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ABSTRACT

Radioactivity in granitic rocks of the central Sierra Nevada varies both regionally and with rock type. It is lowest in the western foothills and increases eastward to the crest of the range. East of the crest radioactivity is generally lower than in the crestal region, but south of Big Pine Creek it increases eastward from low values in the Inconsolable granodiorite to high values (similar to those along the Sierran crest) in the Tinemaha granodiorite of the Poverty Hills. Within any given area radioactivity varies with silica and the alkalis; it is lowest in diorite and gabbro and progressively higher in quartz diorite, granodiorite, and quartz monzonite. On the west slope of the Sierra Nevada, the isotopic ages of the rocks increase westward, opposite to the direction of increase of radioactivity. This relation and preliminary heat flow values (which indicate a westward decrease in heat flow) are consistent with the concept of a vertically fractionated batholith in which the heat sources were concentrated in the upper parts. According to this concept, the oldest rocks have the lowest heat production because they have been eroded to the deepest levels. This concept fits less well with the relations east of the crest where the

isotopic ages of the granitic rocks are even older than those in the western foothills. The picture may be complicated by an original inhomogeneous distribution of the radioactive minerals in the source rocks from which the granitic magmas were derived. The proportions of U, Th, and K are generally constant within any given pluton and in plutons that are compositionally similar and of the same age, but may be significantly different in plutons that are compositionally and temporally unrelated. Different proportions of the radioactive elements in three pairs of plutons that had been correlated on the basis of petrographic similarity suggested faulty correlations. Recent geologic work and isotopic age dating have shown that the correlations were incorrect in two of the cases. A limited study in fission-track autoradiography suggests the U is mainly contained in biotite in rocks rich in biotite and in the non-magnetic accessory minerals in rocks that contain little or no biotite.

I. INTRODUCTION

The Lawrence Radiation Laboratory, in cooperation with the U. S. Geological Survey (USGS), is engaged in a study of the radioactivity and radiogenic heat in the Sierra Nevada batholith. Gamma-ray radiometric and sampling traverses across the batholith near latitude 37°N were begun in 1963 and have continued to the present. Since our initial report (Wollenberg and Smith, 1964), the traverses have been extended eastward across the Sierra Nevada to Owens Valley, and granitic plutons within a north-south band approximately 24 miles wide have been examined. Plutons in Yosemite National Park were also examined by less extensive sampling and radiometry. The general area, geologic units, and sample locations are shown on the map, Figure 1.

Within the past two years the USGS geothermal studies group under the direction of A. H. Lachenbruch has drilled four holes on the western flank of the Sierra and has successfully obtained heat-flow measurements from three of them. We have done detailed surface sampling and radiometry in the vicinity of the holes, and have analyzed the drill cores by gamma-ray spectroscopy. The traverses furnish radiometric continuity between the existing and future heat-flow measurement sites.

By combining radiogenic heat production and heat-flow data (Lachenbruch et al., 1966) with geologic data, one can construct possible geophysical-geological models of the Sierra Nevada. Geochemical data represented by U, Th, and K contents of the granitic rocks can also be used to examine chemical relationships between plutons or in a given pluton.

The portion of the batholith under study has been or is presently begin mapped by members of the USGS. A large part of the area is described generally by Bateman et al. (1963). The geology east of the Sierran crest is the subject of a more detailed report (Bateman, 1965). Nomenclature in our paper is essentially consistent with that used for rock units in Bateman's two reports. One exception is the term "San Joaquin unit" which we use to designate undifferentiated fine-grained quartz monzonite and hornblende granodiorite in the Millerton Lake area where geologic mapping is still lacking.

Prior to this project, studies of the U and Th content of Sierra Nevada plutonic rocks, primarily from the eastern part of the batholith, were made by members of the U. S. Geological Survey. E. S. Larsen Jr. and Gottfried (1961) reported fluorimetric analyses for U on 48 samples; E. S. Larsen, III and Gottfried (1960) published U and Th contents of eight intermediate and acidic igneous rocks from the Bishop area. Sediments from streams on the eastern slope of the Sierra between Big Pine and Lee Vining were sampled for gross radioactivity by Shawe (1953), who found generally high radioactivity in sediments derived from rocks of the Coyote Flat warp southwest of Bishop.

II. TECHNIQUES

Field procedures. Field operations involved: (1) determination of the location, lithology, and plutonic affiliation of the rock exposure under study; (2) radiometric scanning; and (3) sampling. Geologic and topographic control is furnished by maps prepared by members of the USGS, the geologic mapping principally by Paul Bateman and James Moore. Recognition of rock units is based on guidance in the field by Paul Bateman and Franklin C. Dodge.

Instrumentation. Radiometric measurements are made with a portable γ-ray scintillation counter, that uses a 7.6 cm-diam by 7.6 cm-thick NaI(Tl) crystal viewed by a 7.6 cm-diam photomultiplier tube. The indicator unit is a transistorized count-rate meter with values expressed in counts/second. Five switch-selected ranges are available on a single 50-division linear scale, providing a total instrument full-scale range from 25 to 10,000 c/sec. (These full-scale sensitivities correspond to γ-ray dose rates of 0.625 to 250 μr/hr, as determined from calibrations with N. B. S. -certified ^{226}Ra sources.) The low-energy threshold of the instrument is adjusted to be 0.120-MeV γ-ray energy. This value is maintained by frequent standard checks with a natural U source, always carried in the field for this purpose. The general range of γ-radioactivity values in the Sierra Nevada is from 120 c/sec in low-activity terranes to 1300 c/sec in high-activity terraines.

Measurements. Field readings are made in the general area of a prospective sampling location to ensure that the sample is representative of the area. During traverses on foot, the instrument is left turned on wherever practicable, and is continuously monitored to detect any appreciable change in radioactivity. At a sampling location, observation of lithology is combined with the radiometric reading to determine the suitability of the site. When placed on a flat rock surface,

the detector views an area $\approx 0.3\,m^2$ and an effective thickness of 8 to 10 cm. When the detector is raised $\approx$ 1m above the surface, the increased solid angle permits a $\approx 30\,m^2$ effective area in flat terrain. The effective area varies markedly as local relief increases. Where geometry permits, the value at a sampling location is recorded as the mean of readings (1) with the face of the detector on a flat surface, and (2) with the bottom part of the side of the detector cylinder against the lower part of a vertical rock surface. The latter configuration generally yields a higher reading, since source-detector geometry is closer to 4π than it is with the face on the rock. Where vertical surfaces are absent, readings are made only with the detector face against the surface.

Sample collecting and preparation. Pick samples are taken from the freshest material possible. This is fairly easy in glaciated terrain, more difficult in weathered exposures at lower elevations. An attempt is made to sample a fairly broad area, i.e., one of $\approx$ 10 m radius, if constant radioactivity is indicated by radiometric scanning. Samples weigh about 1.5 kg, to provide sufficient material for our $\approx$ 1 kg counting configuration. At the laboratory, samples are crushed to minus 1/2 inch, then placed in a thin-walled polyethylene container, 10 cm diameter by 9 cm long, for counting.

In summary, field radiometry permits radioactive continuity between localities. Observation of lithology and reliance on the geologic map combine to permit the most feasible choice of sampling location.

Gamma spectrometry. Until early 1966, all gamma-ray spectrometry of our Sierran samples was done on one scintillation spectrometer, consisting of a thallium-activated sodium-iodide-crystal detector, 10 cm in diameter by 5 cm thick, providing input for a 100-channel pulse-height analyzer. Recently, we have counted some of the samples on a 20 cm-diameter by 10 cm-thick crystal, coupled to a 1600-channel analyzer.

The detectors and samples are enclosed in 5 cm-thick lead shields, located in a serpentine-concrete room with walls and roof 1.2 to 1.5 m thick (Wollenberg and Smith, 1966). As background in the system is constant, it is easily subtracted when the analyzer's output is evaluated. Resultant 100- or 400-channel spectrums are operated upon mathematically to yield quantitative U, Th, and K assays. We assume that in the U and Th assays each element is in equilibrium with its decay products, and that in the K assays the ratio $^{40}K/^{39}K$ is constant in nature. By application of radiogenic heat values given by Birch (1954)--1 ppm U = 0.73 μ cal/g-y, 1 ppm Th = 0.20 μ cal/g-y, and 1% K = 0.27 μ cal/g-y -- we calculate heat generation values for the specimens. The analytical errors are those due to the statistical nature of the counting procedure and are dependent upon the number of counts and the length of counting time.

III. GEOLOGIC SETTING

The area under study encompasses the principal plutons of the central part of the Sierra Nevada batholith. Generally, the western plutons are older, more mafic, and of higher specific gravity than those occupying the crestal region of the range (Bateman et al., 1963), but not as old--according to age dating by the K-Ar method--as plutons east of the crest (Kistler et al., 1965). Rock types range from pyroxene quartz diorite and diorite, generally in small discrete bodies, to granite. The larger plutons are granodiorite or quartz monzonite, with quartz monzonite predominant in the younger plutons. Masses of granodiorite generally contain both biotite and hornblende, whereas many bodies of quartz monzonite (especially felsic ones) contain only biotite.

The granitic rocks are classified by Bateman et al. (1963), according to the ratio of alkali feldspar (modal K-feldspar + modal albite) to total feldspar:

	% Alkali feldspar in total feldspar
Quartz diorite	0-10
Granodiorite	10-35
Quartz monzonite	35-65
Granite	65-100

IV. RESULTS

Tabulated results. The reader is reminded that all results obtained through gamma-ray spectrometry depend on the validity of:

1. equilibrium in the U and Th series
2. constancy of the $^{40}K/^{39}K$ ratio
3. radiogenic heat conversion factors of Birch (1954).

Although these items have been discussed in Section II, they are repeated here for clarity in presentation.

The radioactivities of the individual plutons are listed in Table 1. Uranium, thorium, and heat production range over an order of magnitude, from averages of 0.7 ppm, 1.8 ppm, and 1.1 μcal/g-y respectively in diorite and quartz diorite to 6.4 ppm, 23 ppm, and 10.2 μcal/g-y respectively in some quartz monzonite bodies. Potassium averages range from 0.8% in diorite-quartz diorite to 4.02% in the Tinemaha granodiorite (values approaching 5% have been determined in individual samples of alaskite, Bateman et al., 1963). Thorium-to-uranium ratios range from 3:1 to 5:1 in all of the units with the exceptions of the quartz monzonite of Big Creek (6.8 :1 avg) the El Capitan granite (6.1:1 avg), and the Taft granite (6.0:1 avg).

Radioactivity profiles. The region-wide distribution of radioactivity is illustrated by the combined profiles (A-A' and B-B') of heat production shown in Figure 2.

In general, radioactivity increases eastward from the Great Valley to the range crest with a gradient of ≈ 0.1 μcal/g-y per lateral kilometer. Eastward from the crest, radioactivity drops off slightly in an area north of Big Pine. However, south of Big Pine heat values

increase toward the east over a distance of 15 km from about 6 μcal/g-y in the Inconsolable Granodiorite to about 10 μcal/g-y in samples of Tinemaha granodiorite in the Poverty Hills (profile C-C', Figure 2).

The distribution of radioactivity can be explained by two hypotheses which are somewhat compatible. The first proposes a layered, vertically fractionated batholith with rock of higher radioactivity in the upper parts (Lachenbruch et al., 1966). The relatively low-radioactivity rocks presently exposed on the western margin then represent older, more deeply eroded material than rocks exposed closer to the crest. This can be expressed quantitatively if we divide the western slope into three units on the basis of radioactivity; unit 1, predominately the Mount Givens-Lamarck granodiorite on the east; unit 2, predominately the "Dinkey Creek"-type granodiorite in the central part; and unit 3, the "San Joaquin" unit on the west. The average radiogenic heat productions in the units are ≈ 10 μcal/g-y, ≈ 5 μcal/g-y, and ≈2.5 μcal/g-y, respectively. Preliminary measurements of heat flow, made in units 1 and 3, are 1.3 and 0.6 μcal/cm^2 sec, respectively. Their difference could be accounted for by the removal from unit 3 of an 8-km-thick slab with the heat productivity of unit 1. However, it is difficult to reconcile a layered radiogenic model for the entire Sierra Nevada when relatively high radioactivities are found in the older plutons east of the present crest.

This brings into consideration a second hypothesis which proposes that the distribution of radioactivity is predominantly a lateral one, reflecting a regional distribution which pre-dates the intrusion of the granitic rocks. Such a regional pattern of U and Th distribution was

found by Phair and Gottfried (1964) in Precambrian and Laramide intrusives and metamorphics of the central Rocky Mountains. There, average U and Th are highest in the Colorado Front Range, and are substantially lower in more distant rocks of similar age and composition. In the Sierra Nevada, the higher radioactivities in granitic rocks of the crestal region, ranging from Triassic into Cretaceous, may represent a situation similar to that in the Front Range. Present sampling and radiometry of the Paleozoic and Mesozoic metamorphosed sedimentary and volcanic rocks, considered the most likely source of the granitics, may disclose a distribution of radioactivity which matches that observed in the granitics. Further sampling of plutons east of the crest, and heat flow measurements in the Owens Valley area, should also help to resolve whether the presently observed distribution of radioactivity is controlled predominantly by vertical fractionation or by distribution of sources in pre-granitic rocks.

Radioisotope fraction. The relationship between U, Th, and K in the various rock units can be examined by means of triangular plots of radioisotope fraction, based on the normalization of U, Th, and K contents: $U_{ppm} + Th_{ppm} + K_{\%} = 1$. The position of points within the triangular plot does not depend directly on the magnitude of the concentrations of U, Th, and K, but rather represents the relationship of the abundance of each with respect to the others. Examination of the plots, Figure 3, indicates characteristic groupings for some of the plutons, i.e., the Mount Givens-Lamarck-Half Dome groupings (Figure 3a, b, c) are quite similar. This similarity supports the hypothesis that they are closely related genetically.

Distinct separations between groups of samples from a single pluton are evident:

1. The bulk of the samples of the "Dinkey-Creek"-type granodiorite are grouped differently from samples of higher-radioactivity granodiorite designated as "Dinkey-Creek"-type in the vicinity of Courtright Reservoir (Figure 3d).[a] Potassium is most dominant over U and Th in hornblende-rich granodiorite of the Millerton Lake area (which visually resembles granodiorite mapped as "Dinkey Creek"-type to the east) and least dominant in the high radioactivity granodiorite of Courtright Reservoir.

2. Rocks mapped as Tungsten Hills quartz monzonite fall into two groups (Figure 3d) which correspond to (a) the Basin Mt. mass and granodiorite facies, and (b) Bishop Creek-Shannon Canyon masses described by Bateman (1963). Potassium is more dominant in the latter group, but the U-Th fraction ranges are approximately the same in both groups. Isotopic ages indicate that the Basin Mt. mass is of Cretaceous age and much younger than the Bishop Creek-Shannon Canyon masses which may be of Late Triassic or Early Cretaceous age. (P. C. Bateman, personal communication).

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a. Field work by members of the USGS in the summer of 1966 has permitted re-classification of the "high-activity Dinkey Creek"-type granodiorite of Courtright Reservoir into a pluton separate from the "Dinkey Creek"-type granodiorite.

3. Rocks designated Cathedral peak-type alaskite and granite (which are now known to include similar-appearing rocks of differing ages) are distinguished from the Cathedral Peak granite of Yosemite National Park (Figure 3f). The latter group has a considerably broader U-Th range than the former. Two samples from a garnet-bearing alaskite on Big Pine Creek [at least 130 million years old (Hurley et al., 1965)] are distinct in having U predominant.

4. Samples of Tinemaha granodiorite from the Poverty Hills are grouped distinctively from Tinemaha rocks in the Sierra to the west (Figure 3g). The Poverty Hills group has a wide range of radioactivity with heat production values from 15.9 μcal/g-y in the Th-predominant sample to a mean of 7.8 μcal/g-y in the more potassic samples.

Radioactivity of heat-flow measurement sites. Field radiometry and sampling were done in the vicinity of the heat-flow measurement sites: San Joaquin Experimental Range (SJ), Jose Basin (JB), Shaver Lake (SL), and Helms Creek (HC); their locations are shown on Figure 1. Laboratory γ-spectrometric analyses were performed on surface samples and core from the drill holes. Radioactivity data are listed on Table 2 and radiogenic heat production profiles of the three holes are plotted on Figure 4. Contours of heat production from surface samples are plotted on Figures 5, 6, and 7. Examination of Table 2 indicates good agreement between mean values of radioactivity parameters of material from the hole areas and radioactivity parameters of materials from extensive surface sampling of the plutons in which the holes are drilled.

The question arises whether the surface samples are truly representative of unweathered material at depth. Rogers et al. (1963), from their study of surface samples and cores of the Conway granite, found a slight depletion of U from the surface, attributable to weathering. This reduces the heat production calculated from surface abundances of U, Th, and K. To check this for the Sierra Nevada heat-flow sites, the heat-production data shown on the contour maps were averaged within radii of 1 and 2 km of the holes; results are listed on Table 3. Within a 1-km radius (and with the exception of the JB hole area), surface samples' average values are quite close to the average of the core. Within 2 km, surface values are higher than the average SL and JB cores, nearly the same as the SJ core, and lower than the HC core average. The consistent similarity between the 1-km radius and core averages, even in strongly weathered rock at the SJ area, indicates that values from these outcrop samples, when averaged, are valid for determining the heat production of the particular unit.

Radioactivity and Isotopic Age. Generally the radioactivity of the plutons varies inversely with their age. A group of samples from plutons encompassed in this study was dated by Kistler et al. (1965) and we subsequently analyzed it for radioactivity. Data are listed on Table 4a, and are plotted as isotopic age versus radiogenic heat (Figure 8). The plot indicates, with two exceptions (hornblende ages of the Tinemaha and McMurry Meadows granodiorites), that for the samples older than about 85 my there is a general decrease of radioactivity with increasing age. Samples younger than about 85 my do not show such a correlation; rather, radioactivity appears to be independent of age. The decrease of radioactivity with increasing age of biotite also holds for the Yosemite, Rocklin, and Belden samples of Curtis et al. (1958) (listed on Table 4b and also plotted on Figure 8).

Broad-scale groupings according to age have been done by Bateman and Wahrhaftig (1966). When radioactivities are assigned to the age group represented in our sampling, the following relationship holds:

Rock Units	U, ppm	Th, ppm	K %	Heat, μcal/g-y
Cretaceous plutons: (include alaskite and fine-grained quartz monzonite; Cathedral Peak granite; Half Dome quartz monzonite; Sentinel, Mt. Givens, Lamarck and Round Valley Peak, granodiorites; and medium- to fine-grained granodiorite)	7.17	21.3	2.77	10.3
Jurassic or Cretaceous ("Dinkey Creek" - type granodiorite)	3.56	11.0	1.88	5.3
Triassic or Jurassic rocks of eastern Sierra Nevada	4.29	18.6	3.78	8.1

We see that, taken as broad groups, the Cretaceous rocks are higher in radioactivity than the "Dinkey Creek"-type granodiorite. The older rocks of the eastern Sierra Nevada appear to be anomalously high in radioactivity.

Increasing radioactivity with later phases of magmatic differentiation is generally acknowledged and was described by Adams (1955) and more recently by Rybach et al. (1962, 1966) and by Heier et al. (1965). These were not large-area studies, however; they were concerned principally with fractionation in volcanic series (Adams, 1955), and in plutons emplaced over a relatively short time span (Rybach et al., 1962 and 1966; Heier et al., 1965). Therefore, it is noteworthy that in the Sierra Nevada, on a regional basis (and with the exception of the older plutons on the east side) there is a similar inverse correlation of radioactivity with age.

Sites of Radioactivity--Autoradiography. A limited attempt was made to determine the sites of Th and U in some of the granitic rocks. We chose the "high radioactivity" granodiorite of Courtright Reservoir (Sample DC-11) and "Dinkey Creek"-type granodiorites [Samples SL-18 from Shaver Lake and BCc-13 from Wishon Reservoir (see Table 4)] as examples with substantial contrasts in radioactivity.

Fission-track autoradiographic techniques were used, similar to those employed by Fleischer et al. (1965) and later adapted to our purposes by Kleppe and Roger (1966). This type of autoradiography lends itself well to thin sections, mainly because exposure times are extremely short compared with times required with conventional film exposure techniques.

A brief résumé of the procedure follows. Uncovered petrographic thin sections of the three rocks were obtained from the USGS through the courtesy of Dr. Franklin C. Dodge. Sheets of high-grade industrial mica, used as a registering medium, were attached to the uncovered rock surface; the sandwiches were exposed to neutrons at the Livermore Pool-Type Reactor, Lawrence Radiation Laboratory, Livermore.

Only sample DC-11 was exposed to fast neutrons, an 80-minute exposure to a broad-spectrum flux of 3.7×10^{12} n/cm^2-sec. Fast neutrons induce fission of ^{238}U, ^{235}U, and ^{232}Th. Upon etching the detecting mica in a solution of HF, it appeared from the fast neutron exposure of DC-11 that U and Th sites were associated with biotite, either as rims around grains or as sites centered in the grains.

Next, all three thin sections with mica attached were exposed to thermal neutrons (ratio of thermal to fast neutrons, 1000) for 1 hour to a flux of 3×10^{10} n - cm^{2} sec. The thermal neutron exposure caused only ^{235}U to fission, permitting better definition of the sites of U. As in the fast-neutron exposure, DC-11 showed U associated with biotite, but also U associated with sphene and other accessory minerals. In SL-18 and BCc-13 where hornblende is the predominant mafic mineral, there are fewer U tracks than in DC-11 (corresponding roughly to the differences in whole-rock radioactivity), and they are associated more with the accessory minerals, principally sphene. Photomicrographs of the tracks registered in mica, superimposed on the mineral grains' thin sections, comprise Figures 9(a), (b), and (c). This limited autoradiography study suggests that in biotite-rich rocks the U is associated mainly with the biotite, but in more mafic rocks U may associate primarily with the non-magnetic accessory minerals.

V. CONTINUING STUDIES IN THE CENTRAL SIERRA NEVADA

A knowledge of the distribution of radioactivity in source material of the granitic rocks furnishes one basis from which the model of a radioactively fractionated batholith can be derived. We are now studying the radioactivity of the material which most likely represents the source of the granitic rock, the Precambrian, Paleozoic, and Mesozoic sedimentary and volcanic rocks of the Sierra Nevada, Inyo, and White mountains. On the basis of recent field γ-ray readings alone, it appears that the radioactivity of these possible source rocks varies by a factor of ten from low values in some carbonate and metavolcanic rocks to highs (comparable to field radioactivities in granodiorites) in the siliceous sedimentary rocks.

Field radiometry and sampling of the Santa Rita Flat pluton of the Tinemaha granodiorite and the granodiorite of Papoose Flat, both in the Inyo Mountains, are yet to be done. It will be interesting to see if the granodiorite of Santa Rita Flat has a high radioactivity similar to that observed in Tinemaha granodiorite in the Poverty Hills of Owens Valley.

An autoradiographic study, using the fission track method, of representative samples of the plutons is also planned, wherein sites of radioactivity will be revealed and U and Th concentrations of the radioactive minerals determined.

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TABLE 1. Average Values for Radioactivity Parameters and Ages of Sierra Nevada Plutons.

Rock Unit	No. of Samples	Field Count Rate, c/sec	U, ppm	Th, ppm	K %	Heat, μcal/g-y	Th/U	Radiogenic Age[a] Hrnbl./Biot. (10^6 y)
San Joaquin-Bishop Region								
Alaskite of Evolution Basin	4	756	4.7	17.0	3.62	7.8	3.7	
Cathedral Peak-type granite and similar rocks	17	757	3.8	15.2	3.54	6.8	4.9	/84
Tungsten Hills quartz monzonite	34	690	4.9	18.9	3.29	8.3	4.2	/75
Mount Givens granodiorite[b]	44	724	6.8	21.5	2.78	10.0	3.5	87/84
Lamarck granodiorite	16	946	6.3	21.1	2.53	9.5	3.4	84/77
Undifferentiated quartz monzonite	17	839	6.4	23.2	3.38	10.2	5.0	
Big Creek quartz monzonite	7		2.6	15.2	3.11	5.8	6.8	
"Dinkey Creek"-type granodiorite[b]	42	429	3.4	11.2	1.86	5.2	3.5	99/88
Fine-grained quartz monzonite of "San Joaquin unit"	33	259	1.5	4.3	1.52	2.4	3.2	
Tinemaha granodiorite	14	829	4.9	21.5	4.02	9.0	4.5	167/96
Quartz diorite and diorite	9	202	0.7	1.8	0.8	1.1	3.0	121/113
Granodiorite of Coyote Flat	8	503	2.8	11.2	2.62	5.0	4.0	/105
Garnet-bearing porphyritic granite	2	—	7.7	13.4	3.45	9.2	1.7	

TABLE 1. (continued)

Rock Unit	No. of Samples	Field Count Rate, c/sec	U, ppm	Th, ppm	K %	Heat, μcal/g-y	Th/U
Yosemite Region							
Tuolumne intrusive series -							
Johnson granite porphry	1	750	5.1	17.1	3.83	8.2	3.3
Hoffman quartz monzonite	1	900	7.0	22.9	3.59	10.7	3.3
Cathedral Peak granite	6	696	6.3	15.3	3.61	8.7	3.0
Half Dome quartz monzonite	8	757	7.3	18.8	2.34	9.7	3.1
Sentinel granodiorite	2	637	5.8	12.8	2.17	7.4	2.2
Taft granite	3	900	5.3	31.4	3.79	11.1	6.9
El Capitan granite	5	580	2.8	15.8	2.37	5.8	6.1
Bridal Veil granite	1	500	1.5	7.1	2.73	3.0	4.6
Granodiorite of the gateway	1	300	1.1	4.1	1.16	1.9	3.7
Granite of Arch Rock	1	550	3.7	7.0	2.39	4.8	1.9
Leaning Tower quartz monzonite	1	600	3.4	10.6	1.65	5.1	3.1
Quartz diorite of western foothills	1	130	0.5	1.3	0.42	0.8	2.5

a. from Kistler et al. (1965).

b. exclusive of samples from heat flow-hole area.

TABLE 2. Radioactivity of Heat Flow Sites and Encompassing Plutons (see also Figure 4)

	No. of Samples	U, ppm	Th, ppm	K %	Heat, μcal/g-y	Th/U
Mt. Givens granodiorite*	44	6.8	21.5	2.78	10.0	3.5
HC hole and vicinity	28	7.7	21.6	3.00	10.8	2.9
"Dinkey Creek"-type* granodiorite	69	3.5	10.8	1.86	5.2	3.4
SL hole and vicinity	28	2.9	9.1	1.70	4.4	3.2
JB hole and vicinity	24	3.0	8.6	1.76	4.4	2.8
Quartz monzonite* and granodiorite of "San Joaquin Unit"	28	1.7	6.1	1.57	2.9	3.4
SJ hole and vicinity†	43	1.5	4.3	1.52	2.4	3.2

*exclusive of hole and vicinity samples

†entirely in fine-grained quartz monzonite

TABLE 3. Radiogenic Heat Production in Rocks of Heat Flow Measurement Holes and in Surrounding Surface Areas.

	Average Values of Heat Production μcal/g-y		
Hole	In hole	1-km radius	2-km radius
SL	3.5	3.9	4.6
JB	4.2	5.4	4.7
SJ	2.6	2.3	2.4
HC	10.7	10.6	9.9

TABLE 4a. Radioactivity of Rocks with Isotope Ages Determined by Kistler et al. (1965).

Sample	U, ppm	Th, ppm	K %	Th/U	Heat μcal/g-y	Age, my hbde./biot.	Age, my Rb-Sr
CL-1 Pyroxene-quartz diorite	0.5	1.3	0.44	2.5	0.8	121/113	
SL-18 Granodiorite-"Dinkey-Creek"	5.2	14.4	2.41	2.8	7.3	91/92	
BCc-13 Granodiorite-"Dinkey-Creek"	5.6	16.0	1.95	2.9	7.8	92/83	
HL-29 Porphyritic biot. granite	10.2	24.7	3.22	2.4	13.3	/83	82
BCc-12 Mt. Givens granodiorite	4.7	17.9	2.47	3.8	7.7	86/87	
BCa-20 Mt. Givens granodiorite	11.0	26.2	2.63	2.4	14.0	87/85	
MG-1 Lamarck granodiorite	5.7	19.9	2.59	3.5	8.9	84/77	
MG-2 Tungsten Hills quartz monz.	3.9	19.6	3.66	5.0	7.8	/76	75
MT-2 Round V. Peak granodiorite	4.7	16.1	2.47	3.4	7.3	84/87	
MT-1 Wheeler Crest quartz monz.	6.9	24.1	3.18	3.5	10.7	/81	
BP-5 Granodiorite of Coyote Flat	2.5	10.5	2.43	4.2	4.6	/88	
BP-3 Similar to Cathedral Peak granite	2.3	17.1	3.53	7.4	6.1	/85	
MG-3 Inconsolable granodiorite	2.5	15.7	2.39	6.2	5.6	98/87	
BP-1 Tinemaha granodiorite	4.4	18.9	2.49	4.3	7.7	150/78	
BP-2 Granodiorite of McMurry Meadows	2.6	13.0	3.19	4.9	5.4	151/104	

TABLE 4b. Radioactivity of Plutons with Isotope Ages Determined by Curtis et al. (1958).

Pluton	Age, (m y)	Radiogenic Heat, μ cal/g-y	U, ppm	Th, ppm	K, %
Hoffman quartz monzonite	83.3	10.7	7.0	22.9	3.59
Johnson granite porphry	82.4	8.2	5.1	17.1	3.83
Cathedral Peak granite	83.7	8.7	6.3	15.3	3.61
Half Dome quartz monzonite	84.1	9.7	7.3	18.8	2.34
Sentinel granodiorite	88.4	7.4	5.8	12.8	2.17
El Capitan granite	92.2	5.8	2.8	15.8	2.37
Gateway granodiorite	92.9	1.9	1.1	4.1	1.16
Arch Rock granite	95.3	4.8	3.7	7.0	2.39
Rocklin pluton	131	3.0	2.8	3.5	1.08
Belden granodiorite*	136	2.4	1.6	4.4	1.5

*Heat value calculated from radioactivity data of Whitfield, J. M., J. J. W. Rogers, and J. A. S. Adams, Relationship between Petrology and the Thorium and Uranium Contents of Some Granitic Rocks, Geochim. Cosmochim. Acta, 17, 248, 1959.

FIGURE CAPTIONS

Fig. 1. Location and geologic map showing sampling site, USGS heat flow measurement sites, and lines of heat-production profiles. (Geologic base from Bateman and Wahrhaftig, 1966).

Fig. 2. Profiles of radiogenic heat production, central Sierra Nevada.

Fig. 3. Radioisotope fraction: (a) Mt. Givens granodiorite, (b) Lamarck granodiorite, (c) Half Dome quartz monzonite, (d) "Dinkey-Creek"-type granodiorite, (e) Tungsten Hill quartz monzonite, (f) Cathedral Peak-type alaskite and granite, (g) Tinemaha granodiorite, (h) "San Joaquin Unit" fine-grained quartz monzonite.

Fig. 4. Profiles of radiogenic heat production in heat flow measurement holes.

Fig. 5. Heat production contours (μcal/g-y) in fine-grained quartz monzonite, vicinity of San Joaquin hole. Decimal points indicate sample locations.

Fig. 6. Heat production contours (μcal/g-y) in "Dinkey-Creek"-type granodiorite, vicinity of Shaver Lake and Jose Basin holes. Decimal points indicate sample locations.

Fig. 7. Heat production contours (μcal/g-y) in Mt. Givens and "high radioactivity" granodiorites, vicinity of Courtright Reservoir and Helms Creek hole. Decimal points indicate sample locations.

Fig. 8. Isotopic age vs radiogenic heat.

Fig. 9. Photomicrographs of rhombic fission tracks registered in detecting mica: (a) fission tracks associated with U, rimming end of grain of biotite and at discontinuities within the biotite,

"high radioactivity" granodiorite, Courtright Reservoir, Sample DC-11; (b) Rhombic fission tracks associated with U (~ 230 ppm) in a grain of sphene, "Dinkey-Creek"-type granodiorite, Shaver Lake Quarry, Sample SL-18; (c) Rhombic fission tracks associated with U (~ 360 ppm) in accessory mineral (sphene?) encompassed by hornblende, "Dinkey-Creek"-type granodiorite, Shaver Lake Quarry, Sample SL-18.

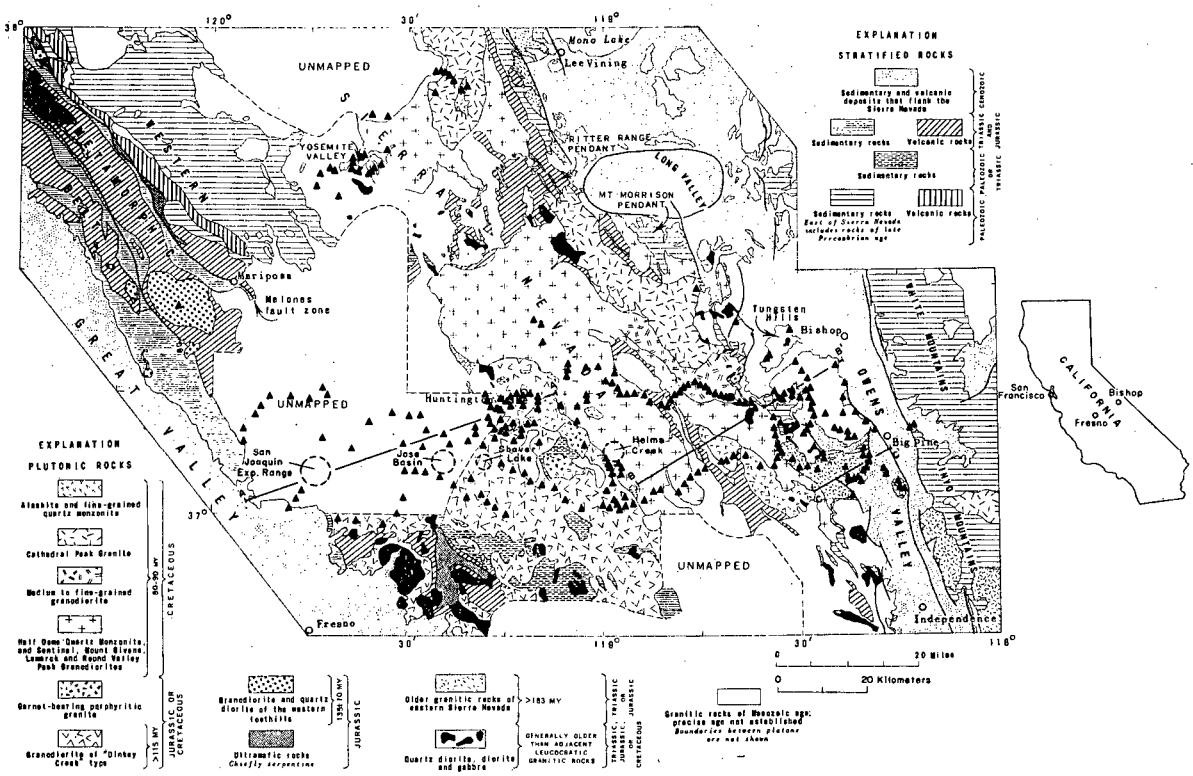

Fig. 1

XBL676-2213

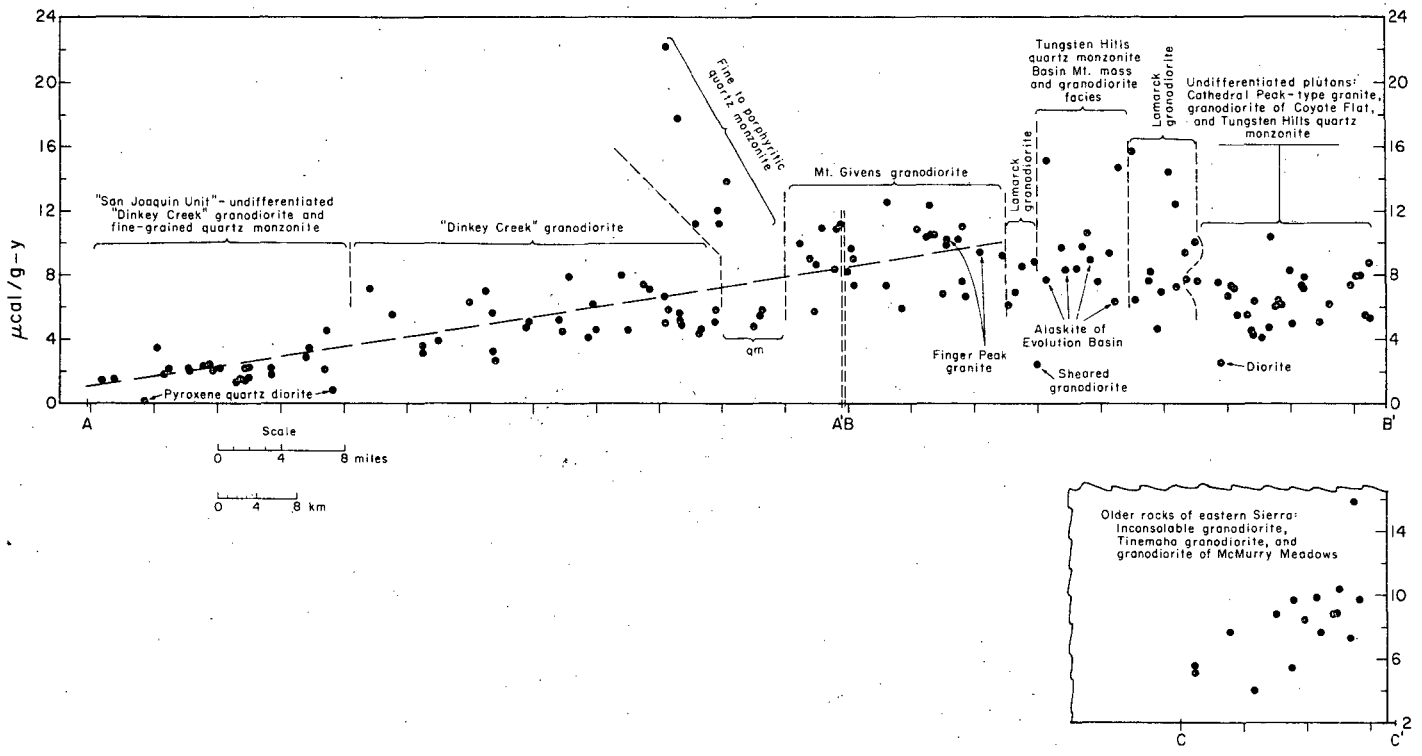

Fig. 2

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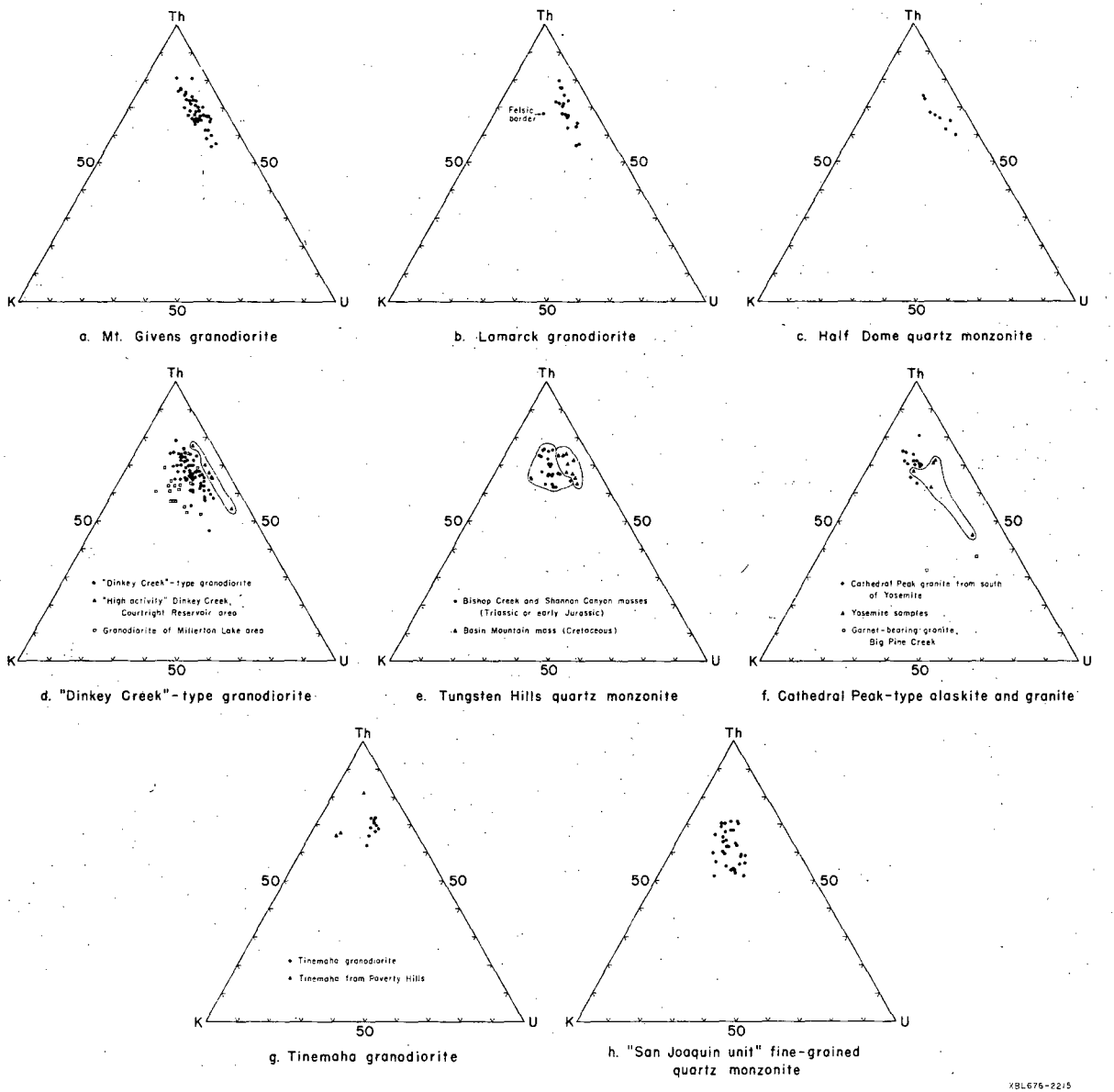

a. Mt. Givens granodiorite

b. Lamarck granodiorite

c. Half Dome quartz monzonite

d. "Dinkey Creek"-type granodiorite

e. Tungsten Hills quartz monzonite

f. Cathedral Peak-type alaskite and granite

g. Tinemaha granodiorite

h. "San Joaquin unit" fine-grained quartz monzonite

XBL676-2215

Fig. 3

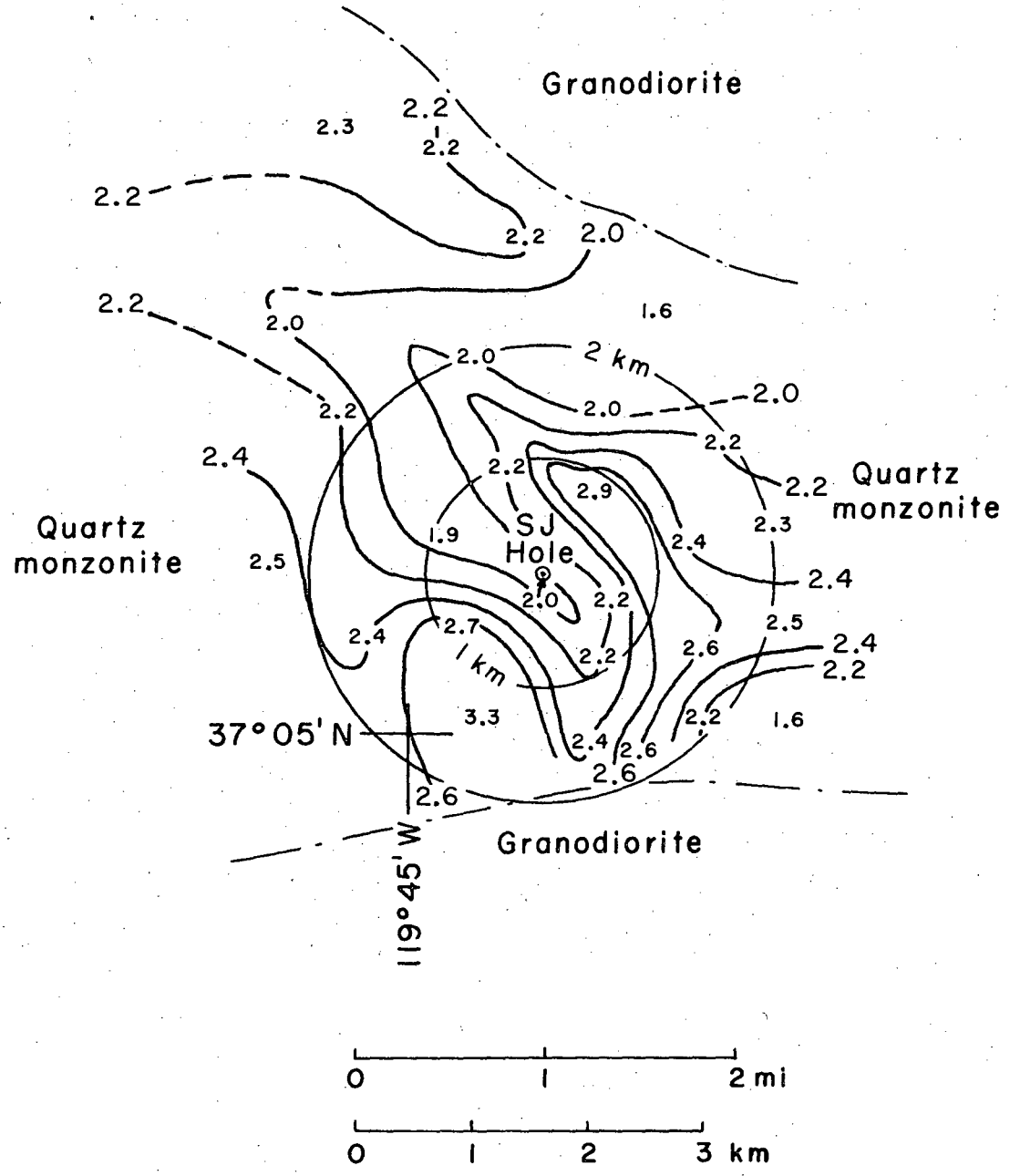

Fig. 4

XBL676-2217

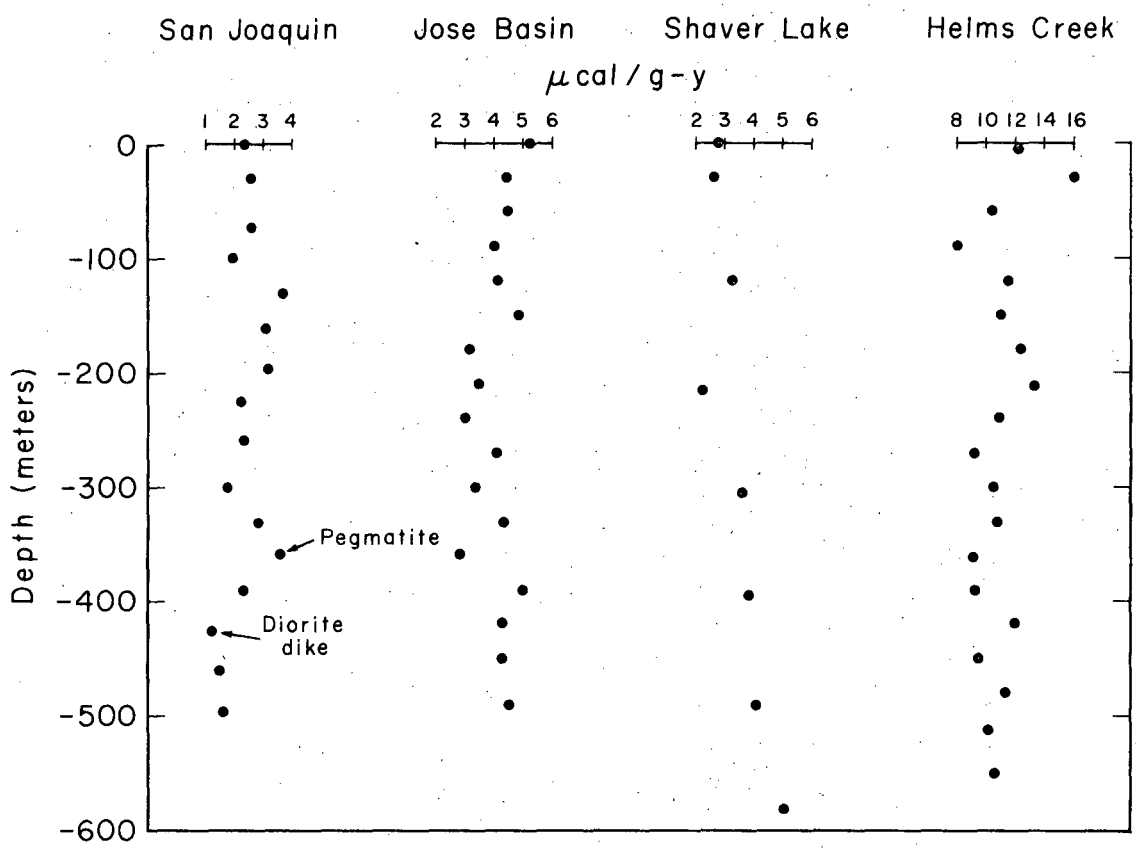

Fig. 5

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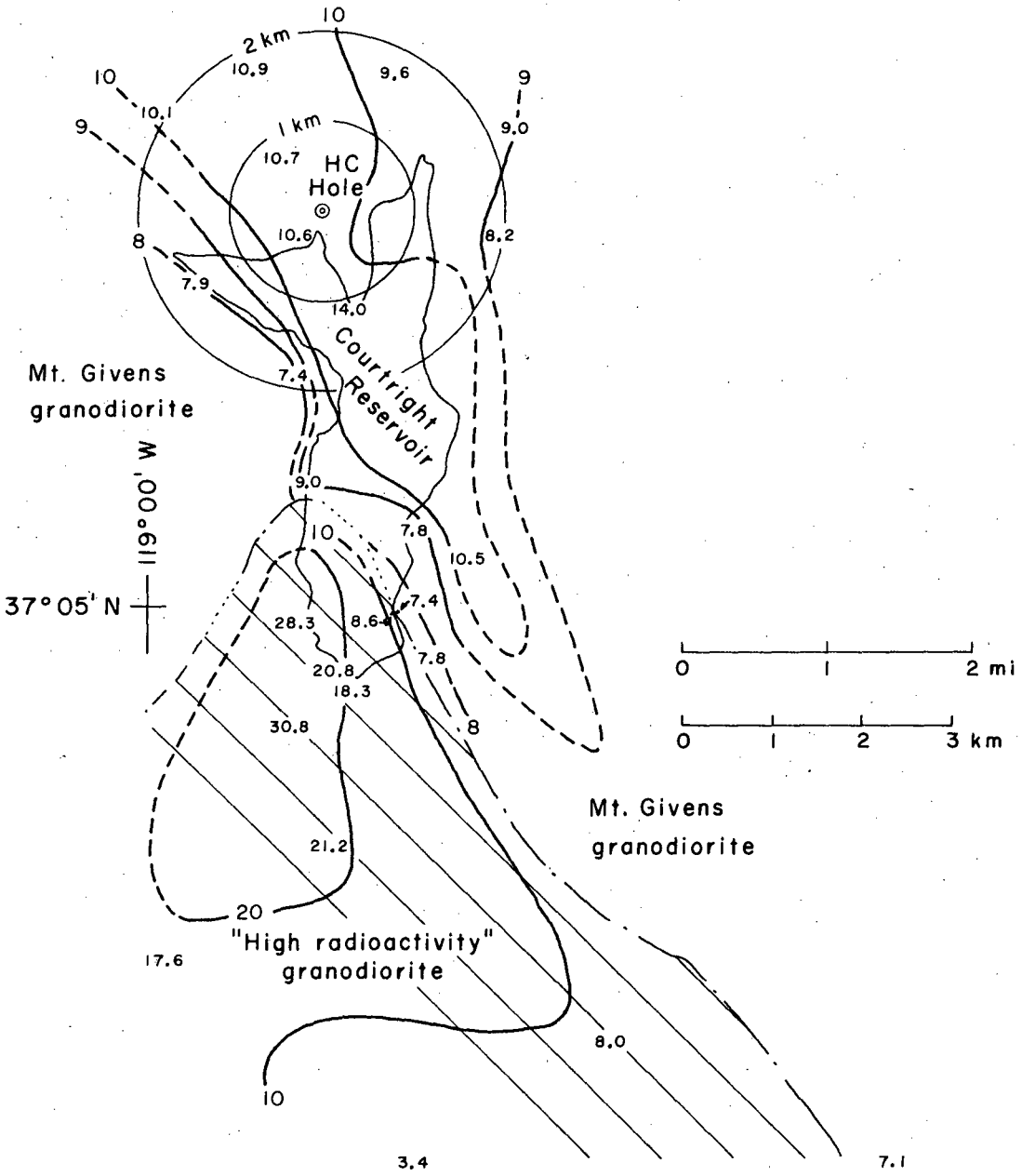

Fig. 6

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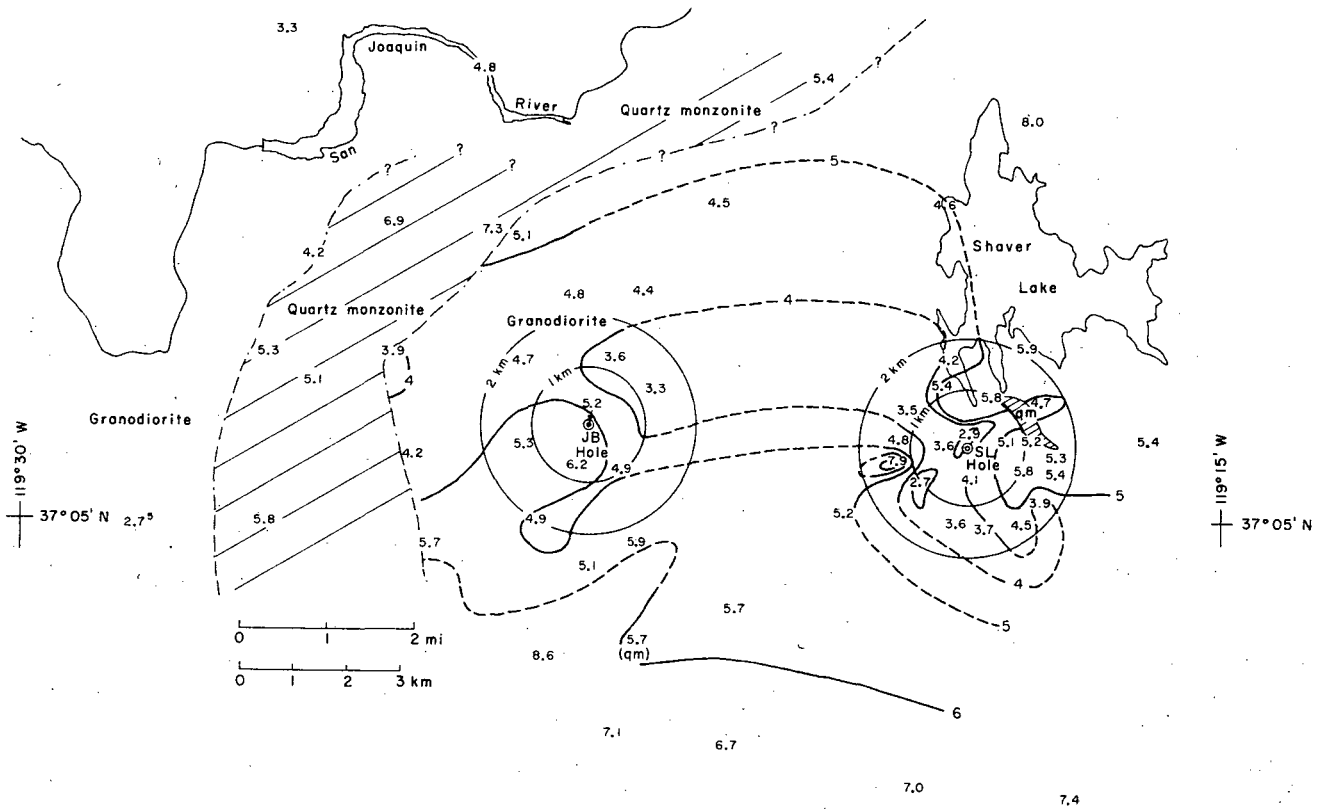

Fig. 7

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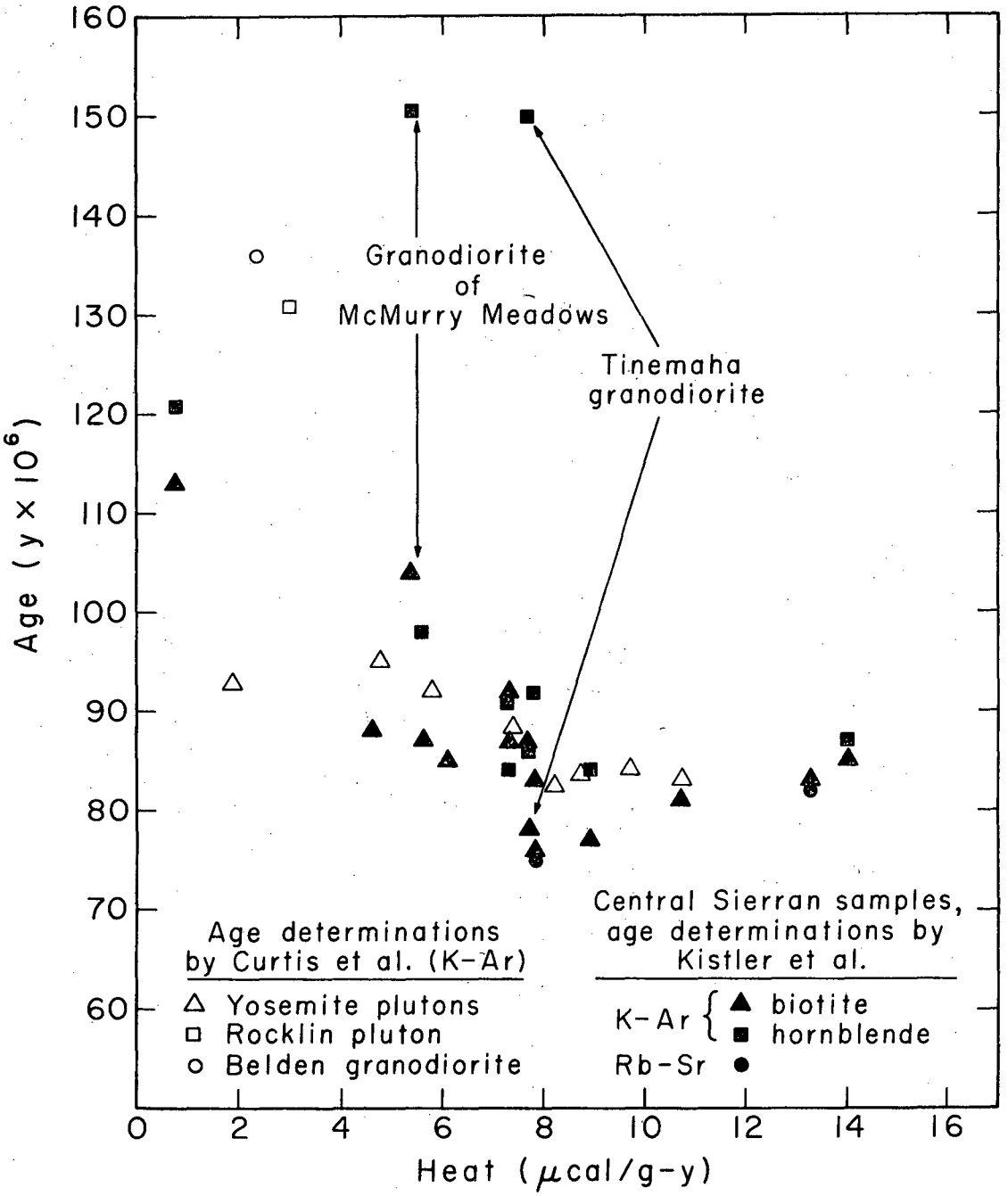

Fig. 8

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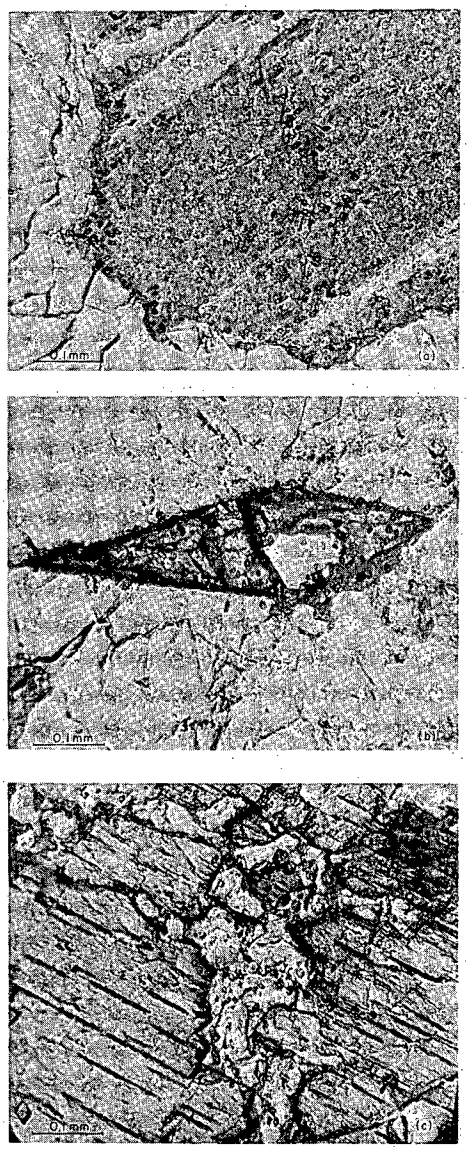

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Fig. 9

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