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ABSTRACT

The γ-ray dose rates measured at nearly all terrestrial locations depend mainly on the uranium, thorium, and potassium contents of the rock or soil. Thus, a knowledge of the geologic character of an area aids greatly in the choice of measurement sites and in the interpretation of observed results. Over the past decade we have measured U, Th, and K in many rock types by γ-ray spectrometry. Igneous rock types measured range from ultramafics to granitics; sedimentary rocks measured include sands and clays, limestones, and eugeosynclinal sandstones; metamorphic types range from low-grade blueschists to eclogite and Precambrian granulites. From the rocks' radioelement contents we have calculated the gamma-ray dose rates at sampling locations; these agree well with dose rates measured by a portable NaI (Tl) detector unit, and by other types of instrumentation operated on intercalibration surveys. Data are adequate to characterize rock types and some of their derived soils by radioelement contents and associated radioactivities.

Variations in radioelement contents within the batholithic and

eugosynclinal sedimentary rocks studied may result from geochemical factors controlled to some extent by features of plate tectonism. Some examples are given: The west to east increase in U, Th, and K in granitic plutons of the Sierra Nevada batholith matches an increasing K_2O/SiO_2 ratio, indicating the implacement of magmas of increasing alkalinity, derived from increasing depths of an eastward-dipping subduction zone. Systematic differences in radioactivities of eugeosynclinal graywackes of the Franciscan Formation match zones of low-grade metamorphism, resulting from different pressures on material caught between subducting and continental plates. In the San Francisco Bay area, soils derived from granitic and metamorphic rocks of the continental Salinian block have appreciably greater radioactivities than soils developed on or derived from lower-radioactivity Franciscan rocks. Th/U ratios of the soils are quite similar to ratios in the parent rocks, indicating no appreciable fractionation between Th and U during formation of these soils.

INTRODUCTION

The natural component of environmental γ radioactivity measured on land depends mainly on the uranium, thorium, and potassium contents of the rock and soil. The distribution and abundance of these radioelements in turn depend on whole-rock chemistry which, in many cases, may be related to global tectonic features. This is illustrated (in a considerably simplified explanation) by a geologic cycle recognized in western North America (the geomorphic map, Figure 1, serves as a guide).

The west-to-east increase in radioactivity in the Sierra Nevada batholith, observed by the authors (Wollenberg and Smith, 1968) matches an increasing K_2O/SiO_2 ratio (Bateman and Dodge, 1970), suggesting the emplacement of magmas of increasing alkalinity, derived in part from material at increasing depths of an eastward-dipping subduction zone. Predominantly Paleozoic sedimentary and volcanic rocks presently exposed in the western Great Basin and in the Sierra Nevada most likely represent material also incorporated into the magma forming the batholith (Wollenberg and Smith, 1970). Subsequent uplift and erosion of the Sierran block furnished sediments which, when deposited in a developing geosyncline to the west, retained to some extent the chemical character of their parent material. Continuing the cycle, the older geosynclinal sediments were incorporated into a prism which became trapped between oceanic and over-riding continental plates; these sediments were metamorphosed at high pressures and relatively low temperatures, forming the sequence of Franciscan graywacke sandstones and related blueschists of the California Coast Ranges. Material eroded primarily from the

Franciscan Formation, and to a lesser extent from granitic and metamorphic rocks of the Salinian block (which is presently being shifted northward along the transform San Andreas Fault), and from Tertiary sedimentary and volcanic rocks, makes up the sediments and soils of the San Francisco Bay area. Their radioelement contents then reflect the combined characteristics of their parental lineage.

Over the past decade we have sampled these and other rock terranes and have analyzed their U, Th, and K contents by laboratory γ-ray spectrometry. At most sampling sites we have measured the total γ-ray dose rate, and later compared these data with dose rates calculated from the abundances of the natural radioelements. In this paper we summarize the results, to date, of our measurements and analyses, demonstrating that such data, though not entirely acquired specifically for dose rate studies, can be used to ascertain the natural environmental gamma radioactivity within a region.

INSTRUMENTATION AND PROCEDURES

The instrumentation mostly used in the course of our studies was that described in the first Symposium on the Natural Radiation Environment (Wollenberg and Smith, 1964). More recently, our laboratory procedure has been facilitated by a 1600-channel pulse-height analyzer, from which we obtain 400-channel spectra covering the γ-ray energy interval 0.1 to 4.0 MeV. The spectra are treated by a computer program which fits, channel-by-channel, standard and sample spectra over selected energy intervals. We are now using primarily an 8-inch-diameter by 4-inch-thick NaI(Tl) crystal to measure samples packed in 6-inch-diameter by 1.5-inch-thick plastic containers. This configuration furnishes improved efficiency over our old geometry: a 4-inch-thick sample on a 4-inch by 2-inch crystal. The field-portable 3-inch by 3-inch detector-ratemeter system and counting procedures are essentially the same as described at the first Symposium. Wherever possible, field readings are taken at sampling locations.

The credibility of our field and laboratory procedures has been substantiated by intercalibration measurements at several field localities in conjunction with parties from the USAEC's Health and Safety Laboratory and Argonne National Laboratory, and J.A.S. Adams, Rice University (Beck *et al.*, 1966). At intercalibration sites and at places where the primary purpose was to measure environmental γ-ray dose rates, the portable NaI(Tl) detector was held approximately 1 meter above the ground. Several readings were made at different points over the area (usually ~ 100 m^2), then averaged. These locations were chosen to have a minimum of topographic relief. Samples were also collected from different points, then composited. At sites where the main purpose was to obtain rock specimens for geochemical studies, usually in steep or broken terrain, portable-instrument readings were taken on the surface to insure that the sampled bedrock was relatively homogeneous with respect to U, Th, and K over the representative area. Dose rates observed at the surface of relatively homogeneous terrane are essentially the same as those observed at 1 meter elevation.

To convert from U, Th, and K contents to γ-ray dose rates that would be observed 1 meter above the ground we have used the factors given by Beck et al. (1966): 1 ppm U=0.76 μr/hr, 1 ppm Th=0.36 μr/hr, 1% K=1.71 μr/hr. Though these were revised more recently (Beck and de Planque, 1968), giving slightly lower dose rates, we have continued to use the 1964-1966 factors, primarily to retain consistency with earlier data.

There is a strong linear relationship between mean values of field-observed dose rates, characteristic of given rock types or geographic area, and mean dose rates from laboratory analyses of natural radioelements in corresponding groups of samples (Fig. 2). The associated regression line has nearly a 45-degree slope and an intercept of 1.7 μr/hr for "zero" U, Th, and K content. Inspection of the tabulations in the following sections also shows a generally higher γ-ray dose rate observed in the field by the portable instrument than the dose rate calculated from natural radioelement contents of corresponding samples. These differences are attributed to the combined effects of atmospheric radon (at sites of low radioactivity) and fallout (at all sites) measured by the field instrument. Beck (1964) has shown that values of U-content measured in the field may be anomalous, because the diffusion of radon from the soil into the atmosphere produces values lower than would be expected from laboratory analysis of representative equilibrium samples. Although the problem must be kept constantly in mind, laboratory study has shown it to be unimportant for the measurements and samples discussed here. The contribution of the cosmic ray flux to portable-instrument response is negligible in field observations over usual rock or soil. This is the case because each detected event contributes equally to the instrument count rate, irrespective of the amount of energy deposited: for example, a cosmic ray muon that deposits 50 MeV in the detector produces only a single count. This is demonstrated by the very low counting rates (15-20 c.p.s., or 0.4-0.5 μr/hr) measured on lakes at 1700 and 2500 meters elevation (latitude 37° N). Many of the field measurements reported here were made in the early 1960's, when substantial fallout was present on the surface. Gamma-ray spectra of surface samples from that time often showed the presence of ^{95}Nb-^{95}Zr, as well as ^{137}Cs; most of the ^{137}Cs is still present in surficial materials.

RADIOELEMENTS AND DOSE RATES

In this section we summarize the results of more than 500 field measurements of the total terrestrial γ-ray dose rate on bedrock terranes, and laboratory determinations of U, Th, and K in representative samples. In keeping with the geologic cycle discussed in the introduction, we shall begin by summarizing the natural γ radioactivity of the predominantly Paleozoic rocks of the western Great Basin and roof pendants on the Sierra Nevada batholith, then progress up the geologic time scale with summaries of the Paleozoic and older Mesozoic rocks of the western Sierran foothill belt, the Sierran batholithic rocks (inserting data on granitic rocks of the Salinian block), middle to upper Mesozoic sandstones of the North Coast Ranges, and Eocene sands and clays derived from the Sierra Nevada. Contrasting very low radioactivities of ultramafic rocks of the Sierran foothills and Coast Ranges are also summarized, as well as the results of continuing radiometric surveys of the San Francisco Bay area.

Predominantly Paleozoic Rocks of the Eastern Sierra Nevada and Western Great Basin

The distribution of these rocks, their western Sierran counterparts, and their spatial relationship to the Sierra Nevada batholith are shown on the geologic map, Figure 3. The sedimentary rocks range in age from Precambrian in the Death Valley region to upper Carboniferous and Permian in the Inyo-White Mountains and in roof pendants of the eastern Sierra Nevada. The Precambrian rocks are moderately to strongly metamorphosed, while the Paleozoic rocks of the Inyo-White Mountains are only slightly metamorphosed. There is appreciable contact thermal metamorphism of the Sierran pendants, which might have caused the lower-than-average Th/U ratios of these rocks. Geologic mapping of the rock units has been adequate enough to permit an estimate of the rock types' relative abundance; the overall weighted mean values listed on Table 1 are based on ~ 30 per cent carbonate, ~ 70 per cent siliceous clastic rock.

The radioactivities were described in detail by the authors (Wollenberg and Smith, 1970), who found substantial differences between overall U, Th, and K of carbonates and siliceous clastics; these two categories have been separated in Table 1 and in the histogram, Fig. 4. The broad range of radioactivity of the siliceous rocks is illustrated in the histogram, in contrast to the carbonates' relatively narrow range. The low radioactivities of the carbonate rocks are consistent with low radioactivities of limestones and dolomites in the western foothills of the Sierra Nevada, at cement plant quarries in California, and in samples of limestone obtained from cement plants in the central United States (Wollenberg and Smith, 1966).

The large discrepancy between the carbonate rocks' γ-ray dose rates observed in the field and those calculated from the natural

Table 1.

Mean radioelement contents and calculated and observed gamma-ray dose rates of predominantly Paleozoic sedimentary rocks of Sierran pendants and western Great Basin.

Description	No. of samples	U (p.p.m.)	Th (p.p.m.)	K (%)	Dose-rate contribution of radioelements (μr/hr)				
					U	Th	K	Total	Observed
Carbonate rocks	33	0.93	1.78	0.36	0.7	0.6	0.6	1.9	5.3
Siliceous clastic rocks	39	3.37	10.0	1.92	2.6	3.6	3.3	9.5	11.6
Overall weighted mean*	72	2.64	7.53	1.34	2.0	2.7	2.3	7.0	9.7

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[*] Mean values weighted by approximate abundances of rock types: carbonates ~ 30%, clastics ~ 70% (Wollenberg and Smith, 1970).

radioelement contents results from the close proximity of higher-radioactivity siliceous clastic rock interbedded with the carbonates, coupled with the effects of steep terrain.

Paleozoic and Mesozoic and Sedimentary Rocks of the Sierran Foothills

The metamorphic rocks of the western foothills of the Sierra Nevada form a roughly north-south trending belt separating the bulk of the batholithic rocks on the east from Tertiary and Quaternary sediments of the Great Valley to the west (Fig. 3). The belt is breached in a few places by mafic (and relatively low radioactivity) plutons, western outliers of the main Sierran batholith. The carbonate rocks of the foothills belt are confined to the Paleozoic Calaveras Formation, while metamorphosed volcanic and clastic sedimentary rocks make up the majority of the Calaveras and the entirety of the Mesozoic units. Taken as a whole, the foothills belt is approximately 5 to 10% carbonate rock, 40% metavolcanic, and 50-55% clastic metasedimentary rock.

The radioactivity of the carbonate rocks (Table 2) is significantly lower than that of the eastern Sierran - Great Basin carbonates. Therefore, these rocks, combined with the relatively low-radioactivity metavolcanics and comparatively low metasedimentary rocks give a regional mean γ-ray dose rate significantly lower than that of eastern Sierran - Great Basin Paleozoics. The histogram, Fig. 5, illustrates the rather confined low-radioactivity range of the carbonate rocks in contrast to the broader range in the metavolcanics and the wide range and relatively high radioactivities of the metasedimentary rocks. The lower overall radioactivity of the foothills belt rocks compared with the higher regional values in the prebatholithic rocks of the eastern Sierran - Great Basin

Table 2.

Mean radioelement contents and calculated γ-ray dose rates of Paleozoic and Mesozoic volcanic and sedimentary rocks of the Sierran foothills.

Description	No. of samples	U (p.p.m.)	Th (p.p.m.)	K (%)	Dose-rate contribution of radioelements (μr/hr)				
					U	Th	K	Total	Observed
Carbonate rocks	8	0.53	0.24	0.03	0.4	0.1	0.05	0.05^5	2.8
Volcanic rocks	8	1.58	4.30	0.36	1.2	1.5	0.6	3.3	3.2
Siliceous clastic rocks	18	2.12	7.52	1.59	1.6	2.7	2.7	7.0	8.9
Overall weighted means*	34	1.78	5.69	0.98	1.3^5	2.0	1.7	5.0	6.2

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* Mean values weighted by approximate abundances of rock types: carbonates ~ 7.5%, volcanics ~ 40%, clastics ~ 52.5% (Wollenberg and Smith, 1970).

matches, though not proportionally, the west-to-east increase in radioactivity observed in the Sierra Nevada batholith, helping to substantiate the hypothesis that these prebatholithic rocks represent eugeosynclinal material incorporated into the early batholithic magma (Wollenberg and Smith, 1970).

The Sierra Nevada Batholith

The batholith, whose plutons were emplaced sequentially over a 130-million-year period throughout the Jurassic and most of the Cretaceous periods (Evernden and Kistler, 1970), has been described by Bateman and Wahrhaftig (1966). More recently, Bateman and Dodge (1970) described the variations of major chemical constituents within the batholith. The authors have reported detailed studies of the distribution of radioelements and radiogenic heat production in the batholith (Wollenberg and Smith, 1968); the data was combined by Lachenbruch (1968) with heat flow measurements and incorporated into a geothermal model of the Sierra Nevada.

For the purposes of this paper the numerous granitic rock units of the central portion of the batholith, shown on the geologic map (Fig. 6), were combined into three major groups: granitic rocks of the western foothills; intermediate granitic rocks of the western slope of the Sierra; and granodiorites, quartz monzonites, and granites of the upper regions and eastern side of the range. The western foothillls group is that of Bateman and Dodge, and includes mafic granodiorites, quartz diorites, and diorite. The intermediate group incorporates primarily Bateman and Dodge's Shaver sequence and Yosemite rocks, while the upper regions-east-side group includes their John Muir, Palisade Crest, and Scheelite sequences and Tuolumne Intrusive Series.

The accompanying table (3) and histogram (Fig. 7) illustrate the characteristic radioactivities of the three rock groups, which vary by approximately a factor of 3, from about 5 μr/hr in the western foothills' granitics to over 16 μr/hr in the granitics of the upper regions. Within each of these groups radioactivity generally increases continuously from west to east with little apparent discontinuity at the borders of the groups. This radioactivity continuum matches increasing K_2O/SiO_2 (Bateman and Dodge, 1970) and heat flow (Lachenbruch, 1968). Though these data are mainly from a sampling of a broad zone across the central part of the Sierra, scattered samples of granitic rocks to the north suggest similar radioactivities in that region. The rock types making up the Sierra Nevada batholith encompass essentially the full range of Plutonic rocks one would most probably encounter elsewhere.

Granitic Rocks of the Salinian Block

The Salinian block of the central and northern Coast Ranges is bounded on the east by the San Andreas Fault, along which the block has been and is presently creeping northward (Fig. 1). This motion, continuous perhaps for tens of millions of years, has juxtaposed granitic rocks of the block into direct contact with Coast Range rocks of entirely different radioactivity. Some writers have proposed that the granitic rocks are the northward-displaced equivalents of granitic rocks of the Southern California batholith (for example, Curtis et al., 1958). Cretaceous age dates of the granitics are similar to those of the Southern California batholith and of central Sierran intermediate granitics.

Table 3.

Mean radioelement contents and calculated γ-ray dose rates of Sierra Nevada granitic rocks.

Description	No. of samples	U (p.p.m.)	Th (p.p.m.)	K (%)	Dose-rate contribution of radioelements (μr/hr)				
					U	Th	K	Total	Observed
Granitic rocks of western foothills	25	1.3	3.7	1.34	1.0	1.3	2.3	4.6	6.0
Intermediate rocks of western slope	91	3.4	12.8	1.96	2.6	4.6	3.4	10.6	12.2
Granodiorites, quartz monzonites, and granites of upper regions and east side of Sierra	169	5.6	19.6	3.18	4.3	7.1	5.4	16.8	18.0
Mean values	285	4.5	16.0	2.63	3.4	5.8	4.5	13.7	15.1

The Salinian igneous and metamorphic rocks have been described by Compton (1966). Dodge and others (1969) summarized the natural radioelement content of the granitics, and pointed out their similarity in radiogenic heat production with the granodiorite of Dinkey Creek, the Sierran rock unit which makes up the bulk of our intermediate group. The histogram of γ-ray dose rates in the Salinian granitics (Fig. 8) shows a range of values and a peak similar to those in the histogram of intermediate Sierran granitics. Mean radioelement contents are: U, 2.49 p.p.m.; Th, 9.26 p.p.m.; K, 2.15%; leading to a calculated mean dose rate of 9.9 μr/hr (σ, ± 5.9 μr/hr). The corresponding mean field-observed rate is 11.5 μr/hr (σ, ± 4.8 μr/hr). Erosion of these rocks has contributed material to soils at some of the sites measured in the San Francisco Bay area.

Mesozoic Sandstones of the Northern Coast Ranges

The graywacke sandstones of the northern Coast Ranges were deposited during the late Mesozoic in a geosynclinal environment, most likely receiving its sedimentary material from the early erosion of the granitic and sedimentary rocks of the ancestral Sierra Nevada and Klamath mountains (Bailey *et al.*, 1964). Two major rock units make up this group: light to moderately metamorphosed graywackes of the Franciscan Formation and, in fault contact to the east, unmetamorphosed graywackes of the Great Valley sequence. In the aforementioned reference Bailey *et al*. described the Franciscan rocks, while Page (1966) summarized the Great Valley rocks and discussed their relationship to their Franciscan and Sierran antecedents.

In this paper we have divided the graywackes into three units

Table 4
Mean radioelement contents and calculated and observed γ-ray dose rates of North Coast Range rocks.

Description	No. of samples	U (p.p.m.)	Th (p.p.m.)	K (%)	Dose rate contribution of radioelements (μr/hr) U	Th	K	Total	Observed
Sandstones of Great Valley sequence	20	1.06	3.49	0.94	0.8	1.3	1.6	3.7	5.4
Pumpellyite and Lawsonite metagraywacke of Franciscan Fm.	37	2.01	6.73	1.24	1.5	2.4	2.1	6.0	6.8
Laumontite metagraywacke of Franciscan Fm.	29	2.02	7.68	1.61	1.5	2.8	2.8	7.1	8.2
Mean values of sandstones	86	1.79	6.30	1.29	1.4	2.3	2.2	5.9	6.9
Glaucophane schist and eclogite	4	0.53	1.44	0.48	0.4	0.5	0.8	1.7	

(Table 4); they are depicted on a generalized geologic map of the sampled area, Fig. 9. The Upper Jurassic Cretaceous rocks of the Great Valley sequence are considered separately from the metagraywackes of the Franciscan Formation as are the metagraywackes of the Franciscan's Coastal Belt unit. The authors, accompanied by E.H. Bailey, made radiogeologic traverses across the northern Coast Ranges (Wollenberg et al., 1967) from which data the results presented here have been synthesized.

The metagraywackes of the Franciscan Formation exhibit varying degrees of high pressure (relative to temperature) regional metamorphism, ranging from a low grade in the Coastal Belt rocks (characterized by the mineral, laumontite) into higher grades in the postassium feldspar-poor eastern Franciscan graywackes (characterized by pumpellyite and lawsonite), and culminating in glaucophane schists and eclogite. Somewhat conflicting models to explain this metamorphic sequence have been proposed by Blake et al. (1969) and Ernst et al. (1970). Generally, the radioelement contents of these rocks decrease with increasing metamorphic grade, as shown in Table 4. This inverse relationship has been demonstrated by Heier and Adams (1965) in geologic terranes of much higher metamorphic grade.

The histogram, Fig. 10, shows the distribution of higher γ-ray dose rates of the Coastal Belt graywackes compared with dose rates of the eastern Franciscan and Great Valley rocks. Unmetamorphosed, and of relatively low radioactivity, the Great Valley graywackes are not genetically related to the Franciscan, but are in thrust-fault contact. Material from graywackes such as these of the northern Coast Ranges makes up a significant portion of the Tertiary sedimentary rocks in the San Francisco Bay area, and Franciscan graywackes comprise the bulk of the bedrock of the area.

Eocene Sandstones and Clays

Shallow-water and deltaic deposits of interbedded sands and clays, the Ione Formation Eocene in age, crop out in a narrow belt along the western margin of the Sierra Nevada. The sandy members of the Ione contain appreciable dark streaks, mainly zircon and ilmenite, suggesting their derivation from a predominantly granitic source, the Sierra Nevada batholith. Sands and clays of similar composition, the Eocene Tesla and Domengine Formations, crop out on the western edge of the Great Valley; they are considered also to be derived from the Sierra Nevada (Allen, 1941; Huey, 1948; and Todd and Monroe, 1968).

A study of the radio- and trace-element contents of Eocene sedimentary rocks derived from the batholith (Wollenberg and Dodge, in press) resulted in a comparison of U, Th, and K contents with other trace elements. It was found that high radioactivities were closely associated with dark heavy-mineral streaks in sandy beds; and that there were positive correlations between U, Th, Zr, Ti, and La, but essentially no correlation between radioelements and gold.

Comparison of the dose-rate histogram for the Eocene sediments (Fig. 11) with that for the Sierran granitic rocks (Fig. 7) shows that the range of radioactivities in the granitics is matched in the Eocene sediments. However, most of the Eocene rocks are relatively depleted in potassium, an overall mean value of 0.65%, but contain appreciable U and Th averaging 3.97 and 14.0 p.p.m. respectively. The associated mean dose rate, 9.2 μr/hr, is somewhat lower than the average for the granitics (13.7 μr/hr), and reflects the significantly lower K content of the Eocene samples. It should be pointed out that the majority of the samples were collected in the Ione - Buena Vista area where the sands and clays are quite low in K. In more northerly exposures of the Ione Formation and in the Tesla and Domengine formations K averages well over 1%. These regional differences coupled with the close association of U and Th with dark sands indicate that processes associated with transportation and deposition of the sediments, rather than just the composition of the source rocks, strongly influenced the rocks' radioelement contents.

Ultramafic Rocks

Lenses, pods, and elongate zones of Mesozoic serpentinized ultramafic rocks are associated primarily with fault zones cutting the Coast Ranges and transecting the metamorphic belt of the Sierra Nevada foothills. The extremely low radioactivity of this rock type was demonstrated by the authors at the first Symposium on the Natural Radiation Environment (Wollenberg and Smith, 1964). Generally, uranium and thorium are present only in the tens of p.p.b. range, and potassium contents are of the order of 40-200 p.p.m. (Goles, 1967).

Although field radioactivity over these rocks is quite low, the ultramafic rocks themselves contribute essentially none of the measured radioactivity. Mean γ-ray dose rates over the freshest available exposures of serpentine, at open-pit mines and roadcuts in the Coast Ranges and Sierran foothills, average 1.1 μr/hr with a standard deviation of 0.22 μr/hr. This is somewhat lower than the intercept value of

1.7 μr/hr on the curve of observed versus "natural" dose rates (Fig. 2), but falls well within the curve's envelope of statistical variance. Thus, we attribute the radioactivity measured over ultramafic rock primarily to the factors already mentioned; fallout and atmospheric radon. Of course, if the measuring point is near enough to a contact of rock with "normal" radioactivity, this rock would also contribute to the observed counting rate.

The slight effect of atmospheric radon alone on measurements in an ultramafic environment was demonstrated by observations under more than 100 meters of rock cover in a magnesite mine in serpentine of the Coast Ranges. The mine had several openings to the outside atmosphere, and a constant draft of air moved down through the workings. The closest contact with rock of "normal" radioactivity was approximately 1 km away on the surface. Radon concentrations in the moving stream of air varied from about 100 to over 500 picocuries $/m^3$, depending on the time of day and season (Jones and Kleppe, 1966). Corresponding γ-ray dose rates measured by our NaI(T1) detector were in the range 0.05 to 0.1 μr/hr, part of which must be assigned to slight radioactivity of components of the detector. Gamma-ray spectra taken concurrently underground by Beck et al. (1966) indicated only the presence above background of Rn daughters. Samples of the mine's wall rocks were were essentially devoid of uranium and thorium. We were not able to ascertain whether the radon emanated from cracks and openings in the mine, or whether the mine acted as a radon trap, concentrating the element in low places as the air moved through the workings.

The San Francisco Bay Area

The soils of the San Francisco Bay area are characteristic of four regions, shown on the map, Fig. 12:

(1) The Bay plain - Santa Clara Valley soils are derived from the Franciscan Formation as well as from younger Tertiary sedimentary and volcanic rocks. The soil types range from bay muds to sandy and gravelly alluvium, and stiff clayey "adobe."

(2) The Santa Cruz Mountain region is transected by the San Andreas Fault zone. East of the fault are the Franciscan Formation and overlying Tertiary sediments. Lying west of the fault, metamorphic and granitic rocks of the Salinian block are overcapped in places by Miocene sandstone and shale. Soil in the Santa Cruz Mountain region formed essentially in place, or was transported only short distances from the source rocks.

(3) The Coastal Terrace and Plain region borders the ocean shoreline from Monterey Bay northward along the San Francisco Peninsula. The Tertiary and Quaternary alluvial and terrace sediments were derived mainly from rocks of the Salinian block.

(4) The North Bay - Franciscan region, situated east of the San Andreas Fault zone, has soils developed predominantly from graywacke sandstones of the Franciscan Formation.

Soils derived from granitic and metamorphic rocks of the Salinian block have appreciably greater radioactivities than soils developed on or derived from lower-radio-activity Franciscan rocks. A Series of locations, also shown on the map, have been surveyed periodically since 1958, primarily to determine the fallout component of terrestrial γ

radioactivity. This was accomplished by combining field measurements at the sites with laboratory γ-ray spectrometry of corresponding soil samples. Results of these surveys were reported by Wollenberg et al. (1968).

Table 5 summarizes the radioelement contents and observed and calculated dose rates from the four regions. The mean values for the Bay Plain - Santa Clara Valley soils and North Bay - Franciscan soils are quite similar, attesting to the predominance of Franciscan bedrock as their ultimate source. The Tertiary sedimentary rocks contributing to these soils are made up primarily of material eroded from the Franciscan; therefore, their overall radioactivities are also similar to those of the Franciscan as well as to the soils' radioactivities. The overall mean Th/U ratio for the soils of the San Francisco Bay area is 3, slightly lower than the mean Th/U ratios of the bedrock types contributing to the soils. However, the soils' Th/U is within the standard deviations of the bedrocks' mean, indicating that there was no appreciable fractionation of Th with respect to U during erosion, transportation, or deposition of the soil-forming materials.

The range of natural γ-ray dose rates of San Francisco Bay area soils, shown on the histogram, Fig. 13, is encompassed by the ranges in rocks of the Salinian block and the Franciscan Formation.

CONCLUSION

Western North American, presently undergoing active tectonism, contains a wide variety of rock types. The data presented here, from rocks of California and western Nevada, cover a broad range in lithology, from ultramafic to granitic plutonic igneous rocks and from carbonate

Table 5.

Mean radioelement contents and γ-ray dose rates of soils and rocks of the San Francisco Bay area.

Description	No. of samples	U (p.p.m.)	Th (p.p.m.)	K (%)	Dose rate contribution of radioelements (μr/hr)				
					U	Th	K	Total	Observed
Bay Plain - Santa Clara Valley soils	7	1.6	5.2	1.13	1.2	1.9	1.9	5.0	4.9
Santa Cruz Mts. soils	4	2.4	7.2	2.67	1.8	2.6	4.6	9.0	8.5
Coastal terrace and plain soils	4	2.9^5	5.6^5	1.38	2.2	2.0	2.4	6.6	5.7
North Bay - Franciscan soils	12	1.6	5.6	1.13	1.2	2.0	1.9	5.1	5.3
Mean values for soils	27	1.9	5.7^5	1.40	1.4	2.1	2.4	5.9	5.7
Franciscan sandtone from northern San Francisco peninsula	15	2.2	6.0	1.7	1.7	2.2	2.9	6.8	8.7
Tertiary volcanic and sedimentary rocks of the Berkeley Hills	6	1.3	4.6	0.9	1.0	1.7	1.5	4.2	4.0

to siliceous clastic sedimentary rocks. The dose rate histograms of the rock types containing appreciable radioactivity are shown in Fig. 14. Within these categories natural radioelement contents and associated γ-ray dose rates also vary over broad ranges; for example, in plutonic rocks over an order of magnitude between low-radioactivity diorites and gabbros and more radioactive quartz monzonites and granites. Though not reported in detail in this paper, we have also observed that volcanic rocks, depending on their composition, vary in radioactivity similar to their plutonic counterparts.

Of all the rocks exposed on the earth's surface the ultramafics are the least radioactive, with radioelement contents generally below the limit of detection of γ-ray spectrometric instrumentation. Dose rates measured over these rocks then derive from fallout contamination, atmospheric radon, and the cosmic-ray flux.

Of the sedimentary rocks the carbonates, limestones and dolomite, are generally lowest in radioactivity. The radioactivity of clastic sedimentary rocks depends mainly on their source material; for example, the relatively high radioactivity Eocene sandstones and clays, derived from a predominantly granitic terrane. The degree of regional metamorphism effects the rocks' radioactivity, exemplified by decreasing radioactivity in eugeosynclinal graywackes of increasing metamorphic grade.

Inspection of the radioelement and dose-rate tabulations for the various rock types shows that, with the exception of the carbonate rocks, potassium and thorium individually contribute more to the total natural γ-ray dose rate than does uranium. In the eastern Sierran carbonate rocks, many of which are somewhat silicified, the U contribution is slightly greater than potassium's or thorium's. The U contribution of the carbonate rocks of the Sierran foothills greatly exceeds those of Th and K. The relative deficiency of U as a contributor to the γ-ray dose rates of soils over the United States is indicated in nearly all of the measurements by Beck et al. (1964). We expect that given "normal" K:U:Th ratios, such a condition holds for essentially all siliceous rock terranes.

In the geologic cycle: emplacement or extrusion of magmatic rocks → subsequent uplift → erosion → transportation and deposition of sediments, bedrock and soil data (mostly from the San Francisco Bay area) suggest that the natural radioelements are recycled with little overall fractionation of one with respect to the others. Thus, the dose rates of Quaternary sediments and soils, upon which most people live and from which most human sustenance is derived, reflect the composite of dose rates of their parent materials.

FOOTNOTES AND REFERENCES

[*] Work done under the auspices of the U.S. Atomic Energy Commission.

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FIGURE LEGENDS

Fig. 1. Map of northern and central California, showing geomorphic provinces

Fig. 2. Gamma-ray dose rates observed by the portable NaI(Tl) instrument, versus mean values of dose rates calculated from natural radioelement contents of corresponding groups of samples.

Fig. 3. Portion of California between 36 and 39 degrees north, showing major lithologic units of the Sierra Nevada and Great Basin provinces.

Fig. 4. Frequency distributions of γ-ray dose rates calculated from U, Th, and K contents of predominantly Paleozoic sedimentary rocks of Sierran pendants and the western Great Basin province.

Fig. 5. Frequency distributions of γ-ray dose rates calculated from U, Th, and K contents of Paleozoic and Mesozoic metamorphosed volcanic and sedimentary rocks of the Sierran foothills.

Fig. 6. Geologic map showing the location of sampling sites in the Sierra Nevada batholith. Circled areas are heat-flow measurement sites; lines denote heat-production profiles (Wollenberg and Smith, 1968).

Fig. 7. Frequency distributions of γ-ray dose rates calculated from U, Th, and K contents of granitic rocks of the Sierra Nevada.

Fig. 8. Frequency distributions of γ-ray dose rates calculated from U, Th and K contents of granitic rocks of the Salinian block.

Fig. 9. Simplified geologic map of a portion of the northern Coast Ranges. Q, Quaternary rocks; T, undivided Tertiary rocks; K, Cretaceous rocks west of San Andreas Fault. Great Valley sequence: UK, Upper Cretaceous rocks; LK, Lower Cretaceous rocks; UJ, Upper Jurassic rocks; Fcb, rocks of the Franciscan's Coastal Belt unit; F, Franciscan rocks. Width of circles over sampling sites indicates U content.

Fig. 10. Frequency distributions of γ-ray dose rates calculated from U, Th, and K contents of graywacke sandstones of the northern Coast Ranges.

Fig. 11. Frequency distributions of γ-ray dose rates calculated from U, Th, and K contents of Eocene sandstones and clays.

Fig. 12. Map of the San Francisco Bay area, showing field measurement and sampling locations in the four principal regions covered in radiometric surveys.

Fig. 13. Frequency distributions of γ-ray dose rates calculated from U, Th, and K contents of San Francisco Bay area soil samples.

Fig. 14. Histograms of γ-ray dose rates of various rock types.

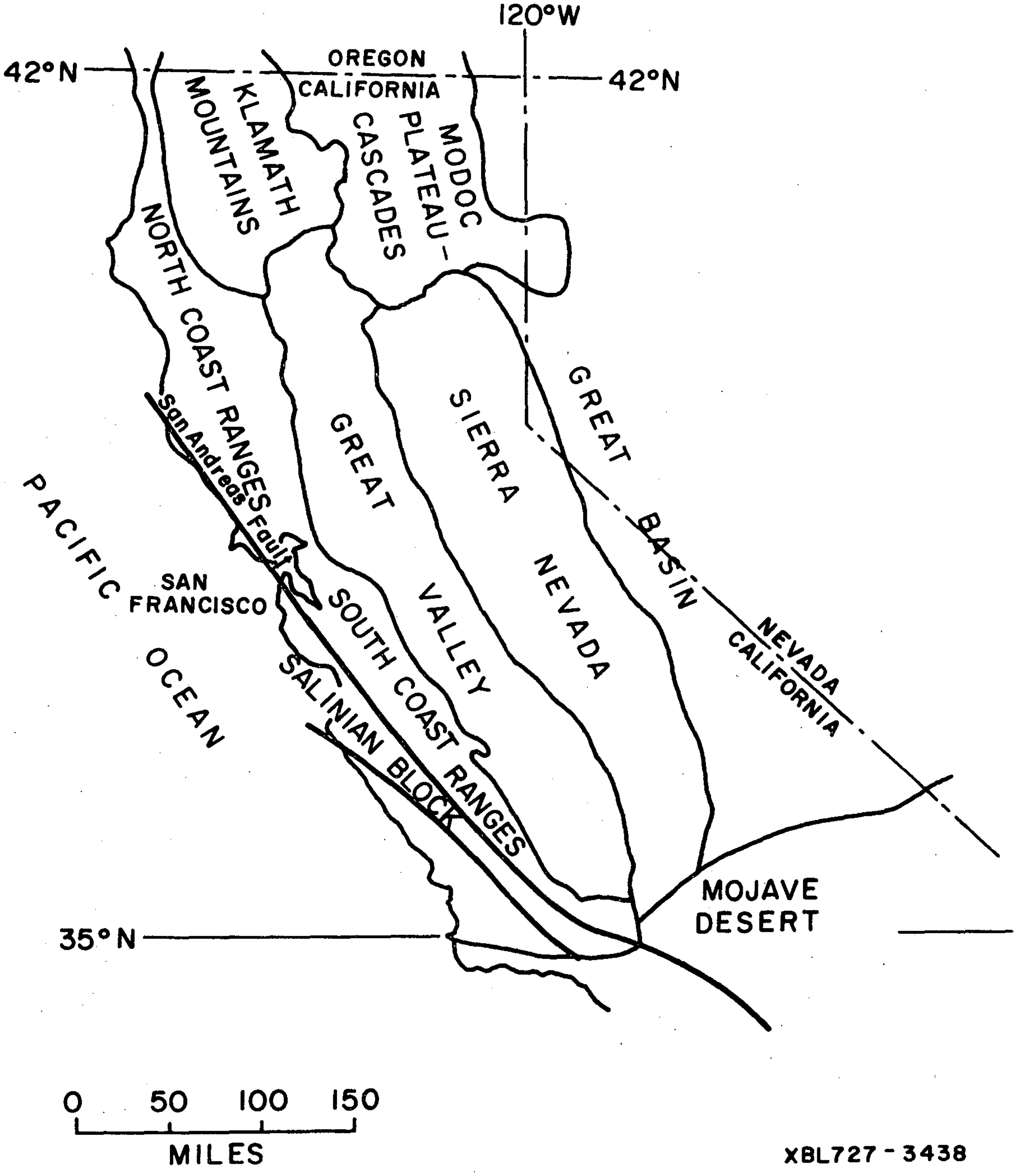
120°W
42°N
42°N
OREGON
CALIFORNIA
KLAMATH MOUNTAINS
MODOC PLATEAU - CASCADES
NORTH COAST RANGES
San Andreas Fault
GREAT VALLEY
SIERRA NEVADA
GREAT BASIN
NEVADA
CALIFORNIA
PACIFIC OCEAN
SAN FRANCISCO
SOUTH COAST RANGES
SALINIAN BLOCK
MOJAVE DESERT
35°N
0 50 100 150
MILES
XBL727-3438

Fig. 1

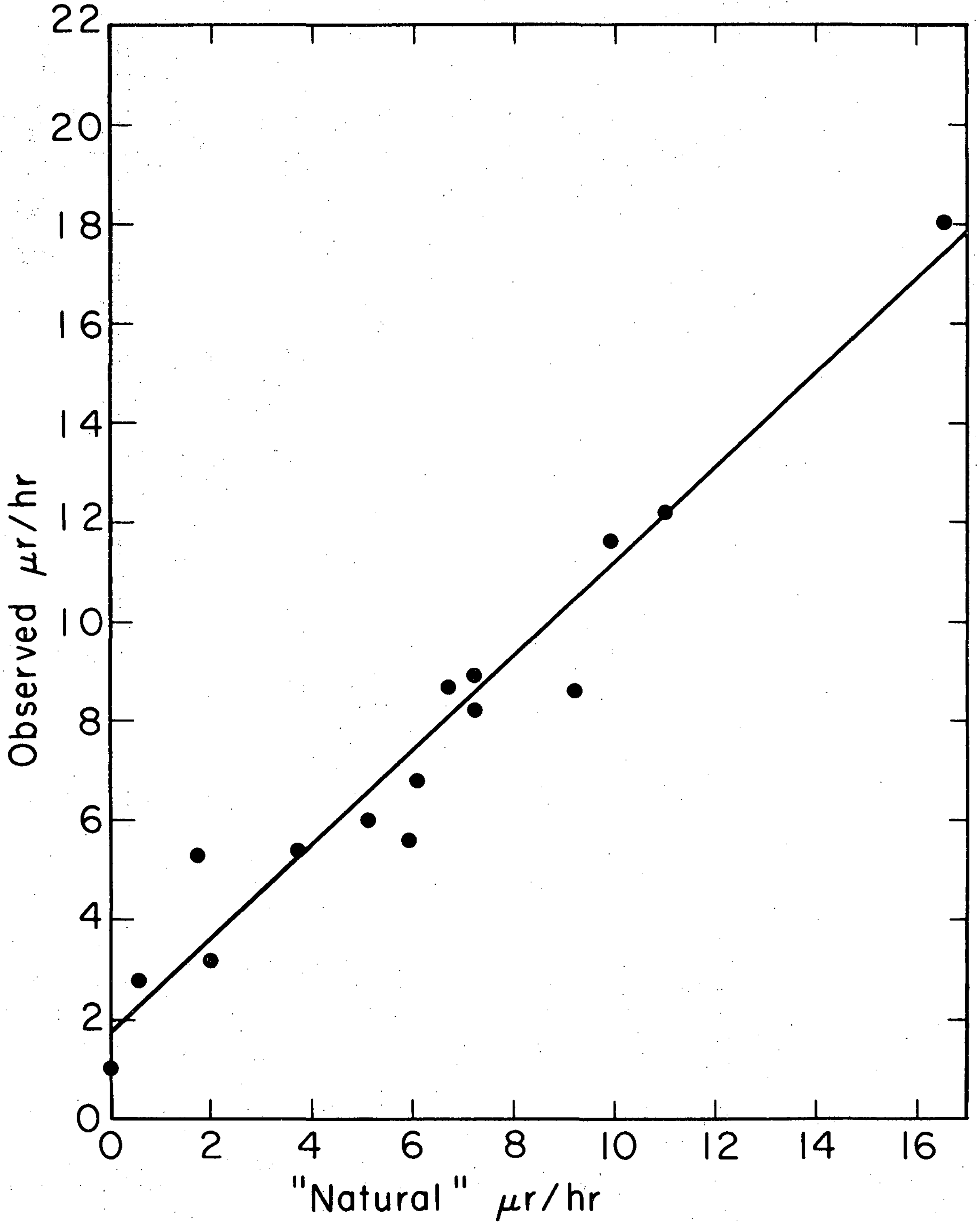

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Fig. 2

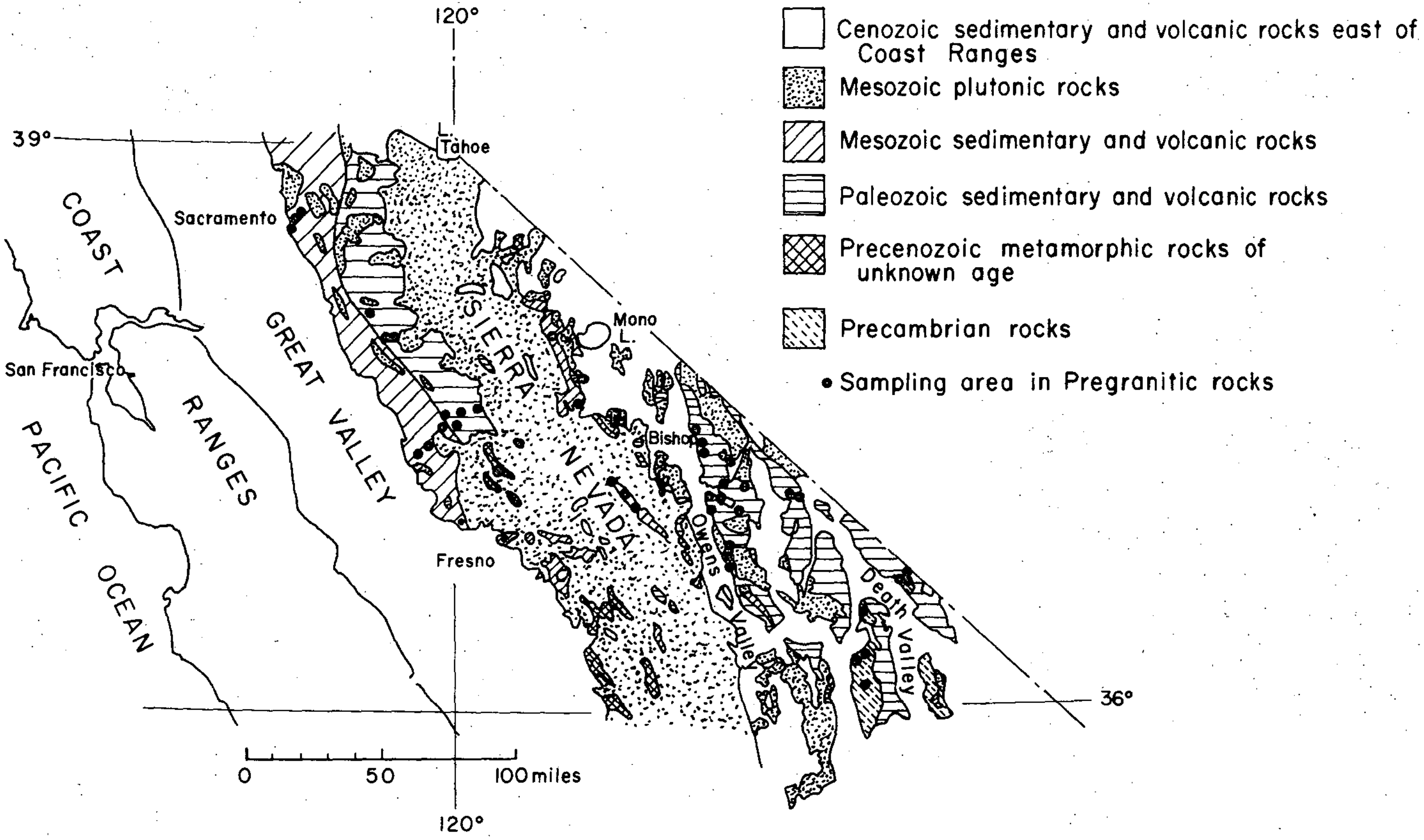

Fig. 3

XBL694-2375

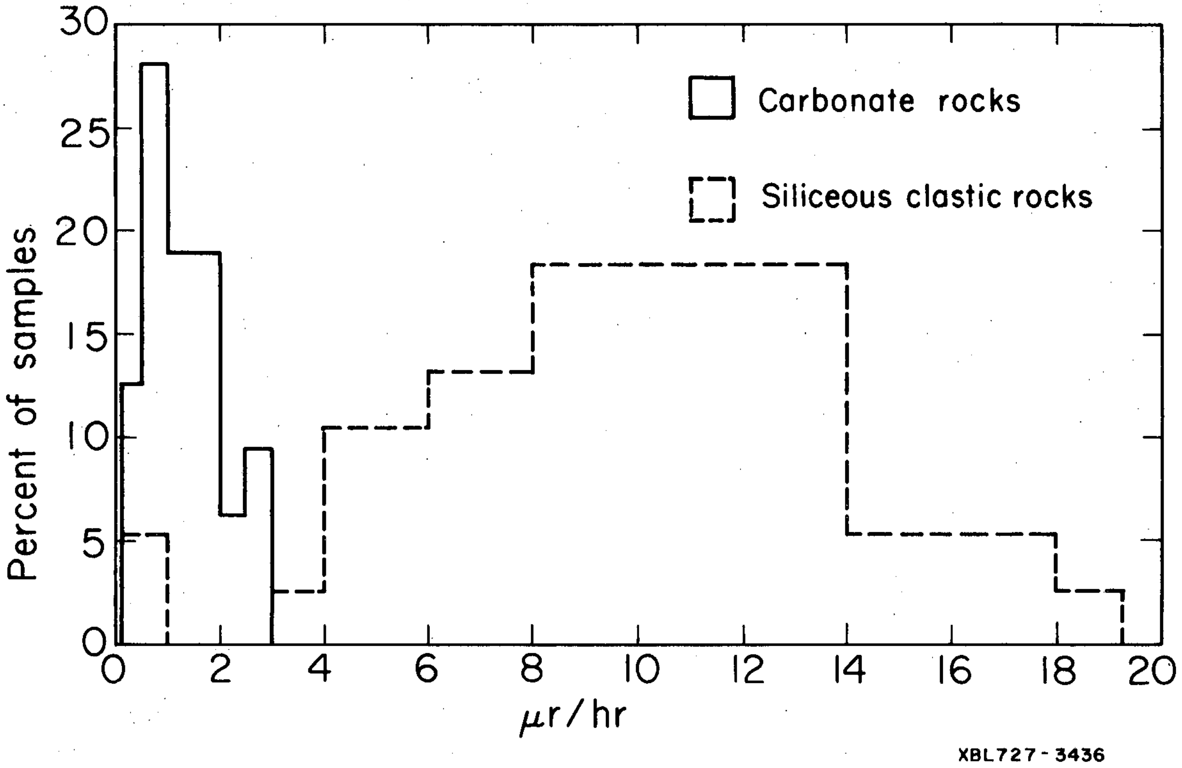
Carbonate rocks
Siliceous clastic rocks
Percent of samples
0
5
10
15
20
25
30
0
2
4
6
8
10
12
14
16
18
20
μr/hr
XBL727-3436

Fig. 4

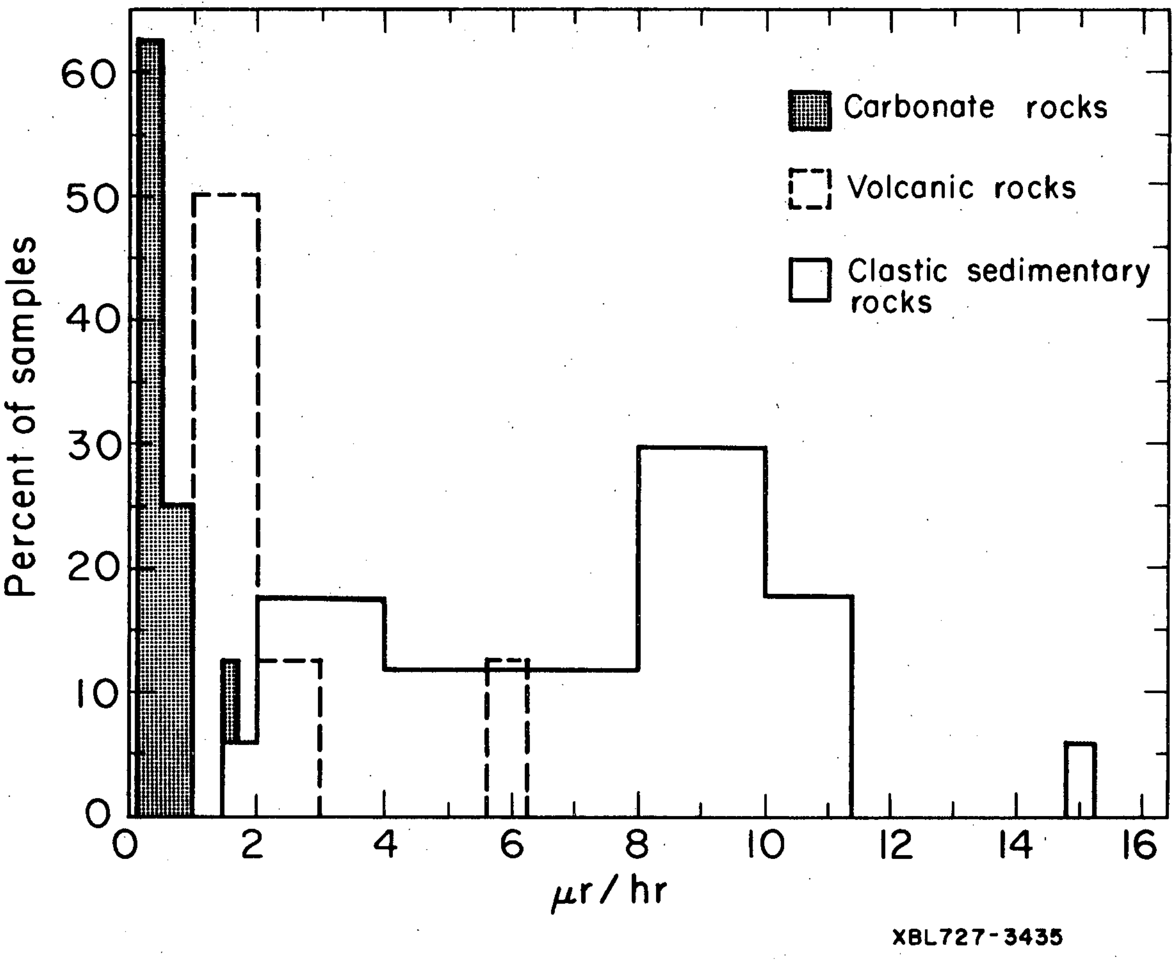
Carbonate rocks
Volcanic rocks
Clastic sedimentary rocks
Percent of samples
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
μr/hr
XBL727-3435

Fig. 5

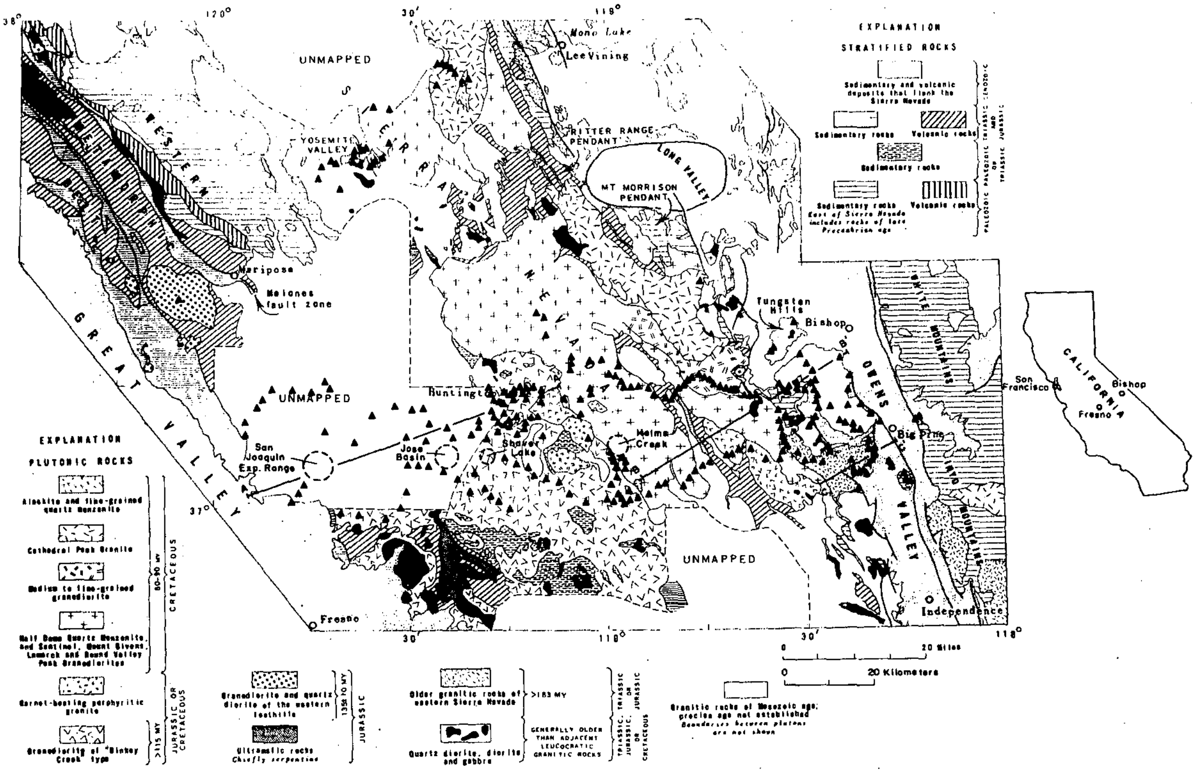

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Fig. 6

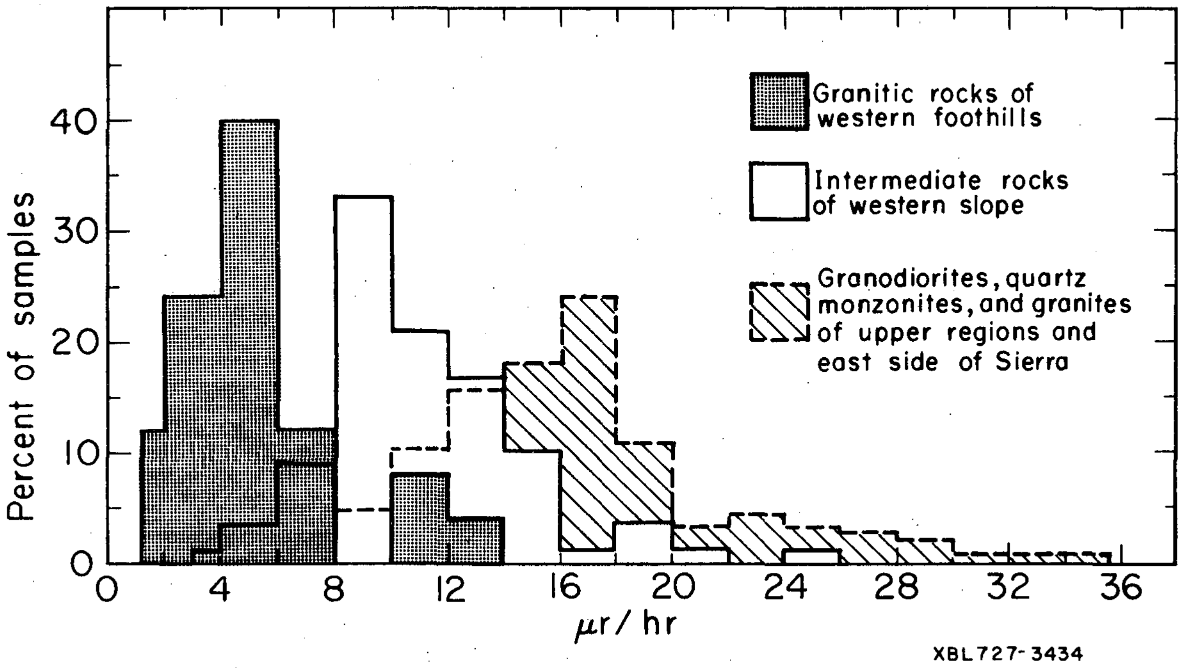
Granitic rocks of western foothills
Intermediate rocks of western slope
Granodiorites, quartz monzonites, and granites of upper regions and east side of Sierra
Percent of samples
0
10
20
30
40
0
4
8
12
16
20
24
28
32
36
μr/hr
XBL727-3434

Fig. 7

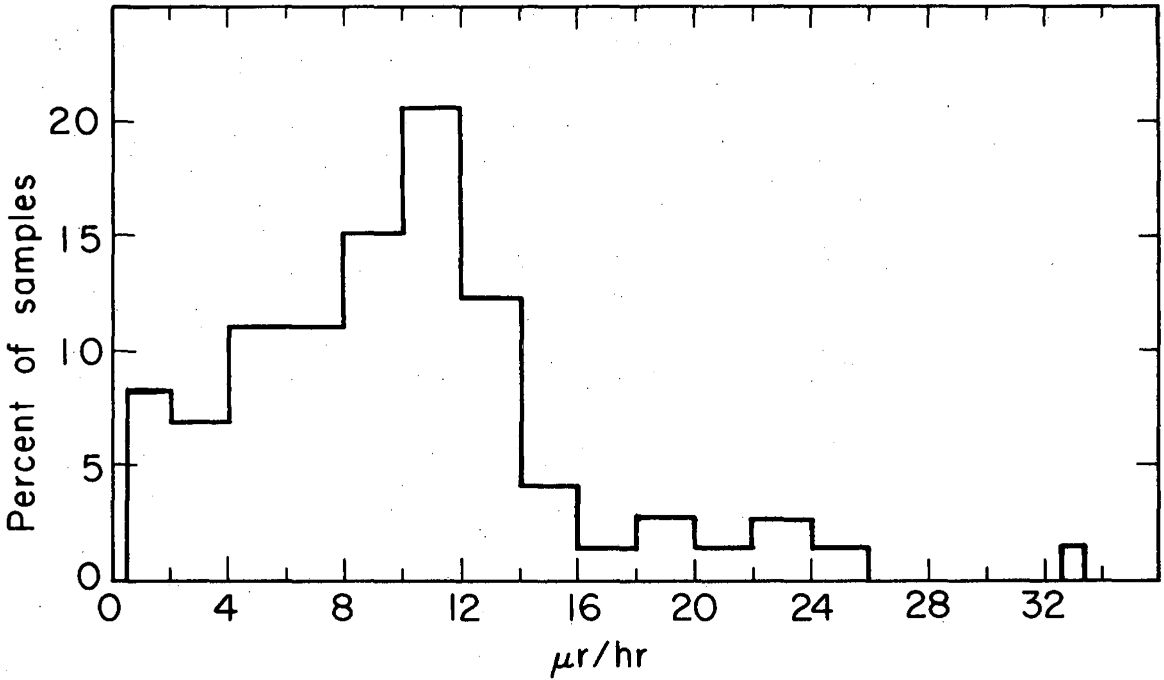

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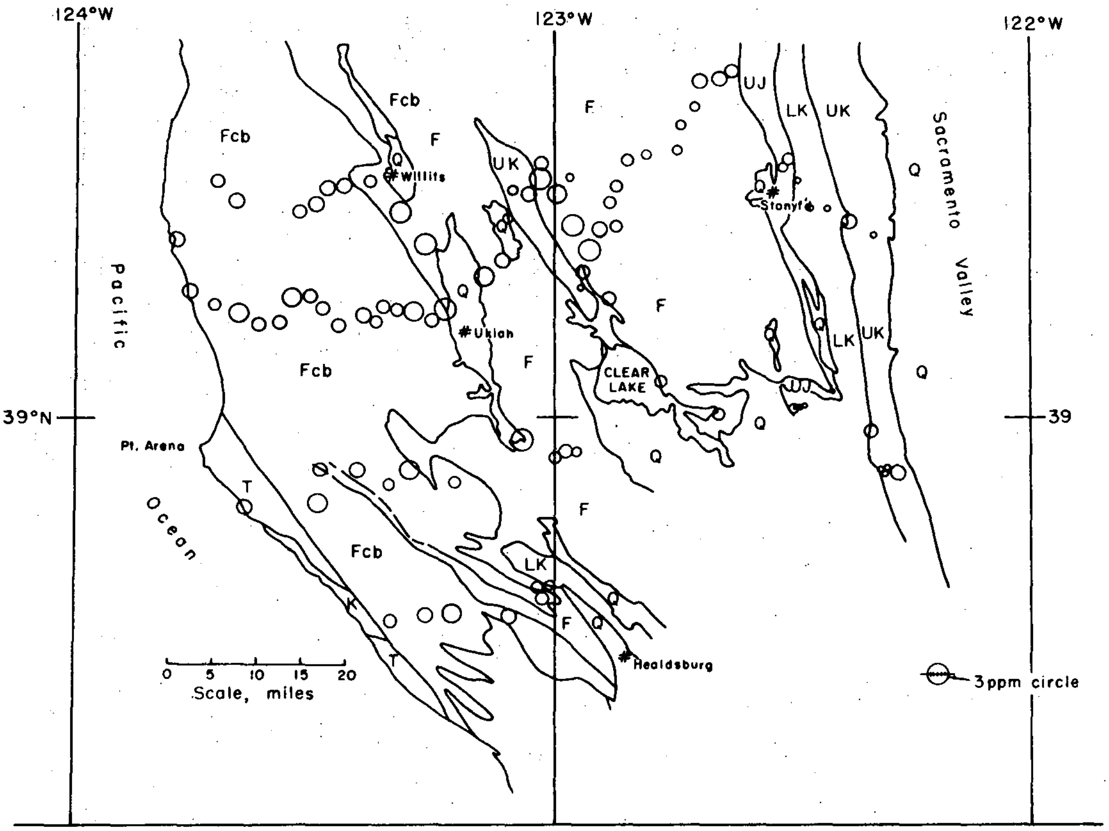
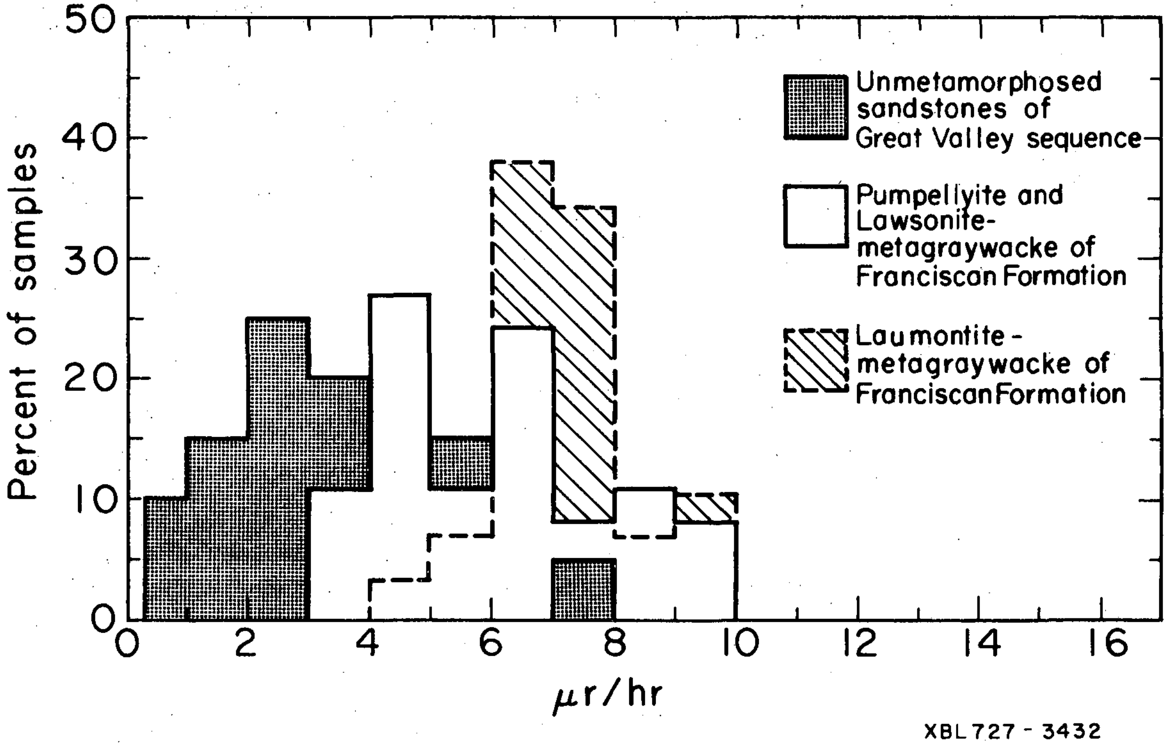
Fig. 8



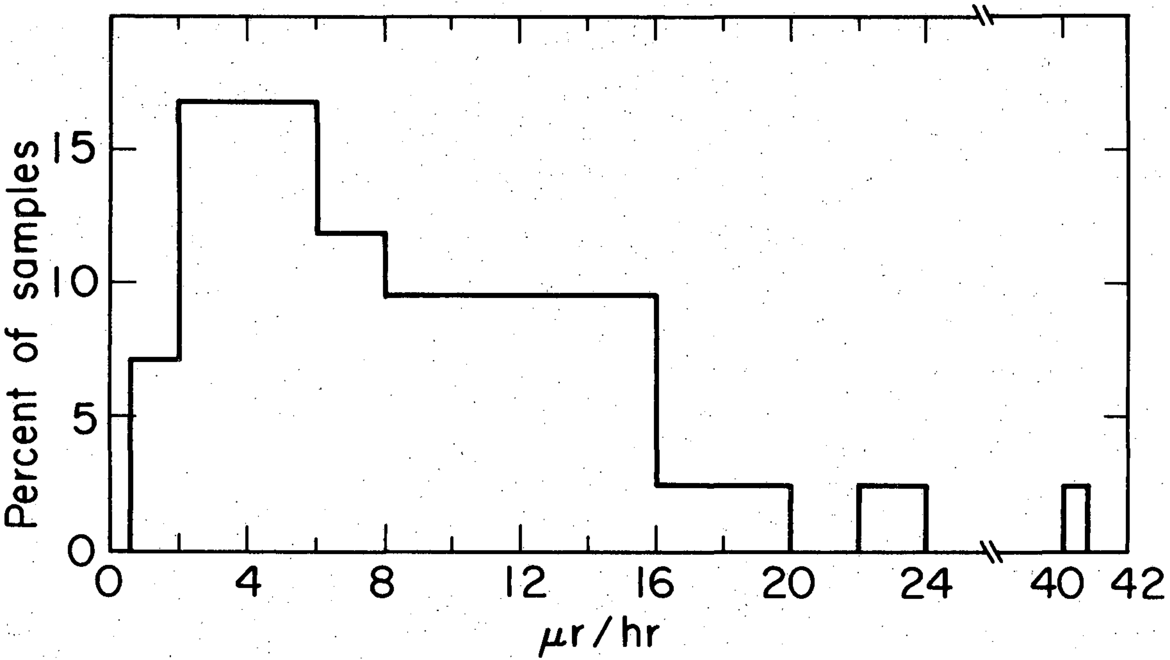
MUB-12852-B

Fig. 9



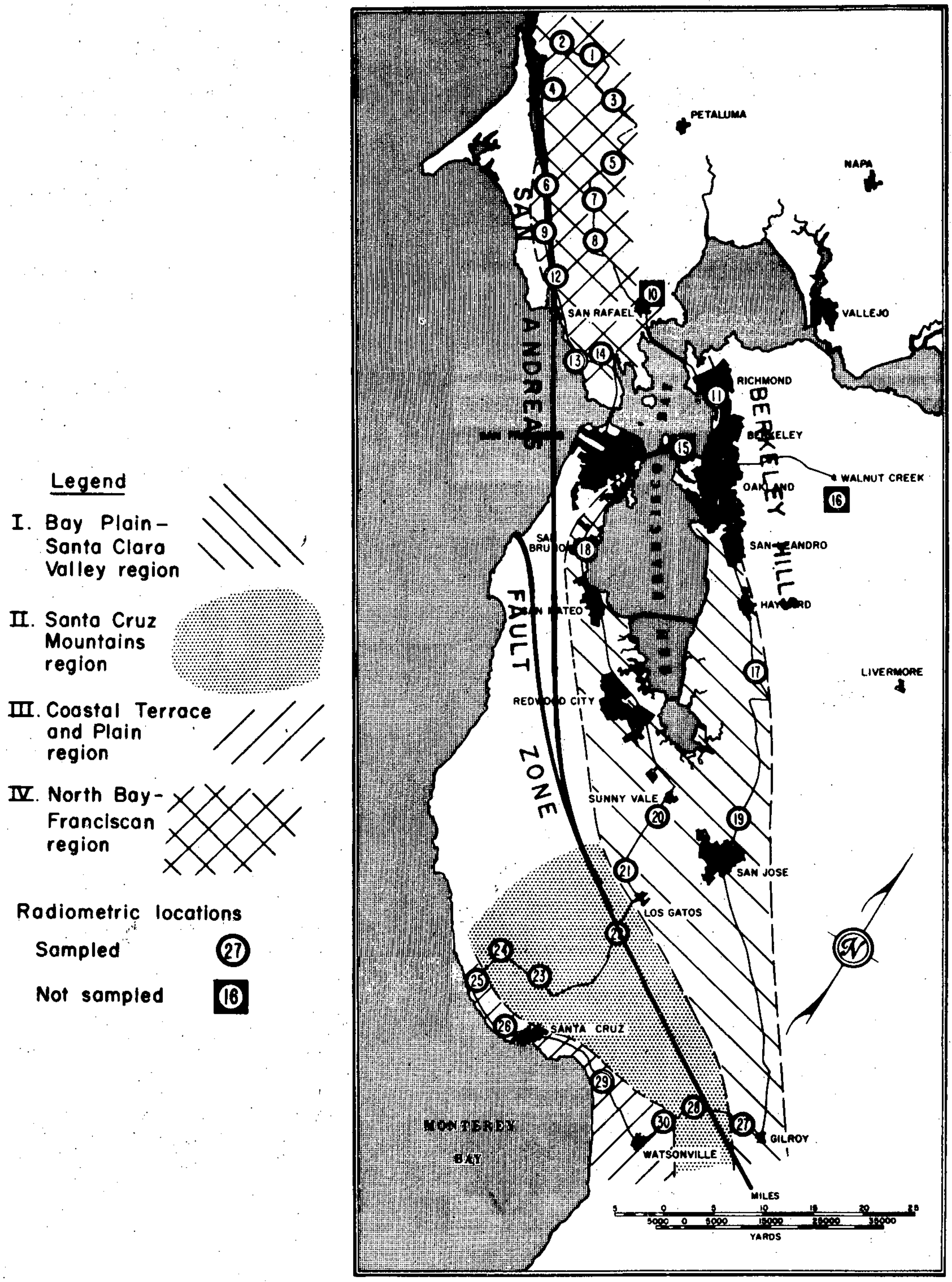
50
40
30
20
10
0
Percent of samples
0
2
4
6
8
10
12
14
16
μr/hr
Unmetamorphosed sandstones of Great Valley sequence
Pumpellyite and Lawsonite-metagraywacke of Franciscan Formation
Laumontite-metagraywacke of Franciscan Formation
XBL 727-3432

Fig. 10



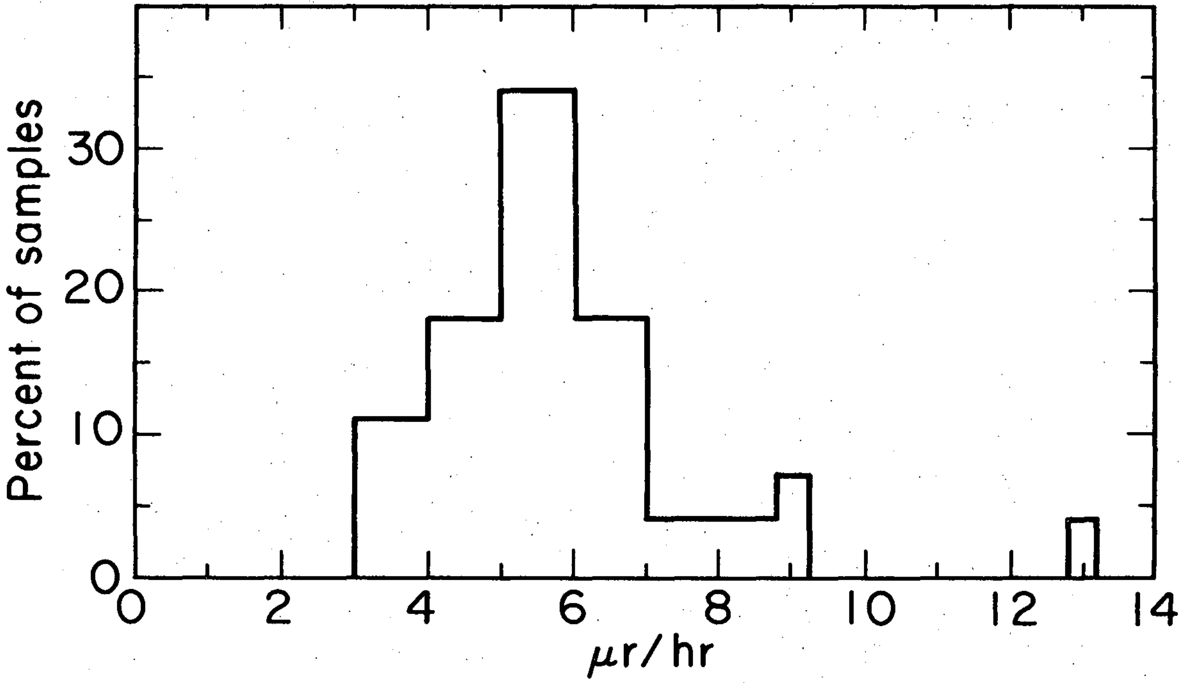
XBL727-3431

Fig. 11



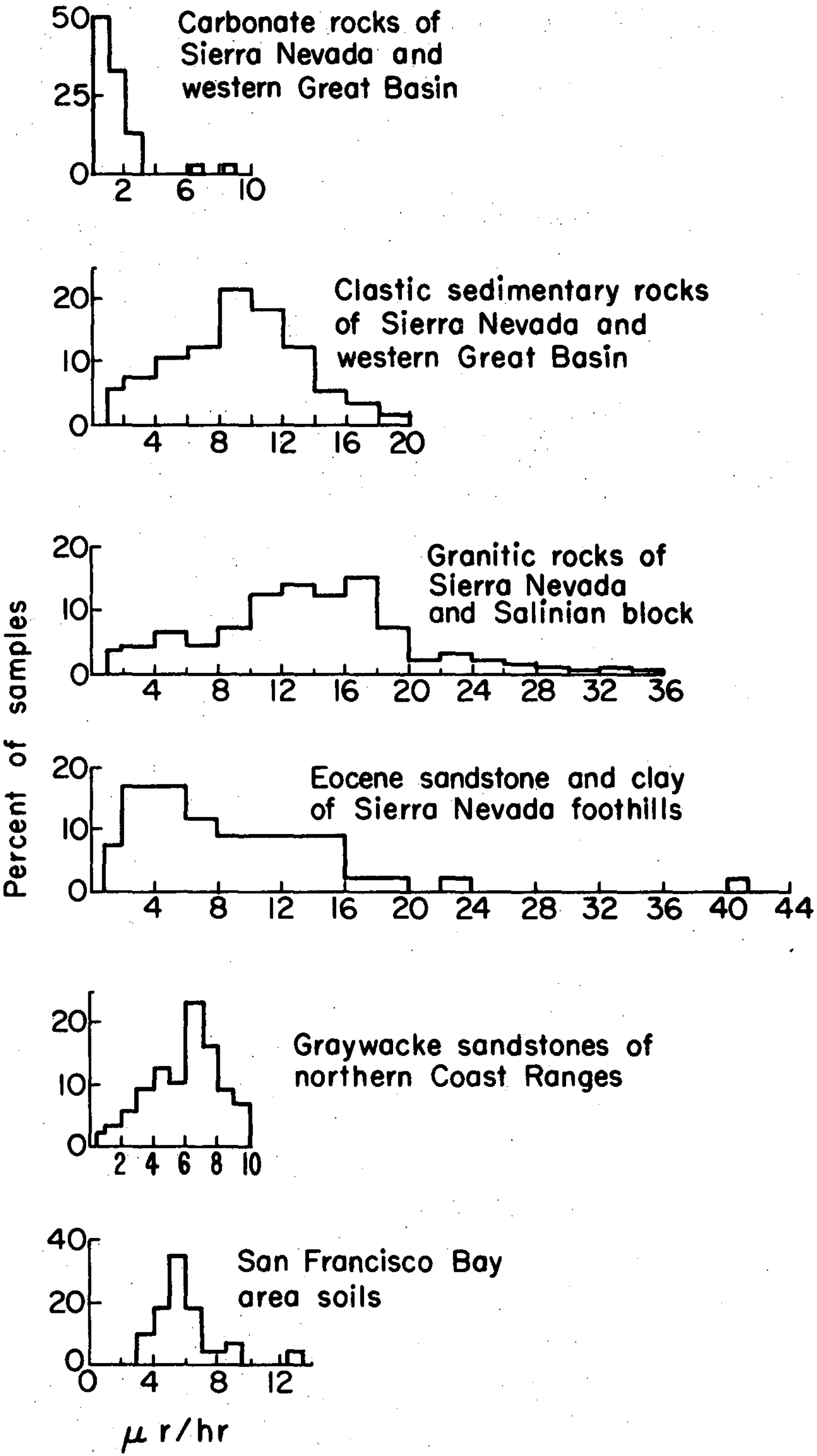
XBL727-3429

Fig. 12



XBL727-3430

Fig. 13



XBL727-3598

Fig. 14

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