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RADIOACTIVITY OF UPPER MESOZOIC GRAYWACKES IN THE NORTHERN COAST RANGES, CALIFORNIA

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ABSTRACT

Traverses across the Coast Ranges north of San Francisco were made to measure the field gamma radioactivity and to sample graywackes of the Franciscan formation, its Coastal Belt unit and the Great Valley sequence. In the laboratory, specimens were analyzed for U, Th, and K by gamma spectrometry; K-feldspar contents were determined by point-counting stained slabs. Average values are given below.

	Number of samples	U (ppm)	Th (ppm)	K (%)	K-feldspar (%)	Th/U	Radiogenic heat production (μcal/g-y)
Franciscan (non-Coastal Belt) graywackes	37	2.01	6.73	1.24	0.0	3.4	3.2
Graywackes of Coastal Belt	29	2.02	7.68	1.61	9.1	3.8	3.4
Graywackes of Great Valley sequence	20	1.06	3.49	0.94	5.3	3.4	1.8

The K-feldspar content has little effect on radioactivity or heat production of the rock units. Low K-feldspar content does not indicate low heat generation; therefore, low-temperature-high-pressure

metamorphism is not related to K-feldspar content. Radioactivity tends to decrease with increasing metamorphic grade. Thorium/uranium ratios fall within the range described by Adams and Weaver (1958) as typical of eugeosynclinal sediments, and are like Th/U ratios in granitic rocks of the Sierra Nevada, the suggested source area. Uranium, Th, and K concentrations of the graywackes are compatible with those of a cratonal source.

When the heat-production values are combined with heat-flow measurements now being obtained, the thicknesses of the sedimentary columns and the effect of the rocks' radiogenic heat on the observed geothermal gradient may be calculated.

INTRODUCTION

The northern Coast Ranges of California consist chiefly of three Upper Mesozoic units that are predominantly graywacke, with interrelationships that are not yet completely understood (Bailey and others[1]). Both field and laboratory γ-ray studies were recently made of these graywackes, to provide additional data regarding their facies relations and radiogenic heat production, as well as their U, Th, and K content.

Two of the dominantly sedimentary units have previously been assigned to the Franciscan Formation, although they are known to have some distinctive characteristics; we follow this assignment, even though it introduces some problems of nomenclature. A western unit, extending chiefly west of U. S. Highway 101, has been called the Coastal Belt (of the Franciscan Formation) by Bailey and Irwin.[2] In this report we call it the Coastal Belt, only the remainder of the Franciscan Formation that occupies the more central part of the northern Coast Ranges is termed Franciscan. The third thick sedimentary unit, known as the Great Valley sequence, is exposed along the west edge of the Great Valley and in a few elongated masses farther west (see Fig. 1).

The content of detrital K-feldspar in graywacke in these units was extensively studied by Bailey and Irwin,[2] who found that most Franciscan graywackes in the northern Coast Ranges contain no K-feldspar, while Coastal Belt and Great Valley graywackes have appreciable concentrations (up to 27% in Coastal Belt and 35% in Great Valley rocks). The general lack of K-feldspar in the Franciscan graywacke suggested that these rocks might have abnormally low

radioactivity, which would result in abnormally low heat production. It was suggested that such low heat-generating capacity might account for the metamorphosis of deeply buried parts of thick piles of these rocks to the unusual blueschists that contain mineral assemblages characteristic of an environment with low temperature relative to pressure. Gamma-ray spectrographic measurements, which measure the abundance of not only ^{40}K but also the other natural gamma-emitting radioisotopes of the ^{238}U and ^{232}Th series, lead to direct knowledge of the total radiogenic heat production. Knowledge of the K, U, and Th content also permits one to evaluate the relation between radioactivity and the source materials, and it places limits on the possible depositional environments of the graywacke.

To make field measurements and collect samples for laboratory counting, the authors made traverses of the Coast Ranges north of San Francisco Bay, following some of the routes taken by Bailey and Irwin in their K-feldspar studies. In the laboratory these samples were analyzed for U, Th, and K by γ-ray spectrographic techniques. Point counts of K-feldspar were made under the microscope on stained slabs of all samples containing visible grains of this mineral.

FIELD PROCEDURES

Field operations involved a threefold procedure: (a) determination of the location, lithology, and formational affiliation of the rock exposure under study, (b) radiometric scanning with a portable scintillation counter, and (c) sampling. Geologic and topographic control was provided chiefly by the Santa Rosa and Ukiah sheets of the Geologic Map

of California (Olaf P. Jenkins edition, published by the California Division of Mines and Geology) and by the larger-scale sources used for these maps. Recognition of rock units was based on the criteria stated by Bailey et al.[1]

Field Radiometry

The radiation detection instrument used for field work was designed and built at the Lawrence Radiation Laboratory; details of the basic circuitry have been published by Goldsworthy.[3] The detector is a 3-in.-diameter by 3-in.-thick thallium-activated sodium iodide [NaI(Tl)] scintillation crystal, viewed by a Dumont 6363 3-in.-diameter photomultiplier tube. The detector assembly is shock-mounted, insulated, and housed in a 5-in.-diam by 12-in.-high 1/16-in.-thick stainless steel case, and is connected to the indicator unit by 5 ft of coaxial cable. To provide better instrument stability, especially with respect to moisture problems, the high voltage supply for the phototube is mounted in the detector case. The indicator unit contains a linear pulse amplifier, a pulse-height selector circuit with a variable discriminator, and a multirange indicator circuit sensitive to count rate. All electrical power for the instrument is supplied by a single self-contained 10.75-V mercury battery.

Five linear ranges in the count-rate circuitry span the intervals of 0 to 25, 0 to 100, 0 to 500, 0 to 5000, and 0 to 10 000 counts/sec by the use of a single metered scale marked with 50 divisions. The five ranges are calibrated by use of a variable-frequency pulse generator, furnishing a check on full-scale deflection and scale linearity. Calibration in terms of radiation intensity is accomplished by exposure to

known intensities of γ rays (corrected for background) from ^{226}Ra sources certified by the National Bureau of Standards. The γ-ray energy threshold of the detector is set at approximately 120 keV. The ^{226}Ra γ-ray calibrations are listed in Table I. The scale most frequently used in this study was the range from 0 to 0.0125 mr/hr. The most sensitive scale, used for lowest-intensity measurements, provides scale divisions corresponding to increments of 0.0125 μr/hr.

For routine calibration checks in the field we use a disk source of refined uranium. The source is placed flat against the end of the detector nearest the crystal. Calibration is verified if we observe the correct count rate when the source is in this standard position; the variable discriminator is used for calibration adjustment.

In smooth terrain, readings are made only with the detector face against the outcrop's surface.

In step-like terrain or in road cuts, field readings are made in two configurations, (a) with the detector face against a surface of the outcrop, and (b) with the bottom portion of the side of the cylinder against the lower portion of the scarp. The latter configuration generally gives a higher reading, since source-detector geometry is closer to 4π than with the face against the rock. Readings in both configurations are recorded in counts per second, and are averaged for each location.

Sampling

Our general field-sampling philosophy is to get the most representative sample of an outcrop from a minimum amount of material (approximately 1.5 kg); therefore the sampling varied somewhat from site to site. In general, where an outcrop is bedded or

Table I. Ranges of the portable scintillation counter, and calibration with respect to ^{226}Ra.

Scale range (counts/sec)	Scale range (mr/hr)	Smallest scale division (mr/hr)
0 to 25	0 to 0.000625	0.0000125
0 to 100	0 to 0.0025	0.00005
0 to 500	0 to 0.0125	0.00025
0 to 5000	0 to 0.125	0.0025
0 to 10 000	0 to 0.250	0.005

strongly laminated, but of a single general lithology, a pick sample is taken perpendicular to the bedding or laminations. Where obviously separate lithologies are in conjunction at a sampling site--e.g., at a sandstone-shale contact or where massive sandstone is interbedded with shale--we attempt to sample these separately. Samples are contained and transported in heavy-duty polyethylene bags. On return to the laboratory samples are reduced in size to less than 0.5 in. in a jaw crusher, then placed in a thin-walled polyethylene container, 4 in. diameter by 3.5 in. long, for counting.

LABORATORY COUNTING EQUIPMENT AND PROCEDURE

Laboratory γ-ray spectroscopy utilizes a detector unit consisting of a 4-in.-diam $\times$ 2-in.-thick NaI(Tl) crystal coupled optically to a Dumont type-6363 phototube. The detector unit is housed in a 2-in.-thick Pb block shield situated in the Lawrence Radiation Laboratory's low-background counting room. The counting room is made of low-radioactivity concrete comprised of serpentine aggregate and a low-

radioactivity cement (the facility is described in detail by Wollenberg and Smith[4]). Components of the measured background are derived primarily from contributions from the cement in the enclosure, activity extraneous to the room (cosmic ray interactions), and activity in the detector; background is a steady 141 counts/min as measured on the 100-channel spectrometer.

Samples are counted with the container lid against the flat face of the detector crystal case. Counting time depends upon the radioactivity of the sample and the precision required for the data. Low-activity samples require counting times on the order of 1000 min, moderate activities 200- to 500-minute runs.

Output from the detector is sent to a UCRL Model 6 linear pulse amplifier whose output drives a Penco PA-4 100-channel differential pulse-height analyzer. The gain of the system is adjusted so that each channel is 20 keV wide, and the total γ energy interval spanned is from 0.08 to 2.08 MeV. The gain stability of the system is checked periodically by use of a ^{137}Cs source.

At completion of a run, stored analyzer data are tabulated on a Victor printer adding machine and are simultaneously plotted on semi-logarithmic paper to produce a curve (spectrum) of counts per channel vs energy.

DATA ANALYSIS

The U, Th, and K contents of a sample are determined from analysis of the 100-channel spectrum. Analyses are based upon calibration spectra from standard samples of assayed equilibrium ores of

U and Th, obtained from the New Brunswick Laboratory of the AEC, and chemically pure KCl. From these standard spectra we determine the contribution of each isotope in specific energy intervals in which decay products of U (^{214}Bi), Th (^{208}Tl), and ^{40}K predominate. Similar techniques are used by many workers studying natural γ emitters; an extensive bibliography is given by Adams.[5]

Data from a sample run yield the number of counts in each of the three intervals. After correction for background count rate, these data are combined with coefficients determined from standard spectra in three simultaneous equations, whose solution gives the contributions of U, Th, and K to the observed spectrum. These results are then combined with sample weight and calibration factors to compute the actual concentrations of U, Th, and K in each sample. (Data reduction is described in detail by Wollenberg and Smith in Ref. 6.) Results for U and Th are based on the assumption that they are in radioactive equilibrium with their decay products. We also assume that the ratio $^{39}K/^{40}K$ is constant in nature. By application of radiogenic heat values given by Birch[7]--i.e., 1 ppm U = 0.73 μcal/g-yr, 1 ppm Th = 0.20 μcal/g-yr, 1% K = 0.27 μcal/g-yr--we calibrate heat-generation values for the specimens.

Actual analysis is performed by use of a computer code which utilizes as inputs counting time, weight of sample, and the number of counts in each of the three energy intervals. The errors considered are only those due to the statistical nature of the counting procedure and are dependent upon the number of counts and the length of counting time.

RESULTS

The geographic distribution of samples is shown on the generalized geologic map, Fig. 1. The area is underlain principally by the Franciscan Formation, its Coastal Belt, and on the east by rocks of the Great Valley sequence. Potassium, K-feldspar, U, and Th contents of the samples of each formation are illustrated on Figs. 1a, 1b, and 1c.

Field and laboratory data are shown on Table II. The data and average values given at the end of the table indicate that the Franciscan and Coastal Belt graywackes are roughly similar in radioactive content, while Great Valley graywackes are considerably less radioactive. The frequency distribution plots for heat, U, Th, and K content (Fig. 2) also indicate this difference as well as the uniformity of values among Coastal Belt samples. Uranium, thorium, and consequently heat values for the Franciscan cover a fairly broad range; 1 to 3.2 ppm for U, 3.3 to 12 ppm for Th, and 1 to 5 μcal/g-yr for heat. Values for Great Valley rocks cover ranges of similar width. Coastal Belt values are more confined; 1.4 to 2.7 ppm for U, 4.5 to 11.5 ppm for Th, and 2.3 to 5.0 μcal/g-yr for heat. This is also illustrated for U in the cumulative frequency plot, Fig. 3, where the Coastal Belt line is straighter than those for Franciscan or Great Valley rocks.

The Franciscan graywacke samples contain appreciable K (up to 2.15%), though practically all showed no trace of K-feldspar. Metamorphosed Franciscan graywacke appears to be slightly lower in K than the unmetamorphosed rock (1.19 vs 1.30%). The average K content determined by γ-ray spectrography of the Franciscan graywackes, 1.24%, compares with 1.61% for Coastal Belt and 0.94% for Great Valley rocks.

Table II. Radioactivity data.

Field No.	Lab. No.	Field count rate (c/sec)	Lab. count rate (c/min-g)	U (ppm)	Th (ppm)	K (%)	K-feld-spar (%)	K in feld-spar* (%)	K not in feld.* (%)	Heat (μcal/g-y)	Th/U
					Franciscan graywacke						
63-288	295-C	220	0.476	1.26	3.44	0.88	0		0.88	1.8	2.8
63-289	309-C	275	0.794	1.67	7.64	1.22	0		1.22	3.1	4.6
63-291	311-C	230	0.486	1.50	4.16	0.53	0		0.53	2.1	2.8
63-292	312-C	275	0.713	1.18	6.54	1.46	0		1.46	2.6	5.5
63-294	314-C	280	0.753	1.62	6.28	1.45	0		1.45	2.8	3.9
63-313	324-C	260	0.629	1.34	5.49	1.14	0		1.14	2.4	4.1
64-300	540-C	420	1.26	3.13	11.2	1.88	0.1	0.01	1.87	5.0	3.6
64-301	549-C	360	1.09	3.05	9.48	1.38	0		1.38	4.5	3.1
64-302	550-C	317	0.78	1.85	7.20	1.17	0		1.17	3.1	3.9
64-304	552-C	295	0.83	2.50	6.31	1.24	0		1.24	3.4	2.5
64-324	622-C	290	0.87	1.92	7.60	1.51	0.7	0.09	1.42	3.3	4.0
64-325	616-C	270	0.88	1.76	7.43	1.76	0.7	0.09	1.67	3.2	4.2
64-326	621-C	255	1.09	2.79	10.6	1.24	0		1.24	4.5	3.8
64-327	617-C	300	1.21	2.77	12.1	1.58	0		1.58	4.9	4.4
64-328	623-C	285	1.04	2.55	8.59	1.80	0.6	0.08	1.72	4.1	3.4
64-329	618-C	300	0.86	2.15	7.15	1.42	0		1.42	3.4	3.3
64-330	627-C	200	0.47	1.26	4.15	0.66	0		0.66	1.9	3.3
64-338	641-C	360	1.25	2.72	11.2	2.15	0		2.15	4.8	4.1
64-339	643-C	325	1.04	2.86	9.54	1.20	0		1.20	4.3	3.3
64-347	630-C	225	0.62	1.55	4.69	1.15	0		1.15	2.4	3.0
64-349	632-C	225	0.49	1.30	3.92	0.78	0		0.78	1.9	3.0
64-333	626-C	260	1.07	2.93	8.81	1.56	0		1.56	4.3	3.0
64-334	639-C	240	0.64	1.78	5.02	1.00	0		1.00	2.6	2.8
64-335	619-C	230	0.52	1.06	4.11	1.15	0		1.15	1.9	3.9

Field No.	Lab. No.	Field count rate (c/sec)	Lab. count rate (c/min-g)	U (ppm)	Th (ppm)	K (%)	K-feld-spar (%)	K in feld-spar* (%)	K not in feld.* (%)	Heat (μcal/g-y)	Th/U
				Franciscan metamorphosed sandstone							
64-336	628-C	315	1.02	2.54	8.67	1.63	0		1.63	4.0	3.4
64-340	644-C	290	0.87	1.95	7.21	1.64	0		1.64	3.3	3.7
64-342	645-C	270	0.66	1.68	5.31	1.13	0		1.13	2.6	3.2
64-343	647-C	245	0.73	2.14	6.54	0.82	0		0.82	3.1	3.1
64-344	648-C	205	0.52	1.49	3.39	1.00	0		1.00	2.0	2.3
64-345	649-C	240	0.64	1.83	4.90	1.02	0		1.02	2.6	2.7
64-346	629-C	230	0.64	1.74	4.72	1.17	0		1.17	2.5	2.7
64-348	631-C	200	0.55	1.23	3.73	1.29	0		1.29	2.0	3.0
64-350	633-C	255	0.54	1.53	4.14	0.88	0		0.88	2.2	2.7
64-351	634-C	255	0.51	1.37	3.63	0.97	0		0.97	2.0	2.7
64-352	620-C	285	0.85	2.16	6.33	1.62	0		1.62	3.3	2.9
64-353	636-C	285	0.78	2.12	5.91	1.30	0		1.30	3.1	2.9
64-354	637-C	250	0.62	1.68	4.68	1.08			1.08	2.4	2.8
				Coastal Belt graywacke							
63-299	320-C	390	1.20	2.53	11.4	1.87	4.5	0.59	1.28	4.6	4.5
63-300	316-C	315	0.83	1.63	7.35	1.57	6.7	0.88	0.69	3.1	4.5
63-301	319-C	325	0.86	2.09	7.26	1.45	7.4	0.97	0.48	3.4	3.5
63-302	321-C	335	0.91	1.81	9.15	1.35	11.9	1.35	0	3.5	5.0
63-303	323-C	375	1.02	2.72	9.49	1.19	14.2	1.19	0	4.2	3.5
63-307	329-C	360	0.97	1.75	9.18	1.79	0.1	0.01	1.78	3.6	5.2
63-308	330-C	485	1.14	2.26	10.2	2.13	13.6	1.78	0.35	4.3	4.5
63-309	327-C	550	1.18	2.37	10.2	2.26	13.3	1.74	0.52	4.4	4.3
63-310	333-C	330	0.84	2.32	7.70	0.97	7.1	0.93	0.04	3.5	3.3
63-312	334-C	360	0.91	1.88	7.75	1.75				3.4	4.0
64-305	554-C	340	0.89	1.83	7.81	1.66	15.4	1.66	0	3.3	4.3
64-306	555-C	320	0.74	1.83	5.66	1.38	9.9	1.30	0.08	2.8	3.1
64-307	557-C	290	0.79	1.84	6.62	1.42	7.5	0.98	0.44	3.0[5]	3.6
64-308	558-C	295	0.83	2.02	6.37	1.61	12.6	1.65	0	3.2	3.2
64-309	569-C	320	0.77	1.94	6.08	1.35	9.1	1.19	0.16	3.0	3.1

Field No.	Lab. No.	Field count rate (c/sec)	Lab. count rate (c/min-g)	U (ppm)	Th (ppm)	K (%)	K-feld-spar (%)	K in feld-spar* (%)	K not in feld.* (%)	Heat (μcal/g-y)	Th/U
64-310	560-C	300	0.81	1.63	6.67	1.68	9.1	1.19	0.49	3.0	4.1
64-311	561-C	305	0.77	1.89	6.14	1.38	9.2	1.21	0.17	3.0	3.2
64-312	562-C	340	0.94	2.35	6.99	1.82	11.9	1.56	0.26	3.6	3.0
64-313	563-C	270	0.81	1.94	6.72	1.39	2.9	0.38	1.01	3.1	3.5
64-314	565-C	295	0.76	1.89	6.08	1.34	3.6	0.47	0.87	3.0	3.2
64-315	570-C	340	1.05	2.42	8.49	1.97	19.5	1.97	0	4.0	3.5
64-316	571-C	265	0.60	1.47	4.52	1.17	9.9	1.17	0	2.3	3.1
64-317	572-C	300	0.96	2.03	7.53	2.05	8.7	1.18	0.87	3.5	3.7
64-318	573-C	240	0.91	2.19	6.31	1.97	7.8	1.02	0.95	3.4	2.9
64-319	574-C	305	0.95	1.85	8.85	1.67	9.8	1.28	0.39	3.6	4.8
64-320	608-C	375	1.02	2.14	9.28	1.72	9.9	1.30	0.42	3.9	4.3
64-321	609-C	280	0.98	1.76	7.90	2.24	11.2	1.47	0.77	3.5	4.5
64-322	614-C	320	0.87	2.29	7.26	1.33	11.2	1.33	0	3.5	3.2
64-323	615-C	265	0.86	1.90	8.15	1.28	6.8	0.89	0.39	3.4	4.3
				Great Valley graywacke							
63-273[a]	276-C	325	1.08	2.30	9.63	1.89	13.8	1.81	0.08	4.1	4.2
63-274[a]	277-C	240	0.45	0.93	4.34	0.74	2.9	0.38	0.36	1.7[5]	4.7
63-276[a]	280-C	185	0.35	0.82	2.20	0.80	5.1	0.67	0.13	1.3	2.7
63-278[a]	284-C	170	0.31	0.82	1.88	0.67	4.6	0.60	0.07	1.2	2.3
63-281[a]	291-C	265	0.73	1.55	5.66	1.47	20.0	1.47	0	2.7	3.4
63-282[c]	292-C	185	0.29	0.66	2.17	0.60	0.2	0.03	0.57	1.1	3.3
63-287[b]	294-C	175	0.20	0.45	1.69	0.33	1.0	0.13	0.20	0.8	3.8
63-305[a]	328-C	130	0.11	0.35	0.67	0.19	1.6	0.19	0	0.4[5]	1.9
63-306[a]	332-C	135	0.10[5]	0.12	0.89	0.28	0.2	0.03	0.25	0.3	7.4
63-314[b]	336-C	280	0.61	1.13	5.15	1.32	15.9	1.32	0	2.2	4.6
64-331[a]	625-C	225	0.67	1.49	5.04	1.44	6.3	0.82	0.62	2.5	3.4
64-332[a]	624-C	335	0.96	2.27	7.23	1.90	12.8	1.67	0.53	3.6	3.2
64-341[a]	646-C	190	0.28	0.69	2.10	0.52	1.4	0.18	0.34	1.1	3.0
64-355[c]	568-C	235	0.48	1.43	3.39	0.82	0.5	0.06	0.76	1.9	2.4
64-356[c]	544-C	205	0.45	1.12	3.14	1.01	1.2	0.16	0.85	1.7	2.8

Field No.	Lab. No.	Field count rate (c/sec)	Lab. count rate (c/min-g)	U (ppm)	Th (ppm)	K (%)	K-feld-spar (%)	K in feld-spar* (%)	K not in feld.* (%)	Heat (μcal/g-y)	Th/U
64-357[b]	547-C	165	0.21	0.70	1.27	0.33	0		0.33	0.9	1.8
64-358[b]	548-C	165	0.18	0.59	1.21	0.27	0.2	0.03	0.24	0.75	2.0
64-359[b]	553-C	215	0.39	0.78	3.11	0.85	1.0	0.13	0.72	1.4	4.0
64-360[a]	556-C	350	1.00	2.10	6.56	2.56	14.7	1.92	0.64	3.5	3.1
64-361[a]	559-C	185	0.35	0.64	2.28	0.88	2.7	0.35	0.53	1.2	3.6
				Average values							
Unmetamorphosed Franciscan				2.05	7.19	1.30				3.3	3.6
Metamorphosed Franciscan				1.80	5.33	1.19				2.8	3.0
All Franciscan				2.01	6.73	1.24				3.2	3.4
Coastal Belt				2.02	7.68	1.61	9.1	1.18	0.43	3.4	3.8
Great Valley											
a. Upper Cretaceous				1.19	4.04	1.11				2.0	3.6
b. Lower Cretaceous				0.73	2.50	0.62				1.2	3.2
c. Upper Jurassic				1.08	2.92	0.81				1.8	2.9
All Great Valley				1.06	3.49	0.94	5.3	0.60	0.34	1.8	3.4
All Samples				1.79	6.30	1.29				3.0	3.5

*based on an ideal formula of $K Al Si_3 O_8$

Standard-method rock analyses on different samples give for the Franciscan graywacke 0.83% K (15 analyses), for Coastal Belt graywacke 1.16% K (3 analyses), and for Great Valley graywackes 0.66% K (14 analyses). K-feldspar averages 9.1% in Coastal Belt and 5.3% in Great Valley samples. In these two units there is a rough correlation between total K and K-feldspar, though the range is broad, as shown on Fig. 4. The absence of K-feldspar in the Franciscan graywackes appears to have little effect on radiogenic heat production in that unit, although in Coastal Belt and Great Valley graywackes, where K-feldspar is present in appreciable quantities, there is a slight correlation between K-feldspar and radioactivity, as shown on Fig. 5. It is interesting to compare average calculated maximum values of "K in feldspar" (based on an ideal formula of $K\,Al\,Si_3O_8$) with "K not in feldspar"; Table II shows that in Coastal Belt graywackes an average of 1.18% K (% of total rock by weight) is in K-feldspar, 0.43% is associated with other minerals. In Great Valley graywackes, averages are 0.60% K in K-feldspar, 0.34% K associated with other minerals. Thus, the ratio of K in feldspar to K in other minerals is appreciably higher in Coastal Belt graywackes (2.74) than in the Great Valley series (1.76).

Thorium-to-uranium ratios are fairly similar in the three major rock units; 3.8 for Coastal Belt, 3.4 for both Franciscan and Great Valley graywackes. The Th/U ratio in specimens of metamorphosed Franciscan graywacke is down to 3.0, while unmetamorphosed Franciscan graywackes average 3.6. The low for Great Valley graywackes is 2.9 in three upper Jurassic specimens, while 12 upper Cretaceous specimens average 3.6.

DISCUSSION

K-Feldspar

The presence or absence of K-feldspar appears to have little or no significant effect on the radioactivity of the rock units. There is a slight correlation in Great Valley and Coastal Belt graywackes, but the absence of K-feldspar in Franciscan graywackes is not accompanied by an apparent depletion of U, Th, or even total K. It follows that low K-feldspar content does not indicate low heat generation; therefore, low-temperature–high-pressure metamorphism is not related to K-feldspar content. In the Franciscan, K must be associated with other minerals--probably micas, clay minerals, and perhaps zeolites.

Metamorphism

Metamorphism in the Franciscan appears on the basis of a few samples to have an effect on U, Th, and K contents, with increasing metamorphic grade accompanied by lower concentrations. A comparison of Franciscan rocks exhibiting varying degrees of metamorphism is shown on Table III. These values indicate the relatively low radioactivity of the blueschist rocks and eclogite compared with the protoliths for these metamorphic rocks. By comparison, it is interesting to note that Heier and Adams[8] observed a decrease in U, Th, and K concentrations in gneissic rocks increasing in metamorphic grade from the epidote-amphibolite to high-granulite facies.

Heat Production

From a knowledge of radiogenic heat production, one can calculate its contribution to the heat flow near the earth's surface. One must assume the length of the column of radioactive material under

Table III. Radioactivity of Franciscan rocks with varying degrees of metamorphism.

Description	U (ppm)	Th (ppm)	K (%)
Average for 24 slightly metamorphosed to unmetamorphosed graywackes	2.05	7.19	1.30
Average of 14 metamorphosed graywackes	1.80	5.33	1.19
Glaucophane schist, (metagraywacke) Sample No. 63-297	0.36	0.47	0.25
Glaucophane schist, (metagraywacke) Sample No. 63-311	1.27	4.62	1.31
Glaucophane schist Sample No. 64-303	0.17	0.44	0.30
Eclogite, Valley Ford	0.31	0.24	0.05

consideration; in the case of the combined Franciscan-Coastal Belt graywackes, 15 km. Radiogenic heat production is about 3×10^{-13} cal/cm^3-sec. Thus, a 15-km column would contribute a heat flow of 4.5×10^{-7} cal/cm^2-sec. This divided by a thermal conductivity estimated at 6×10^{-3} cal/cm-sec-°C yields a contribution to the geothermal gradient (near the surface) of 7.5°C/km. The above heat flow value is about 1/3 of the average measured over the earth. (Heat flow measurements have not yet been made in this sector of the Coast Range, though some will be made soon.)

Consider the equation for steady-state temperature (Tx) in a semi-infinite medium with uniform heat production and thermal conductivity in a layer of thickness x_0 (Jaeger[9]):

$$Tx = 1/K\,(Q_{x_0} x - Px^2/2),$$

where K = thermal conductivity,

Q_{x_0} = heat flow at the surface of the layer, due only to production in the layer,

P = rate of heat production.

When the above values for the Franciscan-Coastal Belt are used, the calculated temperature at 15 km, attributable to heat production in the layer, is 56°C. Similarly, for Great Valley graywackes, using a 12-km thickness and a heat production value of 1.55×10^{-13} cal/cm^3-sec, the temperature attributable to heat production is 19.5°C. When future heat-flow measurements are made one may, with some

validity, calculate the effect on the geothermal gradient due to heat flow from below the layers, in essence adding another term inside the parenthesis of the equation; total temperatures at the bottom of the intervals may then be calculated.

Depositional Environment and Source Area

Adams and Weaver[10] suggest that Th/U ratios can be used as indicators of sedimentary processes. A compilation of 319 Th and U determinations enabled them to group sedimentary rocks into three broad geochemical facies:

I: high Th/U (>7) as found in some beach placers, bauxites, continental shales, and deeply weathered soils;

II: intermediate Th/U (2 to 7); a reflection of poor weathering and rapid deposition of igneous rock detritus, examples are the eugeosynclinal rocks, gray-green shales and graywackes;

III: low Th/U (< 2) as found in marine black shales and phosphates, and carbonate rocks with little detrital silicate material.

In their paper Adams and Weaver had no data for graywackes; gray-green shales had mean values of 3.2 ppm U, 13.1 ppm Th, and Th/U 4.9. Corresponding values for North Coast Range graywackes, though lower than values for gray-green shales, are compatible with the range of Th/U ratios expressed in category II.

Rogers and Richardson[11] present data on Th, U, and K contents of graywackes from the Eocene of western Oregon. These values are used to derive weighted average values for all sandstones. Average values for whole-rock concentrations of ten specimens are 2.1 ppm U, 6.7 ppm Th, 1.16% K, and Th/U 3.2. These are similar to the average

values we found for the 87 North Coast Range samples: 1.79 ppm U, 6.30 ppm Th, 1.29% K, and Th/U 3.5.

On the basis of studies of Tertiary igneous and sedimentary rocks in the Caribbean island arc and western Washington and Oregon, Rogers[12] and Rogers and Donnelly[13] contend that eugeosynclinal material is noncratonal and is most likely derived from the upper mantle. Their conclusion[13] is based on "...the absence of K-feldspar from geosynclinal graywackes and the low content of radioactive materials..." in eugeosynclinal rocks. We find K-feldspar essentially absent from the non-Coastal Belt Franciscan graywackes, but K is fairly abundant, as are Th and U. There is evidence of some upper-mantle-like material of low radioactivity interbedded with or intruding Franciscan sediments--serpentinized ultramafic rock with U < 0.05 ppm, Th < 0.10 ppm, K absent; and submarine volcanic rock with average values (two specimens) U 0.40 ppm, Th 1.62 ppm, and K 0.71%. However, the graywackes are considerably more radioactive, suggesting an appreciable contribution from an intermediate intrusive source.

Rocks of the Sierra Nevada have been suggested as a likely source of the Franciscan and Coastal Belt graywackes as well as for the Great Valley graywackes. The mean Th/U ratio for the graywackes, 3.5, compares well with the ratio 3.2 determined by Wollenberg and Smith[14] for an extensive Sierran pluton, the "Dinkey Creek"-type granodiorite (>115 million years old). Radioisotope concentrations for this granodiorite are 3.5 ppm U, 10.8 ppm Th, and 1.9% K. A Sierran source composed partly of such granitic rock (or older, less radioactive plutonic rock) and partly of metamorphosed Paleozoic and Mesozoic

sedimentary and volcanic rocks considerably lower in radioactivity, could conceivably have contributed material with a radioactivity similar to that observed in the graywackes.

The "Dinkey Creek" pluton, where sampled, is well to the south of the rocks studied in the Coast Ranges, and is probably younger than the Franciscan graywackes. We plan extensive radiometry in older plutons further north, and in the metamorphic rocks, permitting a better comparison of Sierran and Coast Range radioactivities. At this time it is sufficient to state that the Th/U ratio for the graywackes is compatible with that of "average" granitic rocks, and that radioactivities are indicative of a continental source.

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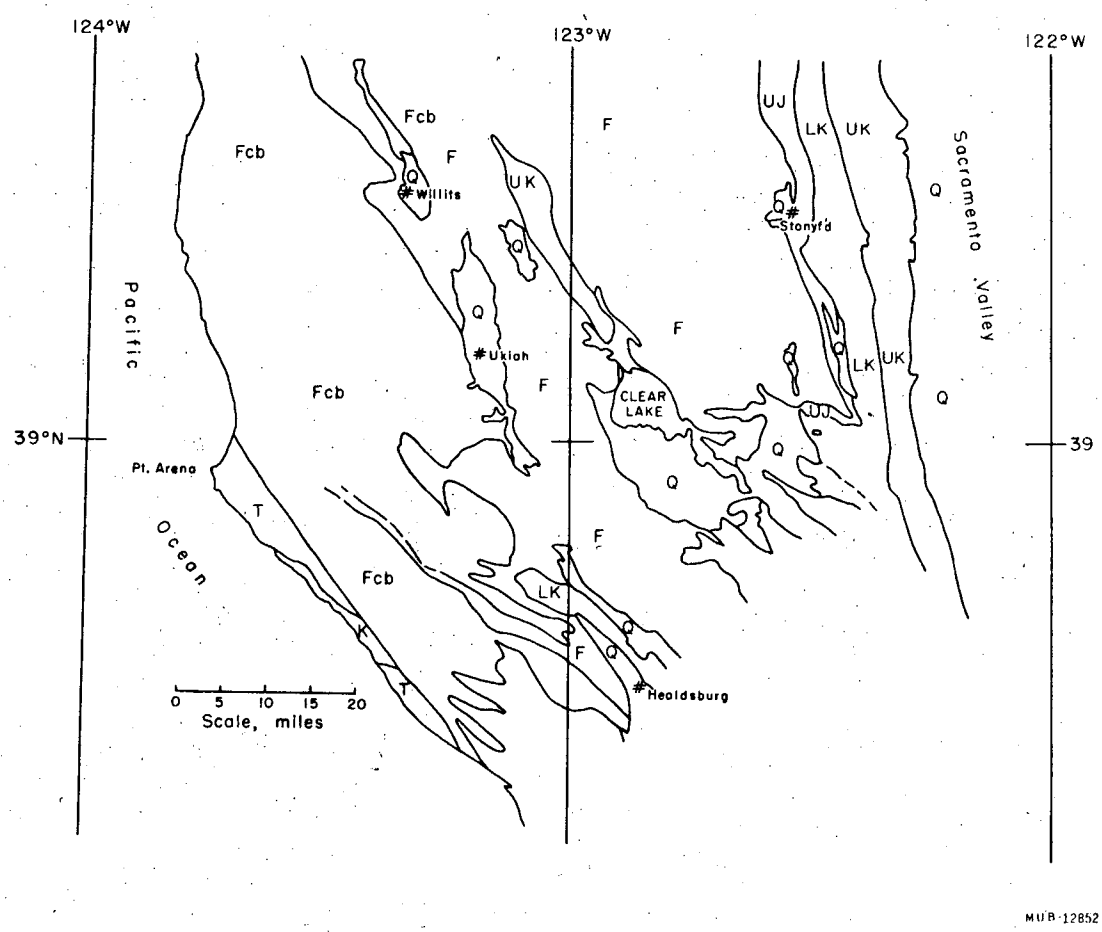
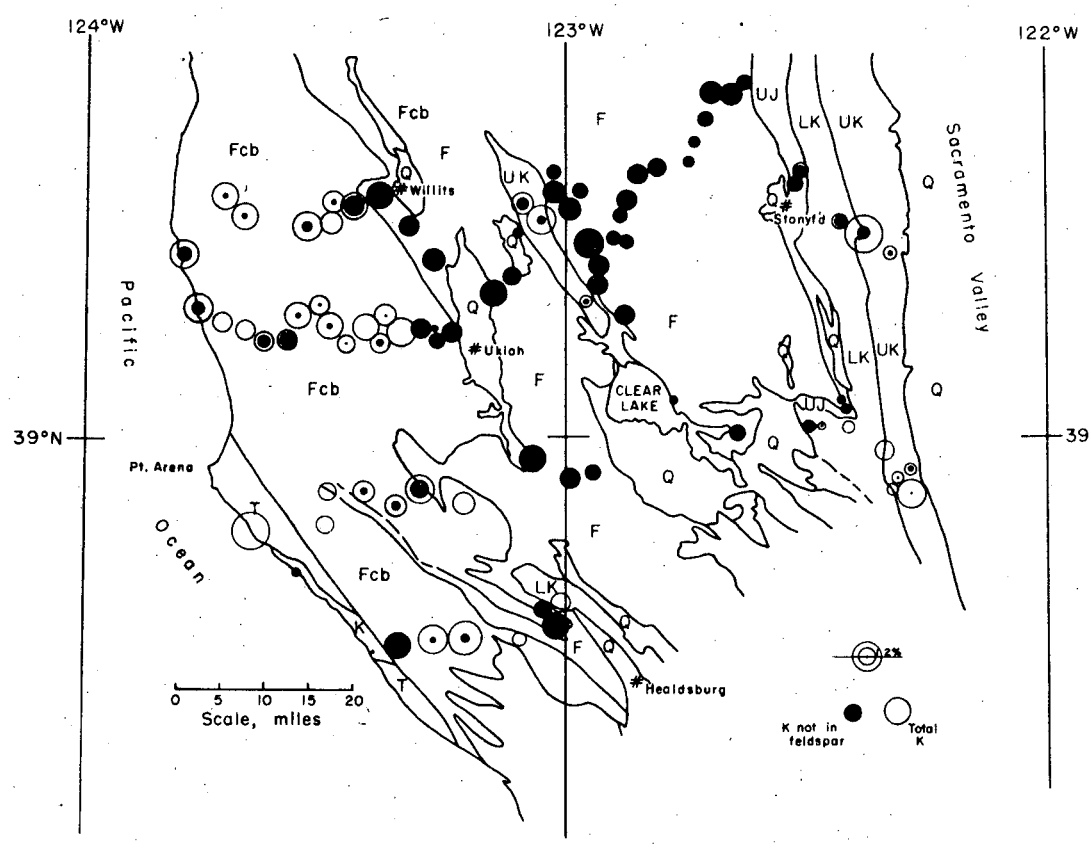


Fig. 1. Location and geologic map, North Coast Range graywacke samples.

Q	Quaternary rocks	
T	Undivided Tertiary rocks	
K	Cretaceous rocks west of San Andreas Fault	
UK	Upper Cretaceous rocks	Great Valley Sequence
LK	Lower Cretaceous rocks	Great Valley Sequence
UJ	Upper Jurassic rocks	Great Valley Sequence
Fcb	Coastal Belt rocks	
F	Franciscan rocks	



MUB-12852-A

Fig. 1a. Potassium distribution map.

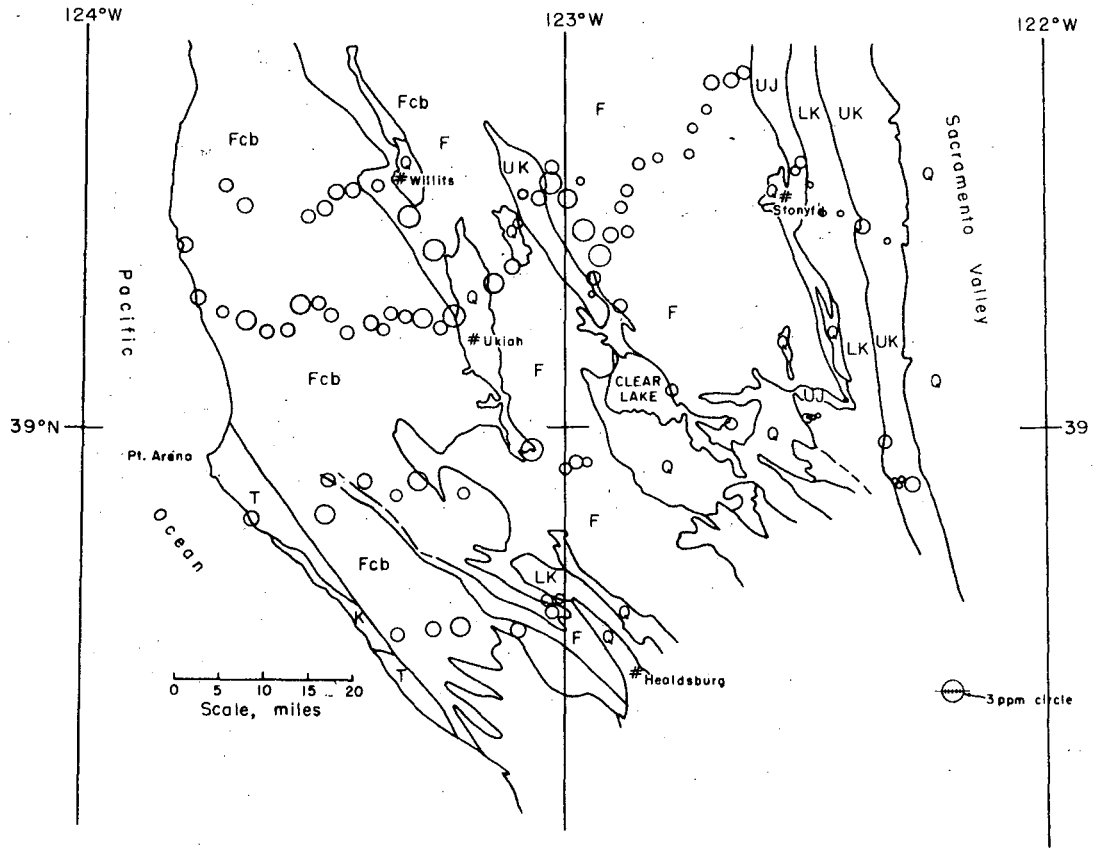


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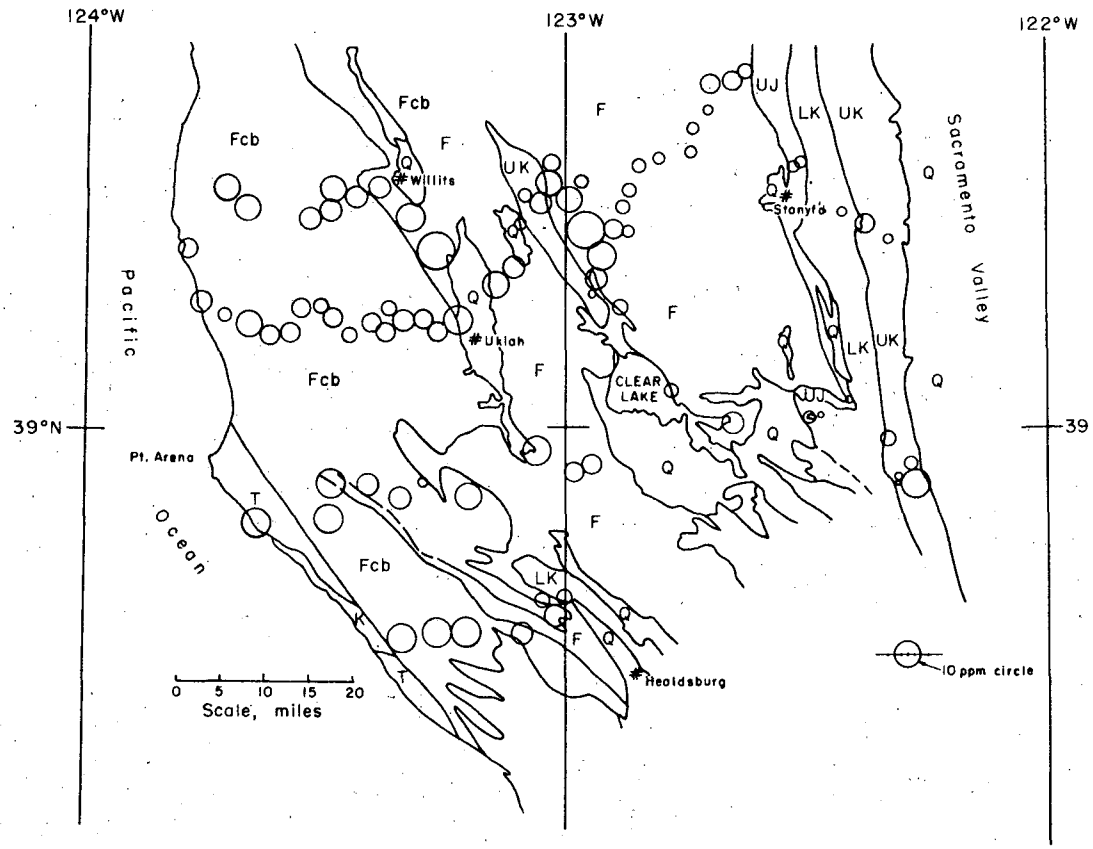
Fig. 1b. Uranium distribution map.



MUB-12852-C

Fig. 1c. Thorium distribution map.

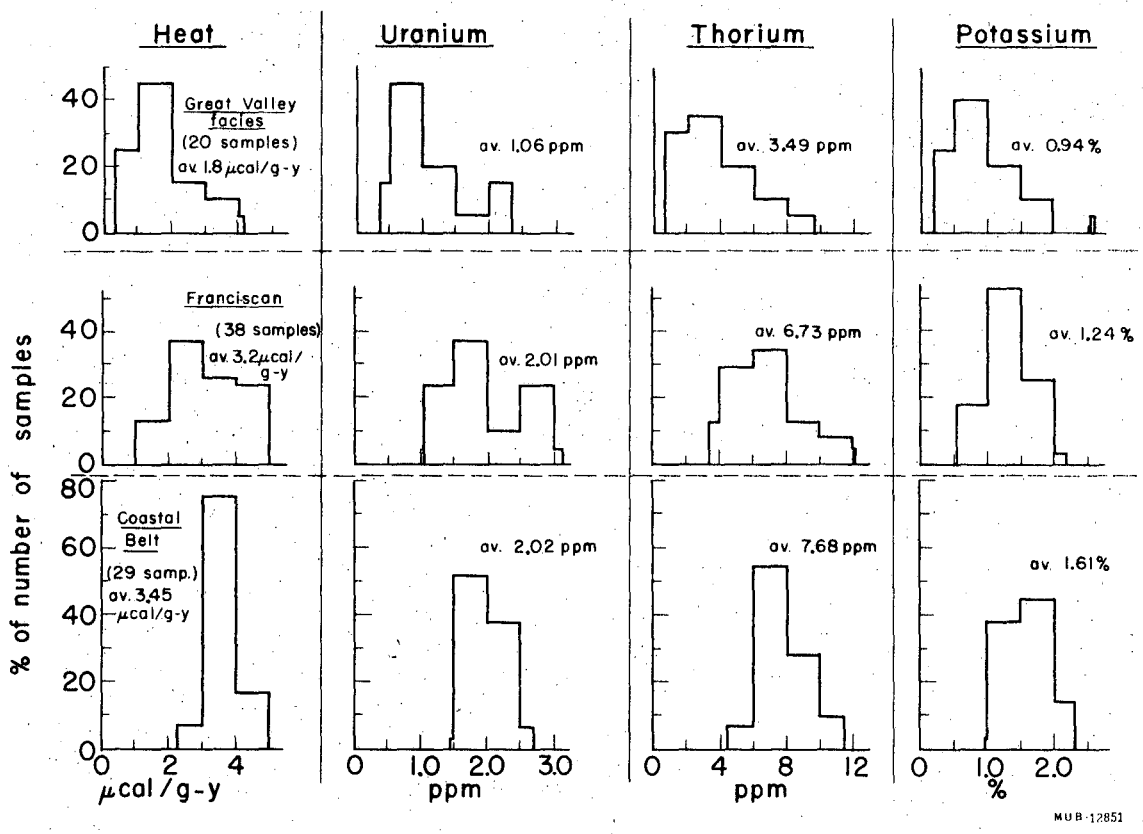


Fig. 2. Frequency distributions for North Coast Range graywacke specimens.

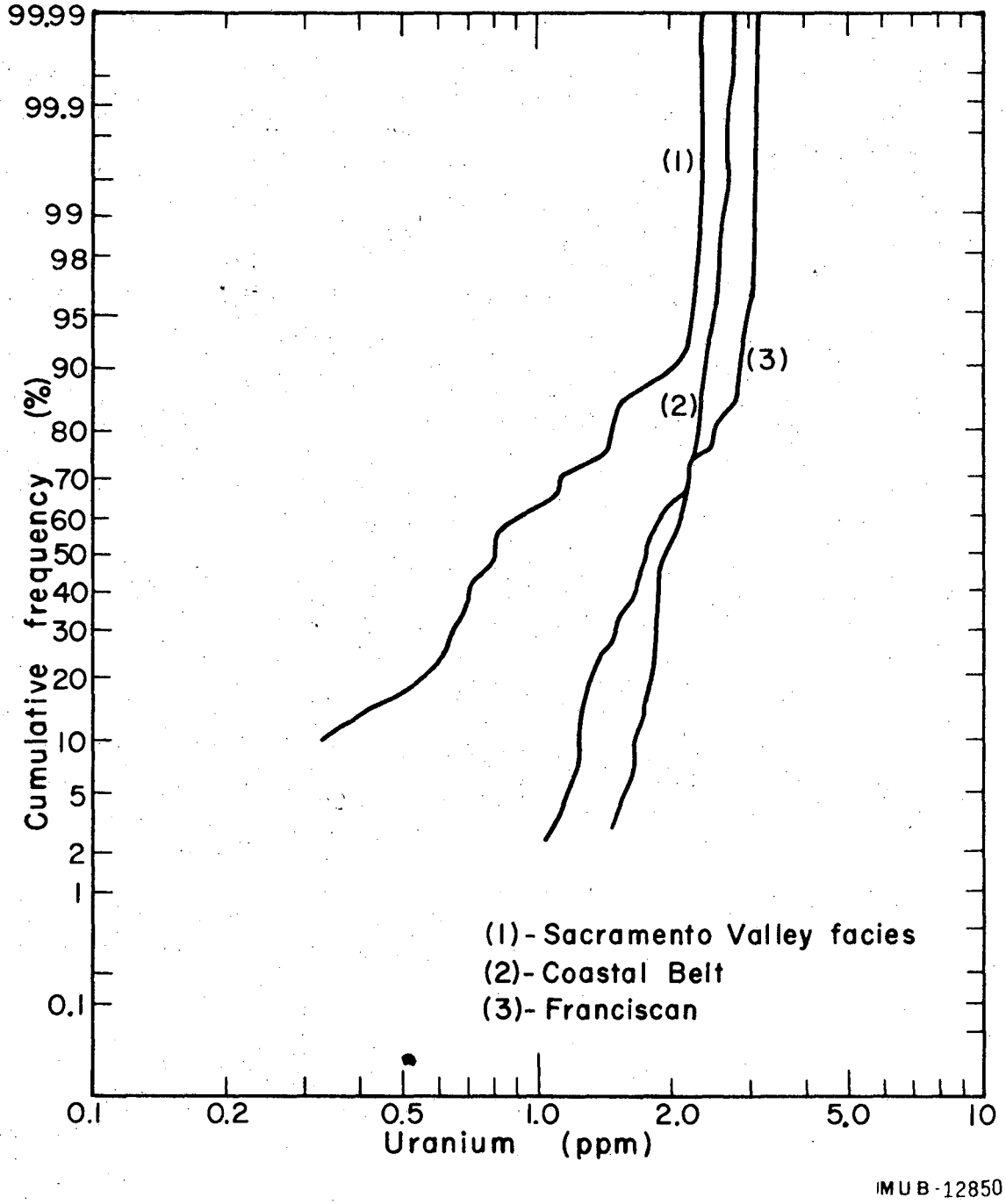


Fig. 3. Cumulative frequency of uranium contents of graywackes.

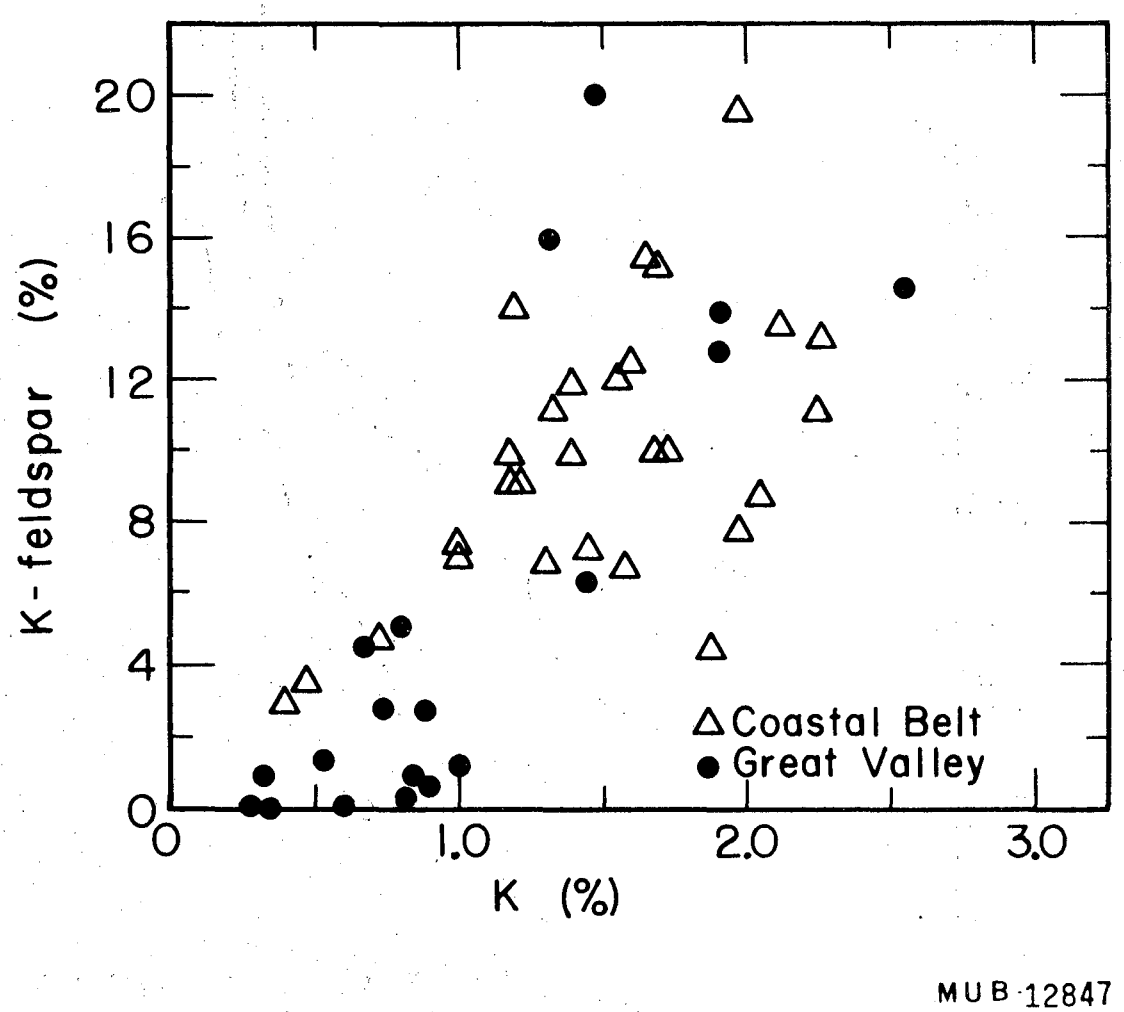


Fig. 4. K-feldspar vs K.

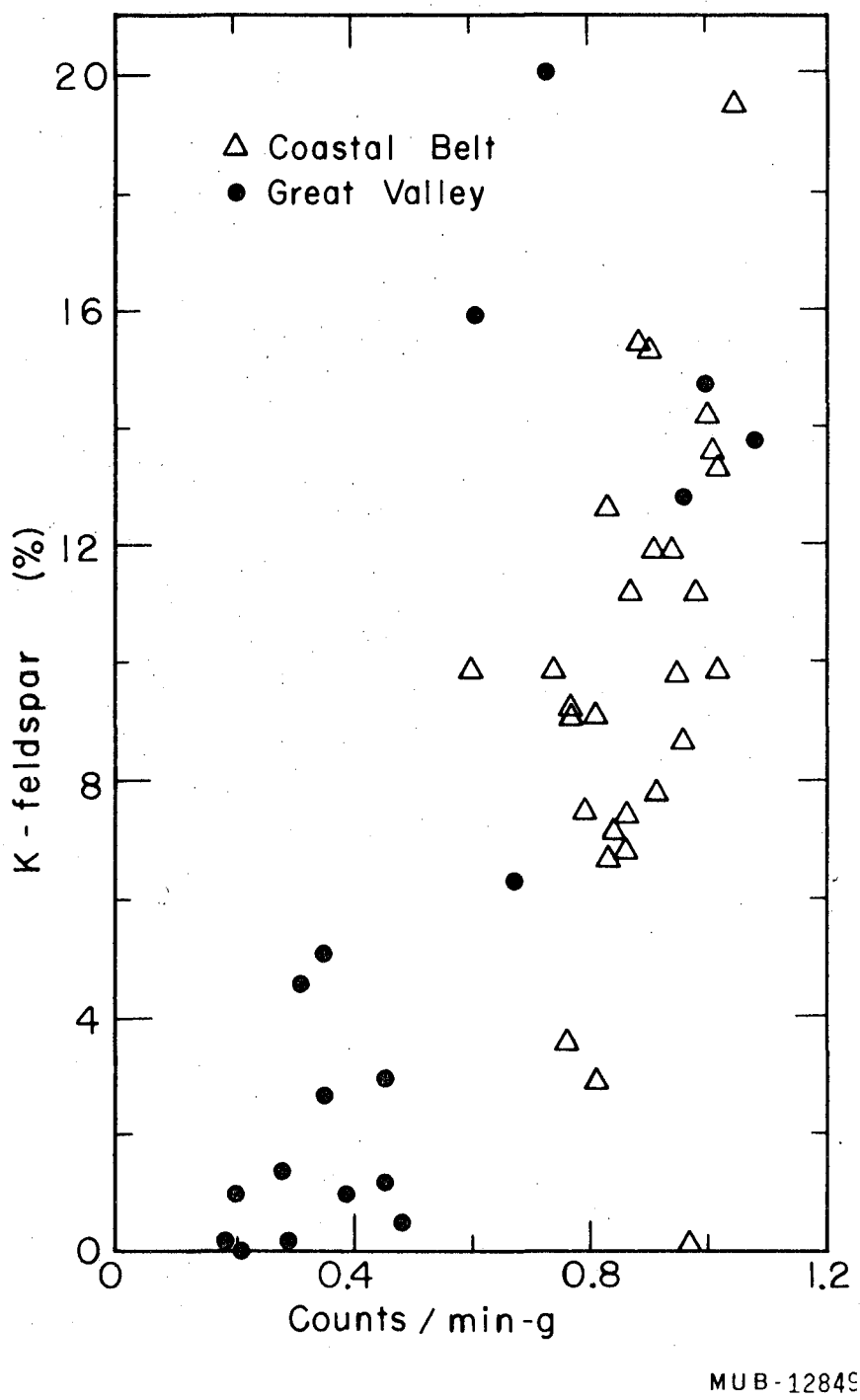


Fig. 5. K-feldspar vs radioactivity.

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