1948). For direct comparison rocks from the Southern California batholith were reclassified using the Streckeisen diagram and the modal analyses published by Larsen (1948) and Chayes (1956). Figure 4 shows that the rocks of the Southern California batholith are shifted relative to the variation trend followed by the Jalisco and Baja California Sur rock series as a result of higher contents of quartz and plagioclase in the former group.

The homogeneity of the Jalisco and Baja California Sur rock series is supported by the major element variations illustrated in Figs. 5 and 6 using respectively AFM and Na-Ca-K projections. The trend followed by the Jalisco and Baja California Sur samples is similar to that of the Southern California batholith (Nockolds and Allen, 1953) but is clearly shifted toward the A and Na apexes in these two diagrams.

Table 2

Chemical Analyses, Modal Composition and Plagioclase Basicities of Plutonic Rocks from Jalisco and Baja California Sur Complexes.

No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O^*	P_2O_5	qu	plag	alkf	bi	hornbl	pyr	tit	ore	ap	bas
				(weight per cent)									(volume per cent)							
J 1	50.44	1.70	16.10	8.73	0.16	4.33	7.93	4.71	1.46	0.92	-	62.7	5.6	10.0	3.1	11.3	-	6.1	1.2	An34
J 2	70.88	0.20	13.29	2.07	0.02	0.56	1.47	3.65	4.81	0.05	25.4	29.9	38.3	4.0	0.3	-	0.5	1.4	0.2	An23
J 3	53.95	1.09	16.57	7.04	0.13	3.69	6.19	5.51	1.78	0.44	-	66.8	7.0	9.8	7.3	4.5	-	4.1	0.5	An28
J 5	61.85	0.99	15.19	5.97	0.11	2.37	4.64	4.26	2.94	0.34	12.5	46.6	18.8	8.4	11.1	0.8	0.2	1.1	0.5	An30
J 6	72.47	0.18	13.26	2.20	0.03	0.36	1.31	3.38	4.72	0.03	29.7	27.4	36.5	5.7	-	-	0.1	0.5	0.1	An22
J 7	77.33	0.08	11.86	0.76	0.02	<0.05	0.60	3.64	4.60	<0.01	34.6	25.5	37.8	1.7	-	-	-	0.4	-	An18
J 8	71.70	0.09	13.34	1.85	0.09	0.39	2.03	4.38	2.88	0.05	29.4	43.0	19.4	6.9	-	-	-	1.1	0.2	An24
J 9	77.10	0.34	13.89	3.59	0.13	1.14	3.04	4.44	2.77	0.16	29.1	42.6	15.4	8.7	3.0	-	0.2	0.7	0.3	An27
J 10	69.14	0.19	14.06	2.17	0.06	0.87	2.48	4.04	3.41	0.10	25.4	41.8	24.7	7.2	0.1	-	0.1	0.5	0.2	An29
J 11	60.68	0.79	15.88	5.21	0.13	1.72	4.33	5.14	1.96	0.37	14.8	62.0	9.0	11.4	2.2	-	0.3	0.8	0.5	An30
J 13	55.92	1.02	16.04	7.20	0.14	4.10	6.68	4.46	1.36	0.41	7.1	63.1	3.3	9.3	15.4	-	-	1.3	0.5	An37
J 14	59.71	0.74	17.46	5.52	0.11	2.34	4.96	5.44	1.96	0.32	8.6	69.8	2.0	18.6	-	-	0.3	0.1	0.6	An33
J 15	74.65	0.06	13.27	1.69	0.02	0.43	2.17	3.51	3.14	0.01	35.2	35.3	21.8	7.4	-	-	-	0.2	0.1	An29
J 16	61.54	0.47	16.53	4.80	0.18	1.07	3.70	5.03	2.20	0.20	14.0	58.5	6.9	15.4	4.7	-	0.1	0.1	0.3	An26
J 17	66.02	0.50	15.66	4.70	0.11	0.54	4.32	5.00	1.36	0.18	20.1	58.1	2.3	11.2	7.8	-	0.1	0.1	0.3	An27
J 18	70.83	0.13	13.97	2.53	0.06	0.28	2.15	4.01	3.45	0.10	27.4	39.8	20.7	11.7	-	-	-	0.2	0.2	An25

Table 2 (continued)

J 19	70.73	0.07	13.51	2.45	0.09	0.18	1.98	4.11	3.45	0.07	28.0	40.1	24.8	6.9	-	-	-	0.1	0.1	An24
J 20	73.98	<0.01	13.29	1.55	0.05	<0.05	1.07	4.17	3.71	<0.01	30.8	34.8	28.6	5.6	-	-	-	0.2	-	An15
J 21	74.55	<0.01	12.92	1.07	0.05	<0.05	0.78	4.40	3.89	<0.01	30.0	34.6	32.0	3.3	-	-	-	0.1	-	An11
J 22	72.86	<0.01	14.28	1.98	0.06	0.20	1.40	4.06	3.81	0.03	30.0	35.6	27.5	6.7	-	-	-	0.1	0.1	An19
C 3	64.23	0.47	15.41	3.85	0.05	1.51	3.93	3.22	3.16	0.21	27.1	38.1	17.9	13.2	3.1	-	-	0.2	0.4	An41
C 4	61.71	0.68	15.27	4.42	0.07	2.27	4.77	4.37	2.20	0.35	13.1	45.3	17.3	2.3	20.5	-	0.1	1.4	0.6	An24
C 5	71.54	0.12	13.23	2.38	0.08	0.66	2.05	3.45	3.57	0.04	28.5	29.9	31.9	9.6	-	-	-	-	0.1	An30
C 6	68.68	0.19	14.13	3.09	0.11	0.74	2.49	4.43	2.65	0.09	25.8	47.4	12.7	13.9	-	-	-	-	0.2	An25
C 7	64.81	0.49	14.26	4.52	0.09	1.64	3.84	3.92	2.30	0.17	28.5	47.3	9.5	11.9	2.6	-	-	0.1	0.3	An34.5
C 8	70.51	0.02	14.46	1.51	0.05	0.76	2.11	4.71	3.01	0.03	25.7	43.1	25.3	4.8	0.7	-	-	0.3	0.1	An18
C 9	48.24	0.44	15.90	5.17	0.05	8.80	14.66	2.34	0.53	0.28	0.5	50.1	-	-	26.5	22.3	0.3	0.1	0.2	An60
C 10	71.90	<0.01	14.37	1.40	0.03	0.69	1.91	4.80	3.30	0.03	25.7	43.9	24.9	4.8	-	-	0.2	0.4	0.1	An20
C 11	71.34	0.06	14.37	1.77	0.05	0.81	2.23	5.08	2.67	0.03	28.4	50.7	17.1	2.9	0.1	-	0.3	0.2	0.1	An21.5
C 12	75.79	<0.01	12.75	1.26	0.01	0.55	1.65	3.31	4.18	<0.01	32.9	27.7	33.6	5.3	-	-	0.2	0.2	0.1	An27
C 13	60.15	0.86	14.23	5.59	0.10	2.74	5.06	3.90	2.06	0.31	17.1	55.2	6.5	15.5	4.7	-	0.5	0.1	0.4	An31.5

(qu-quartz, plag-plagioclase, alkf-K feldspar, bi-biotite, hornbl-hornblende, pyr-pyroxene, tit-titanite, ap-apatite, bas-plagioclase basicity)

*) gamma-spectrometric estimate.

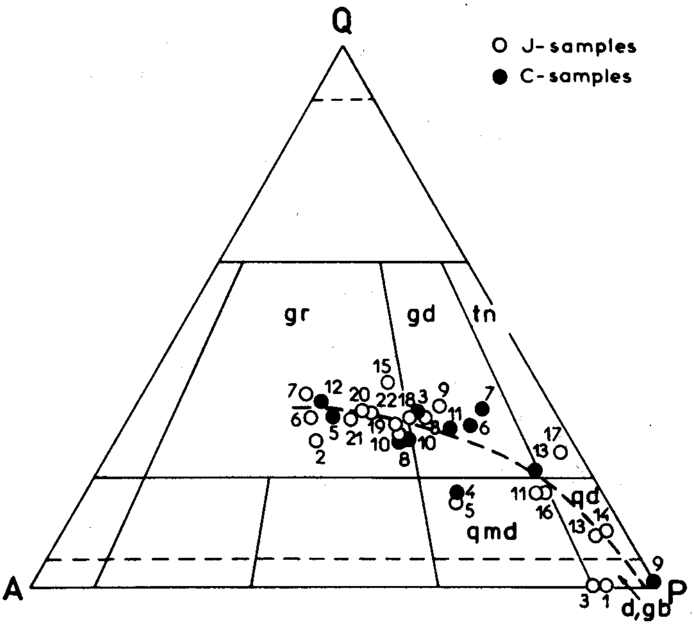

Fig. 3. Position of Jalisco and Baja California Sur granitic rocks in the Streckeisen QAP classification diagram; gr - granite, gd - granodiorite, tn - tonalite, qmd - quartz monzodiorite, qd - quartz diorite, d,gb - diorite, gabbro. Variation trend is denoted by dashed line.

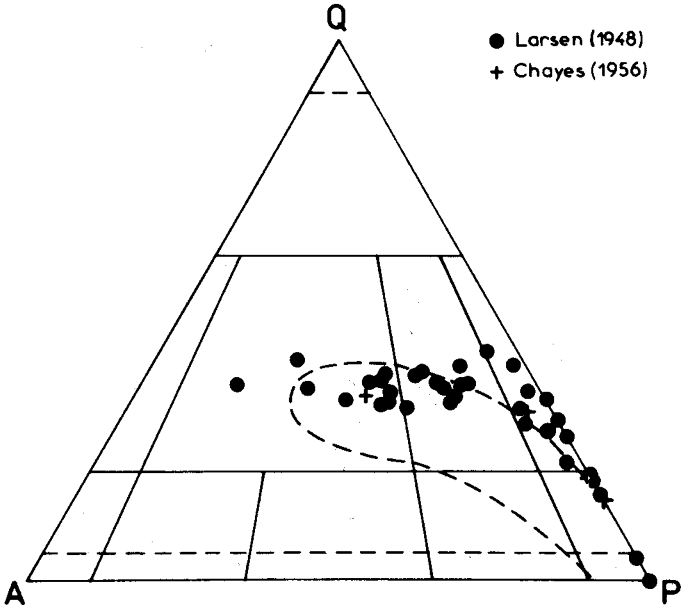

Fig. 4. Position of rocks from the Southern California batholith based on data of Larsen (1948) and Chayes (1956) in the Streckeisen QAP classification diagram. Variation field boundary of the Jalisco and Baja California Sur rock series is denoted by dashed line.

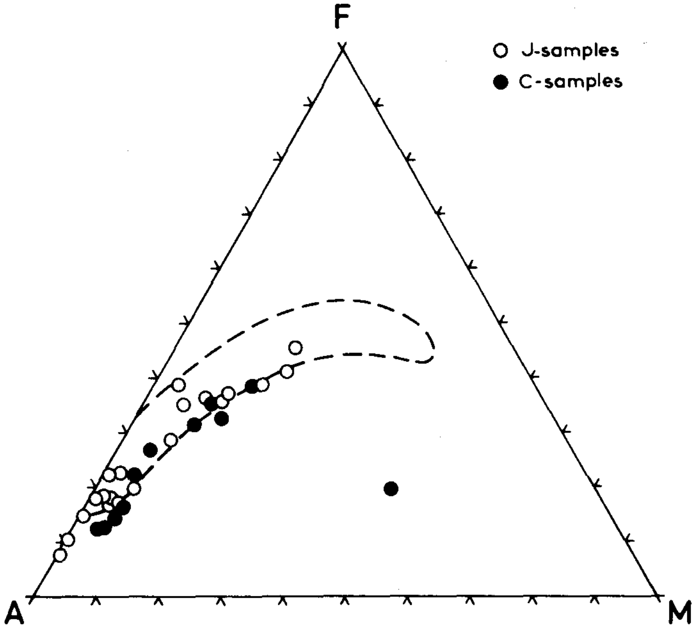

Fig. 5. Position of Jalisco and Baja California Sur granitic rocks in the AFM diagram; the dashed line denotes the corresponding variation field for the Southern California batholith.

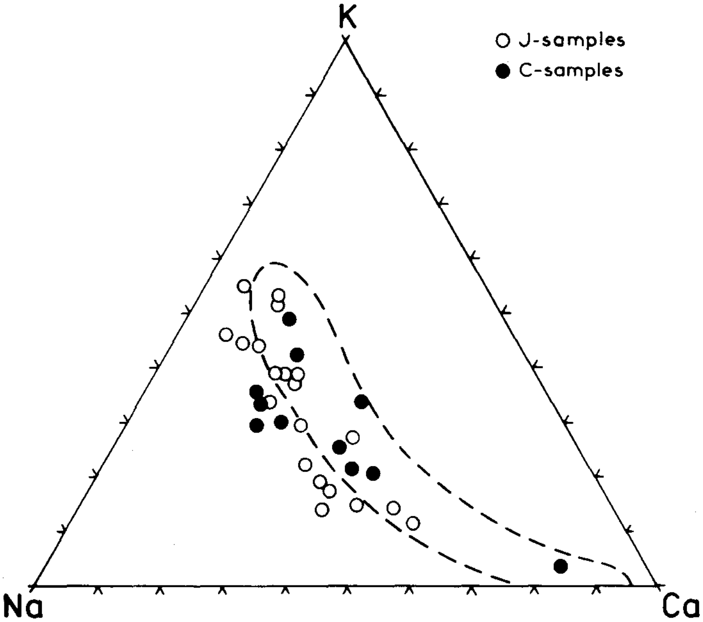

Fig. 6. Position of Jalisco and Baja California Sur granitic rocks in the Na-Ca-K diagram; the dashed line denotes the corresponding variation field for the Southern California batholith.

RADIOACTIVITY AND TRACE ELEMENTS

Radioactive Elements

The concentrations of Th, U and K in rocks from both regions investigated are given in Table 3 together with the ratios Th/U, Th/K and U/K.

Table 3

Concentration of Radioactive and Trace Elements (in ppm, K in %)

No.	Th	U	K	Th/U	Th/k x10^4	U/K x10^4	Rb	Sr	Ba	Y	Zr	V	Cr	Ni
J 1	1.27	0.73	1.21	1.7	1.0	0.6	20	620	834	33	315	169	39	19
J 2	22.90	4.73	3.99	4.8	5.7	1.2	148	149	644	56	224	30	7	< 5
J 3	2.01	0.66	1.48	3.0	1.4	0.4	24	617	992	14	219	178	30	14
J 5	7.88	2.74	2.44	2.9	3.2	1.1	80	255	661	41	262	111	37	9
J 6	23.44	4.24	3.92	5.5	6.0	1.1	170	56	112	52	94	13	5	< 5
J 7	30.36	7.64	3.82	4.0	7.9	2.0	178	96	575	60	219	29	10	6
J 8	8.10	2.13	2.39	3.8	3.4	0.9	69	274	1370	23	89	27	18	< 5
J 9	5.95	1.90	2.30	3.1	2.6	0.8	59	353	986	25	120	51	14	9
J 10	4.29	1.30	2.83	3.3	1.5	0.5	57	357	1920	21	93	37	13	< 5
J 11	5.38	1.78	1.63	3.0	3.3	1.1	54	414	995	40	301	54	17	< 5
J 13	2.42	0.80	1.13	3.0	2.1	0.7	30	584	757	24	144	183	39	10
J 14	3.66	1.54	1.63	2.4	2.2	0.9	55	533	1030	27	214	47	15	< 5
J 15	5.99	1.27	2.61	4.7	2.3	0.5	54	230	935	14	154	22	7	< 5
J 16	8.87	1.86	1.83	4.8	4.8	1.0	42	490	1350	25	270	7	12	< 5
J 17	10.52	1.90	1.13	5.5	9.3	1.7	37	372	826	27	351	17	14	< 5
J 18	9.21	4.72	2.86	2.0	3.2	1.7	120	217	849	45	110	26	12	6
J 19	10.45	4.85	2.86	2.2	3.7	1.7	122	187	766	53	126	15	11	< 5
J 20	9.75	2.37	3.08	4.1	3.2	0.8	138	90	590	47	90	20	13	< 5
J 21	13.40	4.52	3.23	3.0	4.1	1.4	160	45	315	70	78	22	9	< 5
J 22	9.08	1.82	3.16	5.0	2.9	0.6	118	116	824	41	84	20	10	< 5
Average	9.75	2.67	2.48	3.6	3.7	1.0	86	302	866	36	177	53	16	< 5
C 3	12.48	5.49	2.62	2.3	4.8	2.1	133	278	944	50	129	64	30	< 5
C 4	4.97	1.61	1.83	3.1	2.7	0.9	46	568	958	20	115	73	26	< 5
C 5	11.20	2.01	2.96	5.6	3.8	0.7	125	173	971	43	106	33	6	< 5
C 6	10.18	2.57	2.20	4.0	4.6	1.2	97	256	764	42	176	14	11	< 5
C 7	7.56	1.29	1.91	5.9	4.0	0.7	74	296	978	33	159	57	11	< 5
C 8	5.03	1.51	2.50	3.3	2.0	0.6	78	493	1080	24	52	36	16	< 5
C 9	0.67	0.61	0.44	1.1	1.5	1.4	14	400	162	14	11	226	61	25
C 10	4.77	0.96	2.74	5.0	1.7	0.4	88	460	1300	29	53	35	11	< 5
C 11	4.67	1.41	2.22	3.3	2.1	0.6	60	519	1470	22	72	40	11	< 5
C 12	30.21	5.93	3.67	5.1	8.2	1.6	129	234	892	35	70	35	13	< 5
C 13	5.30	1.87	1.71	2.8	3.1	1.1	49	515	898	22	135	107	29	8
Average	8.82	2.30	2.25	3.8	3.5	1.0	81	381	952	30	98	65	21	5

Th content: The concentrations of Th in the granites range from 4.3 to 30.4 ppm (average 14.4 ppm) for J-samples (J 2, J 6, J 7, J 10, J 15, J 19, J 20, J 21, J 22), and from 4.8 to 30.2 ppm (average 12.8 ppm) for C-samples (C 5, C 8, C 10, C 12). For the granodiorites the contents of Th are smaller varying between 5.9 and 9.2 ppm (average 7.8 ppm) for J-samples (J 8, J 9, J 18), and between 4.7 and 12.5 ppm (average 8.0 ppm) for C-samples (C 3, C 6, C 7, C 11, C 13). The concentrations of Th in tonalite, quartz monzodiorites, quartz diorites, diorites and gabbro decrease systematically from 10.5 to 0.7 ppm with increasing basicity of rocks.

U content: The values of the U content in the granites vary from 1.3 to 7.6 ppm (average 3.6 ppm) for J-samples, and from 1.0 to 5.9 ppm (average 2.6 ppm) for C-samples. For the granodiorites the ranges are 1.9 to 4.7 ppm (average 2.9 ppm) for J-samples, and 1.3 to 5.5 ppm (average 2.5 ppm) for C-samples. The U concentrations in the remaining rock types show again a decreasing tendency from 2.7 to 0.6 ppm with increasing basicity.

K content: The K contents in the granites vary from 2.6 to 4.0% (average 3.3%) for J-samples, and from 2.5 to 3.7% (average 3.0%) for C-samples. In the granodiorites the K concentrations range from 2.3 to 2.9% (average 2.5%) for J-samples, and from 1.7 to 2.6% (average 2.1%) for C-samples. The K contents in more basic rock types decrease from 1.8 to 0.4%. A slightly higher K value of 2.4% was found for the quartz monzodiorite J 5, for which a relatively high U concentration of 2.7 ppm was also observed.

Trace Elements

The contents of the trace elements Rb, Sr, Ba, Y, Zr, V, Cr, Ni of the plutonic rocks investigated are given in Table 3.

The average concentrations of individual elements in the granites are as follows: for J-samples 127 ppm Rb, 147 ppm Sr, 742 ppm Ba, 46 ppm Y, 129 ppm Zr, 23 ppm V, 9 ppm Cr, < 5 ppm Ni; for C-samples 105 ppm Rb, 340 ppm Sr, 1061 ppm Ba, 33 ppm Y, 70 ppm Zr, 35 ppm V, 11 ppm Cr, < 5 ppm Ni. In the granodiorites the following average values were obtained: for J-samples 83 ppm Rb, 281 ppm Sr, 1068 ppm Ba, 31 ppm Y, 106 ppm Zr, 35 ppm V, 15 ppm Cr, 6 ppm Ni; for C-samples 83 ppm Rb, 373 ppm Sr, 1021 ppm Ba, 34 ppm Y, 134 ppm Zr, 56 ppm V, 18 ppm Cr, < 5 ppm Ni.

ANALYSIS OF RESULTS

The comparison of the petrological and geochemical characteristics of rocks from the Jalisco and Baja California Sur plutonic complexes was carried out by an analysis of histograms of measured concentrations of radioactive and trace elements, by average concentrations for granites and granodiorites, by variation trends of rock types based on the QAP diagram, and by a correlation analysis of concentrations of selected pairs of elements. Moreover, average concentrations of radioactive and trace elements in the Jalisco and Baja California Sur plutonic complexes were also compared to those published for the Southern California batholith, which represents the nearest well-investigated plutonic member of the North-American Pacific belt of batholiths.

Histograms and Average Concentrations

Histograms of the contents of radioactive elements Th, U and K without distinguishing the rock types are shown in Fig. 7, separately for the Jalisco and Baja California Sur complexes. The corresponding histograms for the trace elements Rb, Sr, Ba, Y, Zr, V, Cr are given in Figs. 8a, b. The intervals of frequency distribution were roughly chosen as 2/3 of the standard deviation σ.

The histograms of the contents of radioactive elements Th, U, K practically cover the same range for both regions in question; the shapes of the histograms for the individual elements appear to be very similar, if we consider the relatively small number of samples (Fig. 7). Both differences in dispersion and in average values between the sets of J- and C-samples were tested statistically by F- and t-tests; for Th, U and K concentrations the differences at the level $p = 0.05$ were found to be statistically insignificant.

The histograms of the contents of trace elements are also similar for both regions J and C. For Rb, Sr, Ba, Y, V, Cr the histograms cover the same range for J- and C-samples, their shapes being reasonably similar (Fig. 8a, b). The only exception is for Zr, which has distinct averages for J and C samples. The statistical F- and t-tests show that the differences in dispersion and in average values are statistically insignificant at the level $p = 0.05$ between the sets of J- and C-samples for Rb, Sr, Ba, Y, V, Cr. The only significant difference between both sets of samples was again found for Zr. However, the distribution of this element, which is predominantly fixed in accessory zircon, may be inhomogeneous in respect to the amount of material sampled and thus may not be representative.

The average concentrations of radioactive and trace elements for the granites and granodiorites from both regions are compared in Fig. 9. The variation limits for more numerous subsets of samples (J-samples for granite, C-samples for granodiorite) are also plotted. It can be seen that in all cases the average concentrations for J- and C-samples are within the variation limits with the exception of Zr for the granites. It follows that statistically there is no difference in the content of radioactive

U, Th and K and in the trace element geochemistry between the granites and granodiorites from the Jalisco and Baja California Sur plutonic complexes.

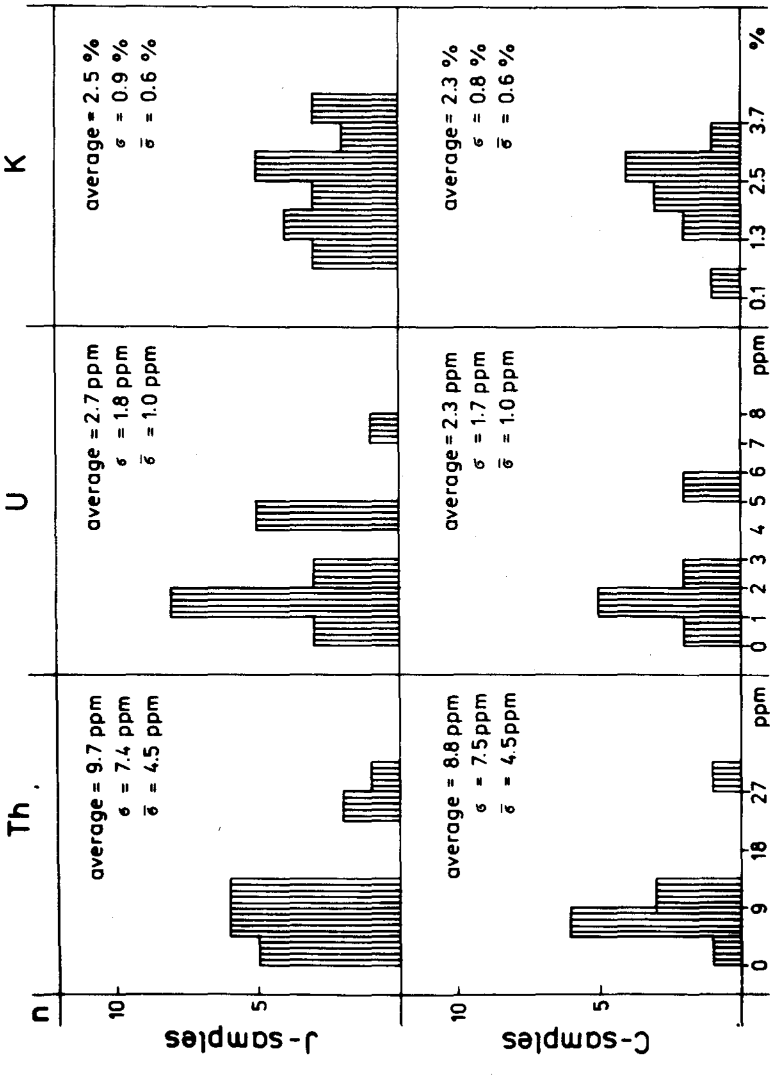

Fig. 7. Histograms of measured concentrations of radioactive elements Th, U, K for J- and C-samples; σ -standard deviation, $\overline{\sigma}$ - interval of frequency distribution, n - number of samples.

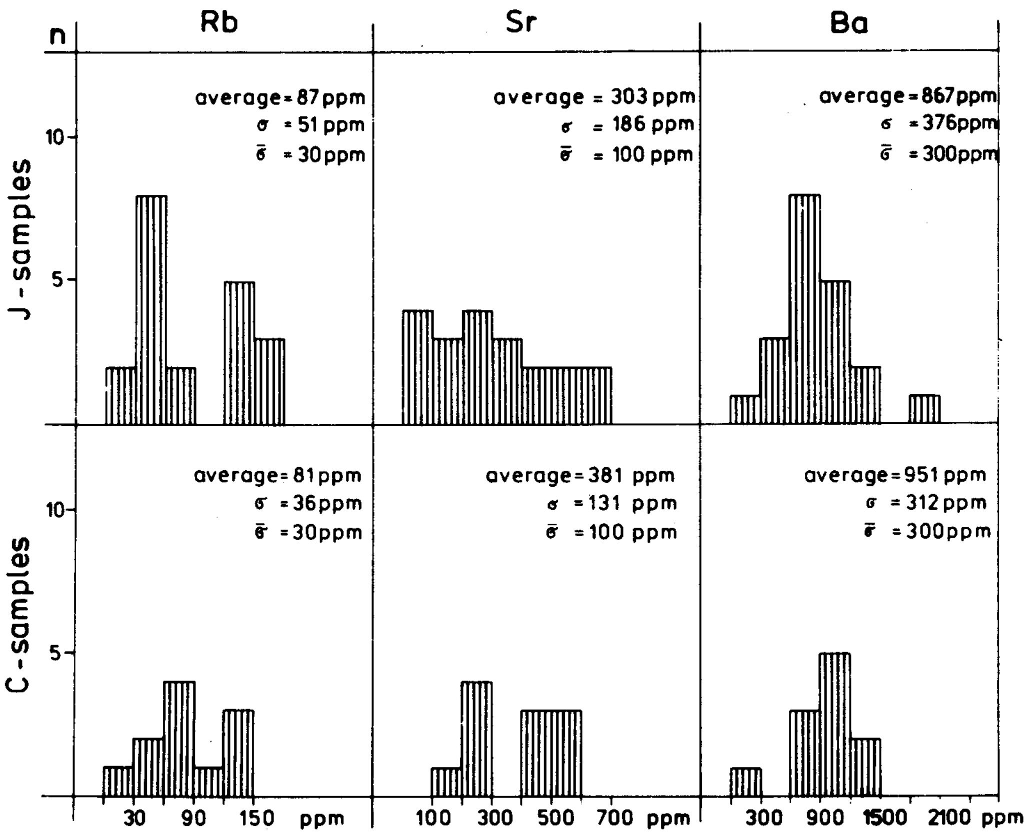

Fig. 8a. Histograms of measured concentrations of trace elements Rb, Sr, Ba for J- and C-samples; σ - standard deviation, $\bar{\sigma}$ - interval of frequency distribution, n - number of samples.

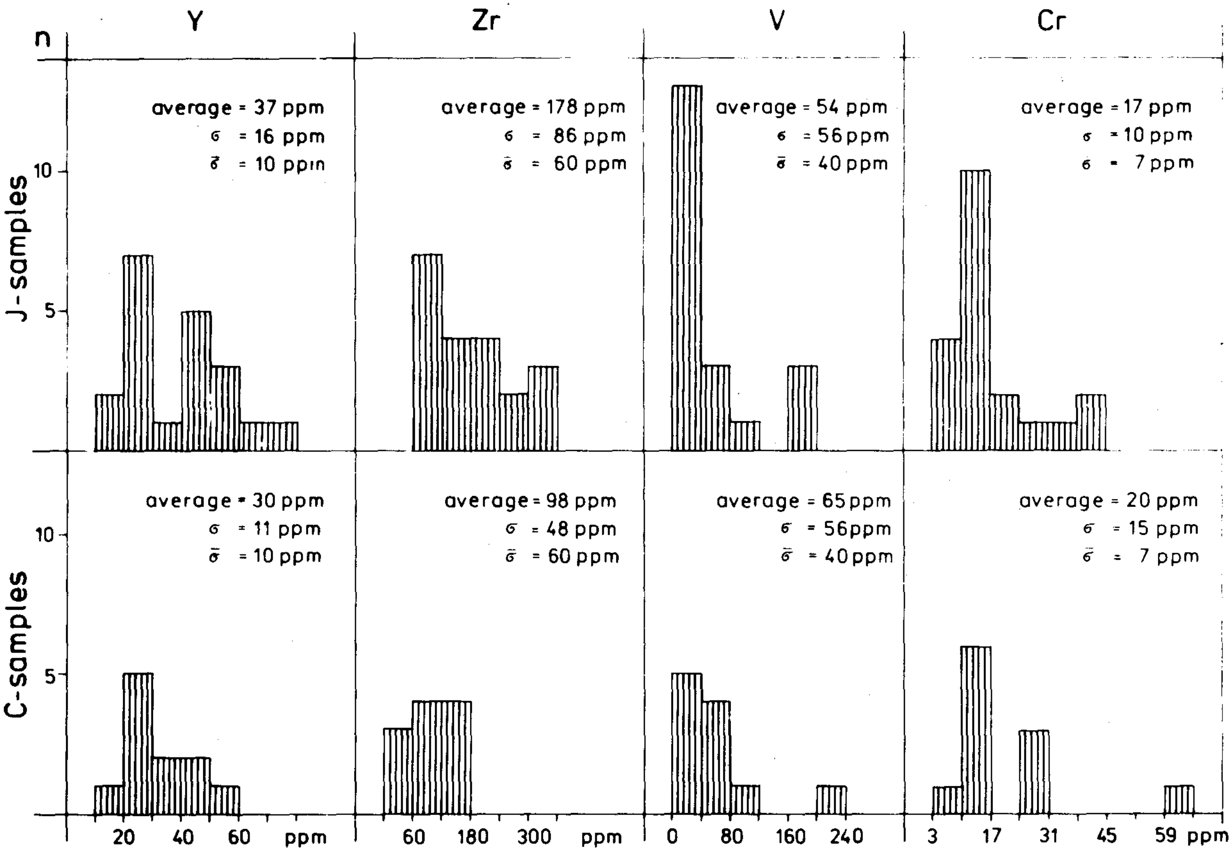

Fig. 8b. Histograms of measured concentrations of trace elements Y, Zr, V, Cr for J- and C-samples; σ - standard deviation, $\bar{\sigma}$ - interval of frequency distribution, n - number of samples.

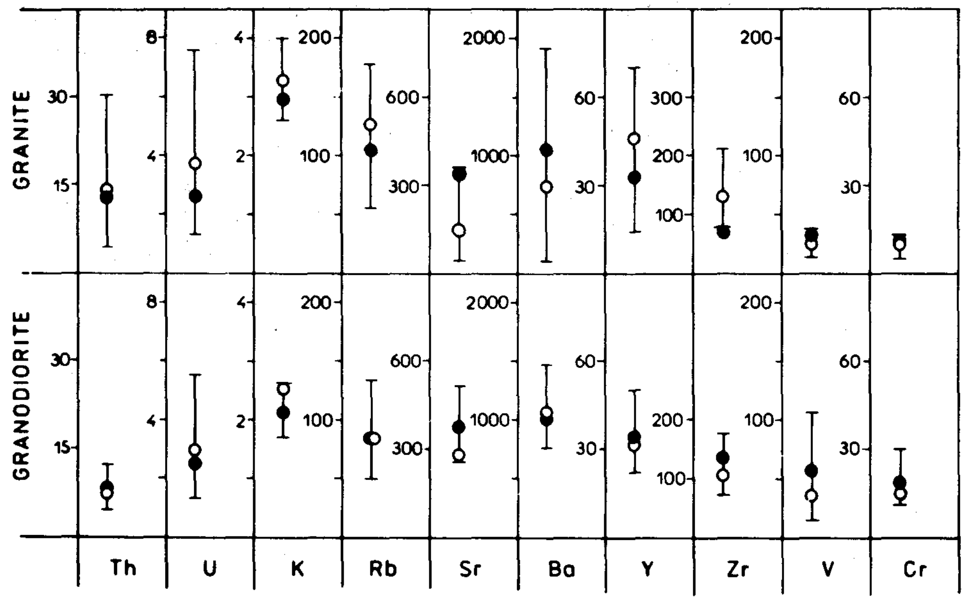

Fig. 9. Comparison of average concentrations of radioactive and trace elements for granites and granodiorites; values for J-samples are denoted by open circles, for C-samples by full circles; for granites variation limits of J-samples, for granodiorites variation limits of C-samples are plotted. Concentrations in ppm, for K in %.

Variation Trends

To compare the differentiation process in the Jalisco and Baja California Sur plutonic complexes, variation diagrams were constructed for the average trace element contents of the individual members of the variation sequence based on the QAP diagram from Fig. 4. The results for Th, U, Rb, Sr, Ba, Y, Zr, V, Cr are summarized in Fig. 10 where the average contents for J- and C-samples are plotted by different symbols. The average trends (dashed lines in Fig. 10) reflect the behaviour of the trace elements along the variation sequence. The contents of Th, U, Rb, and Y show a decreasing tendency with increasing basicity, while the contents of Sr, V and Cr tend to increase with increasing basicity. The contents of Ba stay practically constant except for the gabbro and the contents of Zr vary without any systematic tendency. All the above tendencies are in general agreement with trends observed in igneous rock series from plutonic complexes (e.g., Nockolds and Allen, 1953).

As can be seen from Fig. 10 the average values for J- and C-samples of individual rock types closely follow the same variation trends, thus manifesting a very similar process of differentiation.

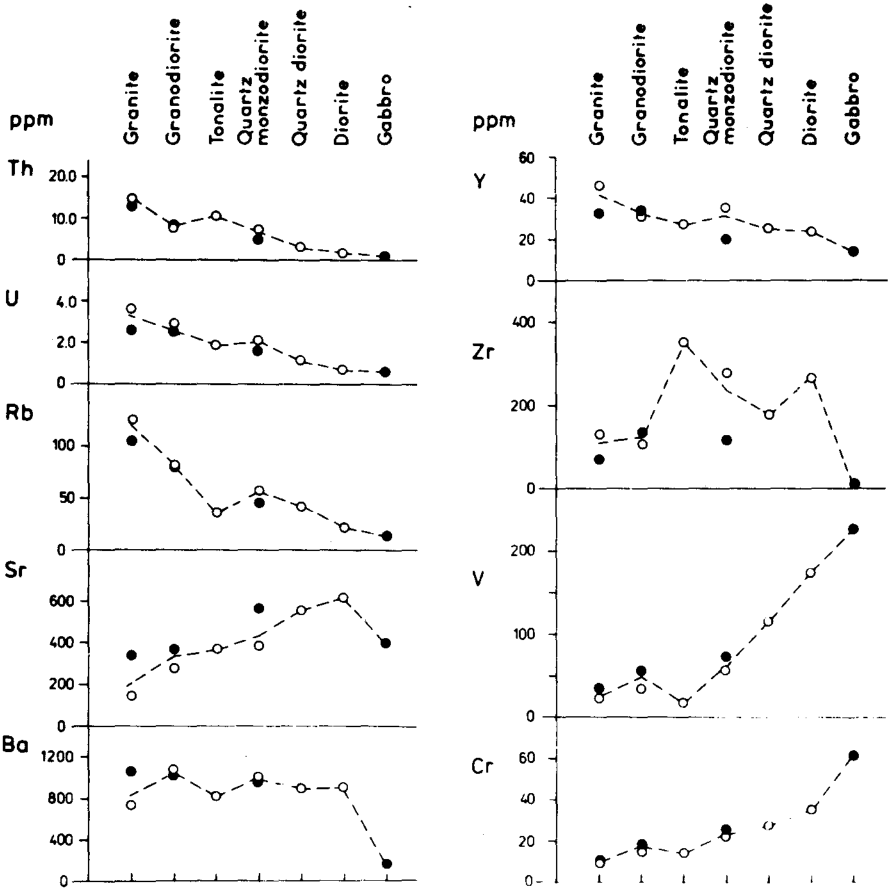

Fig. 10. Variation of the average trace element contents with increasing basicity of the individual rock members from Jalisco (open circles) and Baja California Sur (full circles) plutonic complexes; dashed line - average for both J- and C- samples.

Pair Correlation Analysis

It is known that the concentrations of radioactive and trace elements in rocks are not independent and their relations should provide information on the genesis and evolution of different rock types. Therefore, a linear correlation analysis of all possible pair combinations of elements was performed and the correlation coefficients $\underset{\sim}{r}$ of all relations were computed. The aim of the correlation analysis applied in this paragraph was to compare all strong relations between elements found for the rocks from the Jalisco and Baja California Sur plutonic complexes.

The calculated correlation coefficients $\underset{\sim}{r}$ for both the J-samples and C-samples are given in Table 4. It must be noted that the values for the gabbro sample C 9 were not considered in the correlations because this sample is from an inclusion in

Table 4

Coefficients of linear pair correlation between contents of radioactive and trace elements for J-samples (upper figure) and C-samples (lower figure).

	U	K	Rb	Sr	Ba	Y	Zr	V	Cr
Th	+0.87	+0.78	+0.84	–0.71	–0.54	+0.71	–0.09	–0.50	–0.56
	+0.85	+0.79	+0.71	–0.65	–0.40	+0.46	–0.08	–0.27	–0.14
U		+0.75	+0.86	–0.71	–0.51	+0.82	–0.18	–0.47	–0.49
		+0.62	+0.73	–0.54	–0.39	+0.60	+0.05	–0.05	+0.28
K			+0.92	–0.89	–0.38	+0.68	–0.55	–0.59	–0.66
			+0.82	–0.57	+0.01	+0.45	–0.52	–0.55	–0.40
Rb				–0.90	–0.62	+0.88	–0.47	–0.55	–0.60
				–0.86	–0.26	+0.88	–0.04	–0.49	–0.25
Sr					+0.50	–0.72	+0.53	+0.70	+0.68
					+0.48	–0.89	–0.34	+0.46	+0.41
Ba						–0.69	+0.05	+0.01	+0.09
						–0.40	–0.65	–0.13	–0.24
Y							–0.19	–0.36	–0.36
							–0.40	–0.37	–0.13
Zr								+0.31	+0.38
								+0.24	+0.21
V									+0.92
									+0.80

granite and has no equivalent in our set of J-samples. Also the correlations with Ni were not performed because its content was below the detection limit for 22 samples. Due to the statistically insufficient number of samples in individual subsets the conditions for admissibility of the linear correlation analysis could not be tested. Therefore, only strong relations characterized by $|\underset{\sim}{r}|>0.7$ at least in one subset were considered and were used in the comparison of plutonic rocks from both regions in question. It follows from Table 4 that the relations between the following pairs of elements have $|\underset{\sim}{r}|>0.7$: for J-samples (Th, U), (Th, K), (U, K), (Th, Rb), (U, Rb), (K, Rb), (Th, Sr), (U, Sr), (K, Sr), (Rb, Sr), (Th, Y), (U, Y), (Rb, Y), (Sr, Y), (V, Cr); for C-samples (Th, U), (Th, K), (Th, Rb), (U, Rb), (K, Rb), (Rb, Sr), (Rb, Y), (Sr, Y), (V, Cr). The majority of relations is present in both subsets of samples. Six relations, characterized by $|\underset{\sim}{r}|<0.7$ in the subset of C-samples and by $|\underset{\sim}{r}|>0.7$ in the subset of J-samples, were scrutinized further. It appears that the Y content in the granite sample C 12 was either erroneously determined or anomalously low. After omitting this value we obtained for the subset of C-samples $\underset{\sim}{r}(\mathrm{Th, Y}) = +0.97$, $\underset{\sim}{r}(\mathrm{U, Y}) = +0.73$, $\underset{\sim}{r}(\mathrm{Rb, Y}) = +0.93$, $\underset{\sim}{r}(\mathrm{Sr, Y}) = -0.91$. For the relations (U, K), (Th, Sr), (U, Sr), (K, Sr) correlation coefficients, slightly smaller than $|0.7|$, are caused by a relatively smaller number of samples in the C-subset. However, it seems that the correlation is strong enough to be assumed as significant.

Considering the above analysis we can construct a scheme of correlation coefficients characterizing the relations between the pairs of elements, which are significant for the rocks from both the Jalisco and Baja California Sur plutonic complexes. This scheme is shown in Table 5 by the corresponding signs of correlation coefficients. The significant coefficients, for which $|\underset{\sim}{r}|<0.7$ in the C-subset, are given in brackets.

It is evident that for many pairs of elements no correlation must exist. This also follows from the values of correlation coefficients in Table 4. If we take the condition $|\underset{\sim}{r}|<0.5$ as a criterion for non-existence of any linear correlation between two elements, we can complete the scheme of Table 5 by the cases, for which no correlation exists in both subsets of samples. These cases, denoted by zero in Table 5, play the same role in the comparison of the Jalisco and Baja California Sur plutonic complexes as the relations with significant correlation coefficients. Thus, 28 from 45 possible relations show the same behaviour for rocks from both plutonic complexes considered. However, it does not mean that the remaining 17 cases are at variance with this conclusion; the latter cases are usually characterized by a weak linear correlation in one of the subsets with $0.5<|\underset{\sim}{r}|<0.7$, which cannot be used as significant in comparing both subsets of samples.

Table 5

Scheme of significant linear correlation coefficients (denoted by the corresponding signs) and of non-existing pair correlation (denoted by zeros) for both J- and C-samples.

	U	K	Rb	Sr	Ba	Y	Zr	V	Cr
Th	+	+	+	(–)		+	0		
U		(+)	+	(–)		+	0	0	0
K			+	(–)	0				
Rb				–		+	0		
Sr						–			
Ba								0	0
Y							0	0	0
Zr								0	0
V									+

The above analysis shows that the relations between pairs of elements for rocks from both the Jalisco and Baja California Sur plutonic complexes are very similar and manifest a close geochemical affinity of rocks from both regions. This conclusion is supported by the consistent values of slopes of the corresponding regression lines for significant correlations (see Table 6).

Table 6

Values of slopes of regression lines with significant correlation coefficients for J-samples (upper figure) and C-samples (lower figure)

	U	K	Rb	Sr	Ba	Y	Zr	V	Cr
Th	0.21±0.03 0.19±0.04	0.09±0.02 0.06±0.02	5.7±0.9 2.9±1.0	−17.9±4.1 −12.0±5.0		1.5±0.3 3.4±0.3			
U		0.38±0.08 0.21±0.09	24.5±3.4 13.4±4.5	−74.3±17.2 −44.5±24.3		7.2±1.2 5.9±2.1			
K			51.8±5.4 44.6±11.1	−185.1±21.9 −138.8±70.5					
Rb				−3.3±0.4 −3.8±0.8		0.27±0.03 0.33±0.05			
Sr						−0.06±0.01 −0.07±0.01			
Ba									
Y									
Zr									
V									0.17±0.02 0.26±0.07

Comparison with the Southern California Batholith

The petrological and geochemical similarity of granitic rocks from the Jalisco and Baja California Sur plutonic complexes demonstrated in the preceding paragraphs can be used as an independent argument for the tectonic separation of both complexes by the process of opening of the Gulf of California. However, the weight of this argument depends on the assumption that the individual members of the Pacific belt of Laramide batholiths can be distinguished by the petrology and geochemistry of rocks from these batholiths. Therefore, a comparison with the Southern California batholith, the nearest and geochemically well-investigated neighbour in the belt, is given in Table 7.

The averages for the individual rock types of the Southern California batholith were computed from available published data. The rock types from Nockolds and Allen (1959) had to be re-classified in the Streckeisen system (see Fig. 4) on the basis of modal analyses of the corresponding samples published by Larsen (1948). The same general sequence in trace element content with decreasing basicity is generally observed between the two batholiths, which may be interpreted as to reflect a similar mechanism of formation. However, differences in the average contents of individual elements for the same rock type can be observed between both batholiths, especially for Rb, Sr, Ba, Zr, V and Cr. The differences in the Rb and Sr contents and Rb/Sr ratio are particularly conspicuous.

It must be emphazised that a comparison of average values obtained from a relatively small number of rock samples may be relevant only as a part of a complex of petrological and geochemical investigations. In our case the differences noted between the Southern California and Jalisco-Baja California Sur batholiths are fully supported by the petrological analysis and by the behaviour of major elements (Figs. 4, 5, 6).

Table 7

Comparison of average contents of selected trace elements in the rock members of studied plutonic complexes of Jalisco and Baja California Sur with those of the Southern California Batholith (contents in ppm); standard errors $(\Sigma \epsilon^2/n(n-1)^{1/2}$ are given in brackets.

Rock type	Number of samples				Th	U	Rb	Sr	Ba	Y	Zr	V	Cr	Ni
							Jalisco - Baja California Sur							
granite	13				13.9(2.5)	3.3(0.6)	120(11)	207(39)	839(120)	44(4)	111(15)	27(2)	10(1)	<5
granodiorite	8				7.9(0.9)	2.7(0.5)	83(10)	338(38)	1039(82)	33(4)	124(11)	48(10)	17(3)	<5
tonalite + qz monzodiorite + qz diorite	7				6.2(1.0)	1.7(0.2)	49(6)	459(42)	940(79)	29(3)	237(30)	70(21)	23(4)	5(1)
diorite + gabbro	3				1.3(0.3)	0.7(0.02)	19(2)	546(59)	663(208)	20(5)	182(73)	191(14)	43(7)	19(3)
	a	b	c	d			Southern California*							
granite	5	10	5	7	15.0	4.3(0.4)	279(33)	102(18)	1057(48)	34(3)	121(22)	14(4)	5(2)	<3
granodiorite	31	42	18	7	8.6	2.3(0.2)	168(24)	236(12)	807(73)	31(4)	189(20)	61(7)	6(1)	5(2)
tonalite + qz diorite	15	20	9	10	4.0	1.8(0.2)	100(14)	315(62)	535(71)	19(2)	112(12)	90(15)	26(7)	12(4)
norite + gabbro	9	13	8	5	0.9	0.4(0.1)	5(1)	580(103)	25(10)	8(2)	22(5)	256(73)	105(37)	17(6)

* Data and number of samples: (a) for Th from Whitfield *et al.* (1959), Larsen and Gottfried (1960), Rogers and Ragland (1961), standard errors could not be estimated; (b) for U from Whitfield *et al.* (1959), Larsen and Gottfried (1961), Rogers and Ragland (1961); (c) from Simon and Rollinson (1976); (d) for remaining elements from Nockolds and Allen (1953).

CONCLUSIONS

From the comparison of petrology and geochemistry of granitic rocks of the Jalisco and Baja California Sur plutonic complexes the following conclusions can be drawn:

1) The results of modal analysis show that there is no specific difference in the position of the Jalisco and Baja California Sur samples in the Streckeisen QAP diagram and only one common variation trend can be delimited.

2) Major element composition, plotted in the AFM and Na-Ca-K projections, supports the homogeneity of the whole set of samples from both regions.

3) The histograms of the contents of selected trace elements (Th, U, Rb, Sr, Ba, Y, V, Cr) practically cover the same range and the differences in dispersion and in average values were found to be statistically insignificant for both regions.

4) The variation of the average trace element contents along the sequence granite → granodiorite → tonalite → quartz monzodiorite → quartz diorite → diorite → gabbro shows the same trend for both subsets of samples and thus suggests that the same process of differentiation may have been operative in the formation of both plutonic complexes.

5) The analysis of linear correlations between pairs of trace elements shows a close geochemical affinity of the rocks from both the Jalisco and Baja California Sur plutonic complexes.

6) The comparison with the Southern California batholith shows that the variability in petrology and geochemistry between neighbouring batholiths of the coastal batholithic belt is more pronounced than the differences between both plutonic complexes investigated.

We conclude that the petrological and geochemical characteristics of the Jalisco and Baja California Sur plutonic complexes support the idea of their original contiguity in the same batholithic body and are not in contradiction to their later tectonic separation connected with the opening of the Gulf of California.

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