LBL-18714 c.2
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

RECEIVED
LAWRENCE
BERKELEY LABORATORY

AUG 9 1985

LIBRARY AND
DOCUMENTS SECTION

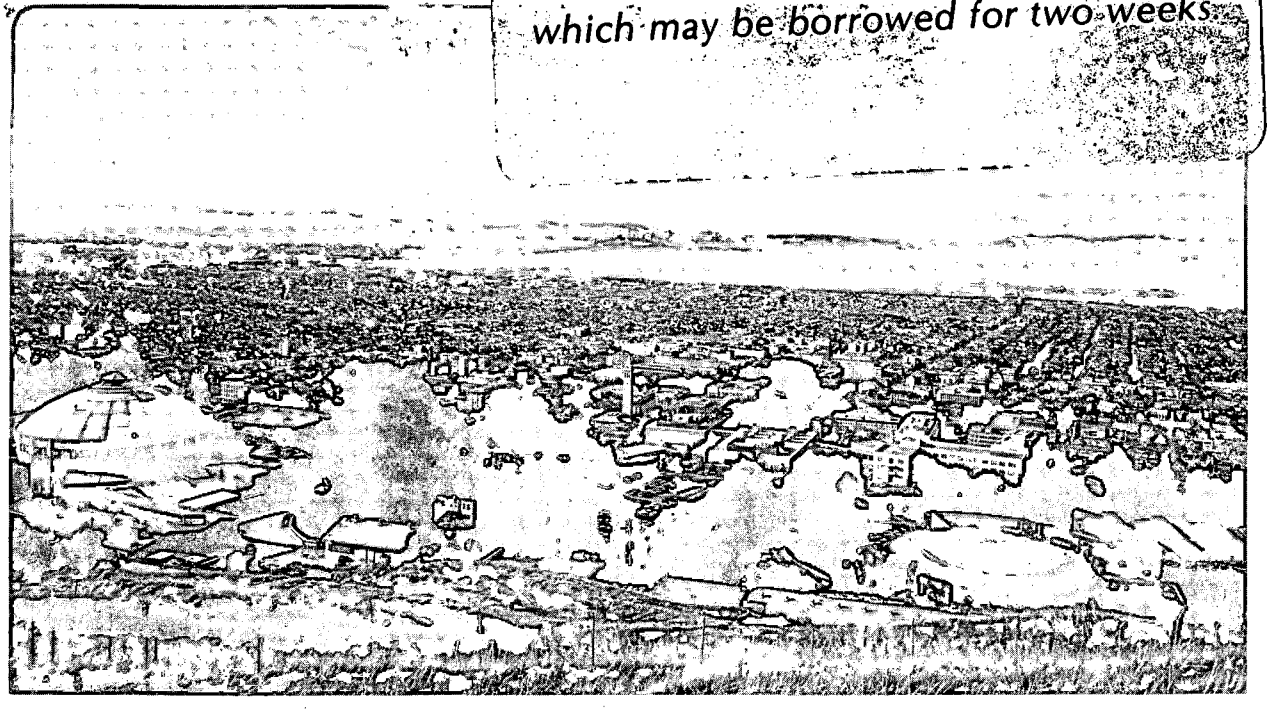
Submitted to Environmental Geology

NATURALLY OCCURRING RADIOELEMENTS AND TERRESTRIAL GAMMA-RAY EXPOSURE RATES: An Assessment Based on Recent Geochemical Data

H.A. Wollenberg and A.R. Smith

November 1984

TWO-WEEK LOAN COPY
This is a Library Circulating Copy
which may be borrowed for two weeks



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-18714 c.2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-18714

NATURALLY OCCURRING RADIOELEMENTS AND TERRESTRIAL GAMMA-RAY EXPOSURE RATES
An Assessment Based on Recent Geochemical Data

H.A. Wollenberg and A.R. Smith

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

November 1984

NATURALLY OCCURRING RADIOELEMENTS AND TERRESTRIAL GAMMA-RAY EXPOSURE RATES
An Assessment Based on Recent Geochemical Data

H A. Wollenberg and A. R Smith
Earth Sciences Division
Lawrence Berkeley Laboratory

ABSTRACT

A survey of the geochemical literature and unpublished data has resulted in the cataloging and characterization of the concentrations of the naturally-occurring radioelements, U, Th, and K and their associated rock types. The purpose of this work is to aid in the planning and interpretation of airborne gamma-radiation environmental surveys of proposed and operating nuclear power reactors and other nuclear energy related sites. A data base of over 2500 entries has been assembled, and formulas relating gamma-ray exposure rates to radioelement concentrations have been applied to these data. The resulting tabulation and histograms illustrate the broad range of radioactivities encompassed by the various rock types.

The gamma-ray exposure rates of igneous rocks generally vary with their silica contents, and, with the exception of shale, sedimentary rocks have lower K/U and K/Th ratios than most igneous rocks. By considering together radioelement ratios, relative abundances, and total gamma radioactivities, the general lithology of overflown terranes may be distinguished by airborne multi-spectral gamma surveys.

In the course of this investigation an appreciable difference was noted between the overall mean terrestrial gamma-ray exposure rate calculated from rock radioelement concentrations ($\sim 8\ \mu Rh^{-1}$) and the mean exposure rate from field measurements over soil ($5.1\ \mu Rh^{-1}$). This difference may be explained by effects of the differences in density of rock and soil, the moisture content of soil, and the apparent depletion of U in unsaturated near-surface material.

(Suggested running title: Natural Radioelements and Gamma Exposure Rates)

INTRODUCTION

An assessment of the effects of man upon the natural gamma radiation environment requires a good understanding of the distribution and abundances of the naturally - occurring radioelements uranium and thorium, their decay products and potassium-40 in rock and soil.

Appreciable data exist, primarily in the geochemical literature describing the distribution and abundance of these elements. A survey of the literature, principally that in English, and compilation of unpublished geochemical data have resulted in the cataloging and characterization of natural radioelements and their associated rock types. A data base has been assembled, incorporating radioelement information classified according to rock type. Formulas relating gamma ray exposure rates to radioelement contents have been applied to these data. The resulting correlations are then expressed as radioelement ratios, as well as histograms of radioelement content and of calculated terrestrial gamma - ray exposure rates.

The primary impetus for this work is to help in the planning and interpretation of airborne multi- spectral gamma radiation surveys to assess the radiation environment in the vicinity of planned and operating nuclear power reactors and other nuclear - energy - related sites. These surveys are conducted by the Aerial Measurements Operations of EG&G/EM for the U S. Nuclear

Regulatory Commission and the U.S. Department of Energy. In this respect, the work reported here was supported by EG&G/EM through a memorandum of understanding with the Lawrence Berkeley Laboratory.

This investigation deals almost exclusively with bedrock materials, because of the nature of the geochemical literature which emphasizes element contents of rock terranes. In many cases, these data are applicable to radioelement contents of soils, especially those derived directly from weathering of bedrock in-place. These residual soils generally reflect the composition of their parent rock. However, soils formed from the transport of rock debris may, depending on the distance of transport, be of an entirely different character than the rock which they overlie. Examples are glacial debris, alluvial fan deposits, fluvial, and shoreline sediments. Therefore, interpretation of airborne gamma surveys requires a knowledge of the geologic setting of the surficial material that includes its origin, mode of transport (by water, wind, or glacier) and its weathering. In addition, the particle size of a soil may influence its radioelement concentration (Jasinska and others, 1980).

In this paper, following the introduction, the general distribution of radioelements in the earth's crust is reviewed, the radioelement data base and the results of the compilations are described, and their applicabilities and limitations are discussed.

THE GENERAL DISTRIBUTION OF RADIOELEMENTS AND RADIOACTIVITY

The principal terrestrial sources of gamma radiation are the radioelements U (uranium - 238), Th (thorium - 232), their decay products, and K (potassium - 40). A minor component, presently less than 5%, is from fission-product fallout from nuclear bomb tests in the atmosphere that occurred primarily in the 1950s and early 1960s. At sites of given altitude and geomagnetic latitude, the varying gamma-ray field from the natural radioelements in rock and soil is superimposed on a nearly constant gamma field from cosmic radiation. The cosmic-ray induced gamma field generally contributes 1/4 to 1/3 of the total; the rest is from the terrestrial radioelements. Therefore, major spatial variations in natural gamma radioactivity are caused by variations in the abundance and distribution of U, Th, and K.

To furnish the reader an idea of the breadth of variation in natural radioelement contents, average abundances of U, Th, and K in some representative rock types are listed in Table 1. Of the igneous rocks, radioelement contents are listed for the intrusives; values are comparable for their extrusive (predominantly volcanic) counterparts. Within the igneous rocks there is a general variation of radioelements with acidity, from ultrabasics, through intermediate, to silicic rocks.

The radioelement concentrations of sedimentary rocks generally reflect the compositions of the source rocks from

which they were derived. However, there is a strong contrast between the broad classes of sedimentary rocks, as indicated in Table 1. Siliceous clastic rocks, comprising the sandstones, conglomerates clays and shales are of relatively high radio activity compared with the carbonate rocks limestone and dolomite.

The radioactivity of unmineralized metamorphic rocks may also reflect their origin. The relatively high radioactivity of felsic igneous rocks and siliceous clastic sedimentary rocks is generally retained in their metamorphosed manifestations, while metamorphic rocks derived from basic to ultrabasic igneous rocks or carbonate sedimentary rocks are of generally low radioactivity. However, as indicated in Table 1, the radioactivity of metamorphic rocks also generally varies inversely with their grade of metamorphism, being lowest in the highest grade, the granulite facies, and highest in the lower - grade amphibolite facies (Heier and Adams, 1965). This is substantiated by more recent work on uranium in metamorphic rocks by Dostal and Capedri (1978). The variation of U and Th with the age of Precambrian meta sedimentary rocks was pointed out by McLennon and Taylor (1980), with significantly higher concentrations of these elements occurring in Proterozoic rocks than in Archean rocks.

The relative abundances of the radioelements are illustrated on a ternary diagram (Fig. 1), within which there are characteristic fields for broad categories of rock types (Wollenberg and Smith, 1968 1970; Wollenberg and others 1967). Most acidic

Table 1
Mean Values of Radioelement Contents of Typical Crustal Rocks

Description	U (ppm)	Th (ppm)	K (%)	Reference
Igneous Rocks				
Acidic	6	20	3.2	Wollenberg and Smith 1968
Intermediate	3	11	2.1	
Basic	1.5	4	1.4	
Metamorphic Rocks				
Granulite Facies	0.6	2.5	2.5	Heier and Adams, 1965
High Amphibolite Facies	1.2	9.4	2.0	
Epidote Amphibolite to Low Amphibolite Facies	3.5	26 5	3.4	
Glaucophane Schist and Eclogite	0.5	1.4	0.5	Wollenberg and others 1967
Sedimentary Rocks				
Siliceous Clastics	2.2	7.0	1.5	Wollenberg and Smith, 1969
Carbonates	0.7	1.0	0.2.	

and intermediate igneous rocks fall into sector A, dominated by Th as do most siliceous clastic sedimentary rocks. Ultrabasic to basic igneous rocks occupy a field which parallels the K Th edge of the triangle, and ranges from sector C, where K predominates, for the ultrabasics to sector A for the basic to intermediate rocks. The carbonate sedimentary rocks occupy a region parallel to the U-Th edge, ranging from the uranium-dominated sector B for the pure carbonates to sector A for carbonates more contaminated by siliceous material. Superimposed on these usual fields are rocks wherein one of the radioelements is concentrated: feldspar-rich pegmatites where K strongly predominates, and monazite- and thorite-rich veins, monazite-rich sandstones, and some peralkaline igneous rocks where Th strongly predominates and, finally, igneous and sedimentary rocks where U strongly predominates.

Also superimposed on these natural abundance patterns are the relative radioactivities of the natural radioelements, (including the radioactivities of the daughter products of U and Th) normalized on the basis of counts per minute (in the gamma-ray energy region above ~ 0.1 MeV) per gram of element: $K:Th:U = 1 : 3.3 \times 10^3 : 8.05 \times 10^3$. Therefore, in a "normal" siliceous rock where relative abundances of $K \cdot Th:U$ may be $1 : 5 \times 10^{-4} : 1.5 \times 10^{-4}$, the contributions of U and Th to the rock's total gamma radioactivity may be respectively 1.2 and 1.6 that of K.

THE DATA BASE

This section includes a brief description of the rock classification system used to segregate the data, and descriptions of rock types and the literature sources that provided the data.

The Classification System

For our purposes the igneous rocks are classified according to a system developed by Williams and others (1954), based essentially on ranges in whole-rock silica content and the abundances of alkali and calcic feldspar.

The sedimentary rocks are divided into two main classes: detrital sedimentary rock, which includes sandstone, conglomerate, shale, and clay; and chemical sedimentary rock which includes limestone and dolomite (the carbonates), gypsum, and evaporites. Because of the abundance of data, these groups were subdivided, in that clay, shale, sandstone and conglomerate, and the carbonates were treated as separate data sets.

Primarily because of the scarcity of radioelement data on metamorphic rock in the literature, only two broad classes of metamorphic rock were considered: those derived from igneous rocks (metaigneous) and those derived from sedimentary rocks (the metasediments).

Igneous Rocks

The categorization of the igneous rocks for this study is shown in Table 2. The categories were chosen to fit the availability of data and yet to remain as consistent as possible with the aforementioned classification of the igneous rocks.

A large portion of the data base for acid and intermediate intrusive rocks was obtained from Marjaniemi and Basler's (1972) investigation of plutonic rocks of the western United States. Significant supplementary information was provided by papers by Larsen and Gottfried (1960 a) Gottfried and others (1962b), Phair and Gottfried (1964), Rogers (1964), Lyons (1964), Malan and Sterling (1970), Wollenberg and Smith (1964, 1968) and Wollenberg and others (1981).

Radioelement data for basic igneous rocks were derived from early papers by Evans and Goodman (1941), Keevil (1944), and more recent papers and reports by Picciotto (1951), Turovskii (1957), Smyslov (1959), Abramovich (1959), Larsen and Gottfried (1960 b), Heier et al. (1964), Heier and Rogers (1963), Malan and Sterling (1970), Gonshavkova and others (1972), and unpublished data by Wollenberg and colleagues at the Lawrence Berkeley Laboratory (LBL).

The much scarcer radioelement information on the ultrabasic rocks is primarily from papers by Gonshavkova and others (1972) and unpublished analyses of California ultrabasics at LBL, supplemented by papers by Tilton et al. (1956), Vinogradov

TABLE 2

CATEGORIES, IGNEOUS ROCKS

ACID INTRUSIVE Aplite. Pegmatite Granite Adamellite, Granodiorite.

ACID EXTRUSIVE: Rhyolite Dacite, Latite.

INTERMEDIATE INTRUSIVE: Quartz Diorite Tonalite, Diorite.

INTERMEDIATE EXTRUSIVE: Andesite.

BASIC INTRUSIVE: Gabbro Anorthosite. some Pyroxenite.

BASIC EXTRUSIVE: Basalt, Spilite.

ULTRABASIC: Peridotite Dunite, Serpentinite. some Pyroxenite.

ALKALI-FELDSPATHOIDAL INTRUSIVE Syenite Nepheline-Syenite, Monzonite, Alkali Gabbro.

ALKALI-FELDSPATHOIDAL INTERMEDIATE EXTRUSIVE Keratophyre. Trachyte Phonolite.

ALKALI-FELDSPATHOIDAL BASIC EXTRUSIVE Nephelinite Leucitite and Melilite Basalts.

(1961), Heier and Rogers (1963), Wollenberg and Smith (1964 b), and Morgan and Heier (1966).

Radioelement contents of acid extrusive rocks are well represented in the recent literature, with contributions by Bowman and others (1972), Wollenberg and others (1977), Smith and Johnson (1981), Crecraft and others (1981), Bacon and others (1981) Mahood (1981), Cioni and others (1983), Deruelle (1982), and Mahood and Hildreth (1983). These data are supplemented by unpublished analyses of Peruvian extrusive rocks, collected by D. C. Noble and H. A. Wollenberg.

A data base of somewhat smaller size exists for the intermediate extrusive rocks, comprised of entries from papers primarily by Gottfried and others (1962a), White (1979), and Wollenberg and others (1979), and unpublished data at LBL on Oligocene andesites from the Basin and Range and Colorado Plateau provinces, and andesites from the Aleutian Archipelago.

The information on radioelement concentrations of basic extrusive rocks (predominantly basalt) was supplied by the work of Gottfried and others (1962a), supplemented by more recent papers by Heier and Rogers (1963), Wollenberg and Smith (1964b), Cioni and others (1983), and by the compilation on the Columbia River Basalt reported by Long and Landon (1981).

The data base on alkali feldspathoidal intermediate intrusive rocks draws heavily on the papers bv Labhart and Rybach (1971), who described radioelements in the syenite of the Aar Massif, and Sass and others (1972) and Lovborg and others (1971),

who reported on the peralkaline rocks of South Greenland. These data are supplemented by entries from the compilation by Murphy and others (1978) on radioelements in alkaline rocks in North America and Brazil. Peralkaline extrusive rocks are represented primarily by the data of Locardi and Mittempergher (1967), while data on alkalic basic igneous rocks are derived primarily from a paper by Gonshakova and others (1972).

Sedimentary Rocks

For the purposes of this study, primarily because their data bases are well defined, clay and shale were segregated into separate categories from the sandstone and conglomerate that comprise the detrital sedimentary rocks. Radioelement information on clay was provided by papers by Wollenberg and Smith (1966), Wollenberg and Dodge (1973), and Jupiter and Wollenberg (1974). A significant contributor to the data on shale is a report by Leventhal and others (1981), describing radioelement contents of Devonian shales of the Appalachian Basin. Other sources of information on shale are the report by Pliler and Adams (1962) on radioelement contents of the Mancos shale, and the paper by Adams and Weaver (1958) on Th/U ratios as indicators of sedimentary processes. Data on sandstone and conglomerate are derived primarily from papers by Murray and Adams (1958) and from those by Wollenberg and others (1967) and Wollenberg and Dodge (1973) that cover

radioelement contents of greywacke of the Franciscan Formation and the Ione sandstone of northern and central California, respectively.

Radioelement concentration data on limestone and dolomite are primarily from Adams and Weaver (1958), supplemented by papers by Baranov and others (1956) and Wollenberg and Smith (1966 and 1970). With few exceptions, data on the non-carbonate chemical sediments, represented predominantly by bentonite, bauxite and gypsum, are derived from the aforementioned papers by Adams and Weaver, (1958) and Baranov and others (1956).

Metamorphic Rocks

The data on metaigneous rocks include primarily those from rocks of moderate to high - grade metamorphism gneiss and orthogneiss, provided by the extensive compilation of Malan and Sterling (1970). Other entries are from the paper by Wollenberg and Smith (1970) that includes metavolcanic rocks of the Sierra Nevada, White, and Inyo mountains, California.

The extensive data base on metasedimentary rocks, that includes the metamorphic grades: slate, phyllite, and schist, also draws heavily from the report by Malan and Sterling (1970), supplemented by a report by Bunker and others (1973) and by data on metamorphosed sedimentary rocks of the Franciscan Formation (Wollenberg and others (1967) and prebatholithic rocks of the Sierra Nevada (Wollenberg and Smith, 1970).

THE COMPILATIONS

The U, Th, and K concentrations compiled from the geochemical literature were classified according to rock type, based on descriptions in the accompanying articles. The data base presently consists of 2522 entries for U, 2510 for Th, and 2079 for K. The computer program DOSECAL then converted these data to gamma-ray exposure rates (at a height of 1 m above ground surface) using the equations of Beck and de Planque (1968):

$$1 \ \mu Rh^{-1} = 0.654 \times \text{the U concentration in ppm,}$$
$$= 0.307 \times \text{the Th concentration in ppm, and}$$
$$= 1.65 \times \text{the K concentration in \%.}$$

The gamma ray exposure rates were summed by DOSECAL, yielding total gamma exposure rates for each sample entry into the data base. The data base is tabulated with entries for radioelement data, individual exposure rate for each radioelement, and the total exposure rate and heat production for the combined radioelements of each sample entry. Rock classification, location, and rock type information are also tabulated as are the method of analysis and a literature citation. The data base was then used by DOSECAL to construct histograms of the frequency distributions of radioelement concentrations and exposure rates within the specific rock categories. Arithmetic means and their

standard deviations of sample populations were also calculated and were displayed on the computer-generated histograms.

The data are summarized by rock class in Table 3. Arithmetic means and ranges in concentration are listed in Table 3a, Table 3b lists means and ranges of the contributions of the radioelements to the total terrestrial gamma-ray exposure rates. In some cases there are different numbers of entries for each radioelement, reflecting the unevenness in the geochemical literature, where concentrations of only one or two of the radioelements are sometimes reported. For example, there are very little data on K in the carbonate rocks, relative to the information on U and Th. In this respect, only entries where the three radioelements were reported were used to calculate total gamma-ray exposure rate. The mean values of total gamma-ray exposure rates from Table 3b and their standard deviations are illustrated in Fig. 2 and 4. Histograms of total gamma-ray exposure rates for most of the rock classes comprise figures A1 through A15 of the Appendix.

DISCUSSION

Distributions and Abundances

Inspection of Table 3 indicates the broad ranges of radioelement concentrations in each rock category and Fig. 2 and 4 illustrate the range of mean values of exposure rates and their large standard deviations. The general variation of radio-

Table 3a. Radioelement Concentrations

ROCK CLASS	U (ppm) MEAN	U (ppm) RANGE	U (ppm) n	Th (ppm) MEAN	Th (ppm) RANGE	Th (ppm) n	K (%) MEAN	K (%) RANGE	K (%) n
Acid Extrusives (AE)	5.7	0.8-23	131	22.4	1.1-116	131	3.7	1.0-6.2	124
Acid Intrusives (AI)	6.3	0.1-30.0	569	27.3	0.1-253	573	3.5	0.1-7.6	573
Intermediate Extrusives (IE)	2.1	0.2-5.2	71	6.7	0.4-28	71	2.0	0.1-4.2	57
Intermediate Intrusives (II)	3.2	0.1-23	271	12.2	0.4-106	273	2.1	0.1-6.2	273
Basic Extrusives (BE)	0.9	0.03-3.3	77	2.5	0.05-8.8	77	0.7	0.06-2.4	77
Basic Intrusives (BI)	0.8	0.01-5.7	119	2.3	0.03-15	110	0.8	0.01-2.7	129
Ultrabasic (UB)	0.3	0-1.6	31	1.4	0-7.5	30	0.3	0-0.8	28
Alkali Feldspathoidal Intermediate Extrusives (AFE)	29.7	1.9-62	138	134	9.5-265	139	6.5	2.0-9.0	36
Alkali Feldspathoidal Intermediate Intrusives (AFI)	55.8	0.3-720	75	133	0.4-880	75	4.2	1.0-9.9	61
Alkalic Basic Extrusives (ABE)	2.3	0.5-12	27	8.9	2.1-60	27	2.2	0.2-6.9	27
Alkalic Basic Intrusives (ABI)	2.3	0.4-5.4	8	8.4	2.8-20	8	1.8	0.3-4.8	8
Chemical Sedimentary Rocks* (CS)	3.6	0.03-27	243	14.9	0.03-132	239	0.6	0.02-8.4	42
Carbonates (CAR)	2.0	0.03-18	141	1.8	0-11	131	0.3	0.01-3.5	35
Detrital Sedimentary Rocks** (DS)	4.8	0.1-80	412	12.4	0.2-362	411	2.1	0.01-9.7	298
Clay (CL)	4.0	1.1-16	40	8.6	1.9-55	40	0.6	0.1-2.6	29
Shale (SH)	5.9	0.9-80	174	16.3	5.3-39	174	3.5	0.9-8.5	126
Sandstone and Conglomerate (SS)	4.1	0.1-62	198	9.7	0.7-227	198	1.2	0.1-8.5	143
Metamorphosed Igneous Rocks (MI)	4.0	0.1-148	138	14.8	0.1-104	138	2.5	0.1-6.1	138
Metamorphosed Sedimentary Rocks (MS)	3.0	0.1-53	207	12.0	0.1-91	208	2.1	0.4-50	207

* Includes carbonates
** Includes clay, shale, ss and congl.

Table 3b. γ-RAY EXPOSURE RATES (μR/HOUR)

ROCK CLASS	U			Th			K			TOTAL		
	MEAN	RANGE	n	MEAN	RANGE	n	MEAN	RANGE	n	MEAN	RANGE	n
Acid Extrusives	3.8	0.5-15	131	7.0	0.3-36	131	6.1	1.6-10	124	16.2	4.2-59	124
Acid Intrusives	5.1	0.1-20	569	8.4	0.03-78	573	5.8	0.2-12	573	18.2	2.7-98	569
Intermediate Extrusives	1.3	0.2-4.4	71	2.0	0.1-8.7	71	3.1	0.9-6.2	57	6.5	2.1-20	57
Intermediate Intrusives	2.1	0.05-15	271	3.7	0.1-32	273	3.5	0.2-10	273	9.4	0.3-41	271
Basic Extrusives	0.6	0.02-2.2	77	0.9	0.02-2.7	77	1.15	0.1-4.0	77	2.65	0.1-8.7	77
Basic Intrusives	0.5	0.01-3.7	119	0.7	0.01-4.6	110	1.3	0.1-10	129	2.7	0.2-16	109
Ultrabasic	0.2	0-1.1	31	0.4	0-2.3	30	0.4	0-1.3	28	1.1	0.1-4.0	24
Alkali Feldspathoidal Intermediate Extrusives	19.4	1.2-40	138	41.1	2.9-81	139	10.7	3.4-15	36	71.5	16.8-117	35
Alkali Feldspathoidal Intermediate Intrusives	36.5	0.2-470	75	40.7	0.1-491	75	6.9	1.7-16	61	42.7	3.3-323	61
Alkalic Basic Extrusives	1.5	0.3-7.9	27	2.7	0.6-18	27	3.7	0.3-11	27	7.9	2.8-37	27
Alkalic Basic Intrusives	1.5	0.3-3.5	8	2.6	0.9-6.0	8	3.0	0.5-7.9	8	7.1	1.6-17	8
Chemical Sedimentary Rocks*	2.4	0.02-18	243	4.6	0.01-40	239	0.9	0.03-14	42	5.2	0.2-45	38
Carbonates	1.3	0.02-12	141	0.6	0-3.3	131	0.5	0.02-5.8	35	1.9	0.2-6.4	32
Detrital Sedimentary Rocks**	3.1	0.05-52	412	3.8	0.1-111	411	3.5	0.02-16	298	9.8	0.4-147	298
Clay	2.6	0.8-10	40	2.7	0.6-17	40	1.0	0.4-4.2	29	6.3	2.1-19	29
Shale	3.9	0.6-52	174	5.0	1.6-12	174	5.7	1.5-14	126	14.5	4.2-63	126
Sandstone and Conglomerate	2.7	0.07-41	198	3.0	0.2-70	198	2.0	0.2-14	143	7.7	0.5-101	143
Metamorphosed Igneous Rocks	2.6	0.1-97	138	4.6	0.02-32	138	4.2	0.2-10	138	11.3	0.8-125	138
Metamorphosed Sedimentary Rocks	2.0	0.05-35	207	3.7	0.2-28	208	3.4	0.02-8.7	208	9.1	0.4-50	207

* Includes carbonates
** Includes clay, shale, ss and congl.

activity within the igneous rocks is illustrated in Fig. 3, where mean values are highest in the acid igneous rocks and range lower through rock types of increasing Fe and Mg and decreasing SiO_2 concentrations. As illustrated in Figure 3, the systematic increase of radioactivity with SiO_2 is evident for the series: ultrabasic → basic → intermediate → acidic (silicic) rocks. Anomalous in this variation are the alkali feldspathoidal intermediate rocks (also termed peralkaline rocks)· nepheline syenites that often contain relatively high concentrations of U, Th, and K, but are low in SiO_2. Alkali feldspathoidal basic igneous rocks, predominantly nepheline basalts, are also somewhat anomalous in this respect. These alkaline rocks comprise probably not more than one percent of all igneous rocks (Barker, 1974).

Fig. 4 illustrates the range of exposure rates in the sedimentary and metamorphic rocks. Within the sedimentary rocks, shale has the highest mean radioactivity, and progressively lower radioactivities occur in sandstone and conglomerate, clay, the chemical sediments, and carbonate rocks.

How well the metamorphic rocks represent their combined igneous and sedimentary predecessors can be examined by comparing their radioelement concentrations and radioactivities (Table 4). The mean value of the radioactivity of the metaigneous rocks and its large standard deviation are consistent with the range of radioactivities of the igneous rocks (excluding the relatively rare high-radioactivity alkali feldspathoidal rocks), shown in

Table 4, Comparison of Radioelement Concentrations and Radioactivities of Metamorphic Rocks and their Igneous and Sedimentary Predecessors

Description	U (ppm)	Th (ppm)	K (%)	Exposure Rate (μRh^{-1})
Combined mean, carbonates, clay, shale, sandstone	4±1.6	9.1±3.0	1.4±1.2	7.6±5
Metasedimentary Rocks	3.0±4.1	12.0±10.5	2.2±1.1	9.1±6
Combined mean, all Igneous Rocks	10.0±3.1	32.6±51	2.5±1.6	16.9±4.1
Combined mean, Ig. Rocks, without alkali feldspathic rocks	2.7±1.6	10.2±3.2	1.9±1.4	8.0±2.8
Metaigneous Rocks	4.0±3.5	14.8±15.7	2.5±1.3	11.3±12

Fig. 2, and mean U, Th, and K concentrations of the metamorphosed and non-metamorphosed igneous rocks are consistent within the broad standard deviations of these groups. The mean radioactivity and radioelement concentrations of the metasedimentary rocks are consistent with the combined mean of the sedimentary groups. Therefore, allowing for the aforementioned variation of radioelements with metamorphic grade (Heier and Adams, 1965; Dostal and Capedri, 1978) and age (McLennan and Taylor, 1980), the radioactivity of the metamorphic rocks reflects fairly well the radioactivity of their igneous and sedimentary predecessors.

Examination of histograms of the distribution of radioactivity (Fig. A-1 - A-15) indicates that the radioelements are log-normally distributed in most of the rock types. Clear log-normal distributions occur in the rock types where the data bases have a large number of entries: intrusive igneous rocks, detrital sedimentary rocks, and the metamorphics. Log-normal distributions are also suggested in most of the other rock types, with the exception of the intermediate extrusives, where a bimodal distribution is suggested in the predominantly andesitic rocks, and the alkali feldspathoidal intermediate extrusives and carbonates where gamma-ray exposure rate data are relatively scarce. However, the strong log-normality of the U and Th data for the carbonates (Fig. A-12a and b) indicates that the distribution of their exposure rates would also be log-normal.

Exposure Rates at the Continental Surface

Knowing the mean terrestrial gamma-ray exposure rates associated with the various rock types, one can estimate the overall mean exposure rate generated by rocks at the continental surface. This was done by multiplying the proportion of the continental surface occupied by each rock type by the rock type's exposure rate, and then summing the resulting products. This calculation is illustrated in Table 5, where the exposure rates from Table 3b were multiplied by percentages of continental surface taken from Ronov and Yaroshevskiy (1967). The resulting weighted overall terrestrial exposure rate is 8 μRh^{-1}.

It is informative to compare this calculated result with compilations of measured terrestrial exposure rates. A number of compilations were reported at the Second International Symposium on the Natural Radiation Environment (Adams and others 1972), and are summarized in Table 6. (More recent data from Canadian airborne surveys (Grasty and others 1983) are also listed). The mean values for the U.S.A., India and Canada are considerably lower than the 8 μRh^{-1} calculated here, while those for Italy and northern Taiwan are more similar.

To explain the difference between the mean values of measurements and the calculated mean based on percentage of rock types we should consider the nature of the measurements and the effects of soil moisture and density. In one of the U.S. surveys, where the terrestrial component (including the fallout contribution) averaged 5.5 μRh^{-1}, Lindeken and others

Table 5

% of area of continental crust* occupied by:		Terrestrial γ-ray exposure rate(μRh^{-1})**	Product
Granite	3	18	54
Granodiorite-diorite	4	9	36
Alkalic igneous rock	0.1	32	3.2
Ultramafic rock	0.1	1.1	0.1
Gabbro	0.7	3	2.1
Rhyolite	1	16	16
Andesite	4	7	28
Basalt	6	3	18
Sandstone and conglomerate	16	8	128
Carbonates and evaporities	18	2	36
Shale and clay	38	10	380
Gneiss	7	11	77
Schist	2	9	18
Marble	0.3	2	0.6
	Σ100.1		Σ = 797
	weighted mean = product/100		≅ 8μRh

*from Ronov and Yaroshevskiy (1967)
**from Table 3b.

Table 6

Mean Values of the Terrestrial Component of the Gamma-Ray Exposure Rate

Location	Mean Exposure Rate (μRh^{-1})	Method	Reference
Northern Taiwan	8.3	Gamma spectrometry of soil samples	Weng and others (1972)
Italy	7.6	Ion chamber	Cardinale and others (1972)
U.S.A.	5.5	Thermoluminescence dosimeters	Lindeken and others (1972)
U.S.A.	5.0	Airborne radiometric surveys	Oakley and Moeller (1972)
India	4.8	Gamma spectrometry of soil samples	Mishra (1972)
Canada	4.4	Airborne radiometric surveys	Grasty and others (1983)

(1972) distributed thermoluminescence dosimeters (TLD) to weather stations at airports. In most cases the TLDs were placed in instrument shelters erected over grass-covered soil surfaces where one expects there was considerable soil moisture. (Variations in soil moisture cause variations in the terrestrial exposure rate. For uniformly distributed radioelement sources, an increase in density of the soil-water medium results in an accompanying decrease in the exposure rate (Beck and de Planque, 1968, Kirkegaard and Lovborg, 1980)). However, the airborne gamma-ray surveys compiled by Oakley and Moeller (1972), where the terrestrial component (including fallout) averaged 5.0 μRh^{-1}, were over areas in both wet and arid regions where soil moisture conditions range from nearly dry to completely saturated. To substantiate these earlier aeroradiometric data, more recent reports of aerial surveys by EG&G's Aerial Measurements Operations of 42 reactor sites in the U.S. were examined and their terrestrial gamma-ray exposure rates summarized. This summary determined an overall mean of 5.1 μRh^{-1}, consistent with the data of Oakley and Moeller (1972). Soil moisture data were available for 19 of the Reactor sites; moisture contents ranged from 2 to 40% with a mean of 17%. The effects of soil moisture are therefore not large enough to completely rationalize the difference between the calculated and measured exposure rates. This difference is primarily accounted for by the differences in density of soil and rock. The densities of rock types covered in this assessment are in the range of 2.4 to 2.8 g/cm^3,

while the range of soils is at least 1.2 to 2.0 g/cm^3. Therefore, for materials of equal radioelement concentration, there are more gamma-radiation sources per unit area of rock surface than there are per unit area of soil surface. However, this effect is partly compensated for by the greater thickness of lower density soil that contributes to the effective radioactivity of a unit area of the earth's surface, compared to the thickness that contributes to the radioactivity of a higher-density rock surface.

Another factor that should be considered to help explain the difference between measured soil and calculated rock gamma-ray exposure rates is the mobility of uranium in the soil zone. Oxidizing conditions in unsaturated soil may favor the removal of U by infiltrating meteoric water near the surface and its deposition in more reducing environments. Near-surface residual soils may then have lower U concentrations than their unweathered bedrock parents. This apparent depletion of U, together with the effects of soil density and moisture, then combine to cause the appreciable difference between the overall terrestrial exposure rate calculated from the radioelement concentrations of bedrock and the mean of exposure rates measured over areas predominantly covered by soil.

Interrelationships Between Radioelements

Because of the capability of airborne gamma spectral systems to quantify the presence of U, Th, and K, it may be possible to

identify from aerial surveys broad categories of rock types by their characteristic radioactivities and the ratios of their radioelement contents. Figure 5, the plot of the K/U and K/Th ratios of mean values for the various rock categories, shows that with the exception of the carbonate and acid intrusive rocks, all mean values fall between Th/U ratios of 2 and 5.5. The sedimentary rocks group much nearer the origin (K is less dominant than U and Th) than all but one of the igneous rock types (the alkali-feldspathoidal intrusives). Within the igneous rocks, the basic and ultrabasic rocks are generally separated from the more acidic rocks. However, there is a significant separation between the intermediate extrusives (predominantly andesite) and their intrusive counterparts (predominantly granodiorite).

The separation between igneous and sedimentary rocks, together with differences with these broad groupings are clearer when element ratios are plotted against gamma-ray exposure rate (Fig. 6 and 7). These figures show that Th and U predominate in the high-radioactivity igneous rock types, while K is more predominant in the basic igneous rocks. In the igneous rocks, $K \times 10^{-4}/Th$ and $K \times 10^{-4}/U$ are lowest in the most radioactive rocks, the alkali feldspathoidal intermediates, and increase to highest values in the basic rocks. This suggests that, though the radioelements all decrease markedly from acidic to basic rocks in the igneous series, there is a sharper decrease

in the abundance of U and Th - rich accessory minerals than in the abundance of K - carrying feldspar minerals as the series progresses from high to low radioactivity rocks.

The opposite trend holds for the sedimentary rocks, where K is more predominant in the higher- radioactivity shales, and Th and U in the clays and chemical sedimentary rocks. Exceptions to these trends in the igneous and sedimentary rocks are the low-radioactivity carbonate and ultramafic rocks, especially exemplified by the strong predominance of U in the carbonates.

These comparisons of ratios can be used to distinguish between terranes of comparable radioactivity. For example, low-radioactivity terranes with relatively high K/U would most likely be underlain by basic to ultrabasic igneous rocks, while low radioactivity terranes where U predominates would most likely be of limestone or dolomite. Similarly, terranes of detrital sedimentary rocks would generally have K less predominant over Th and U than terranes of comparable radioactivity in the igneous rocks.

Another way of illustrating radioelement relationships is the triangular diagram (Fig. 1 and 8) relating the relative abundance or contribution of each radioelement. Fig. 8 shows the relative contributions of each radioelement to the mean total gamma-ray exposure rates of the rock types. Here again we see that, with the exception of the alkali feldspathoidal intermediate rocks, there is a separation between the sedimentary and igneous rocks. The field of mean values of the sedimentary

rocks suggests that U generally contributes more than 25% of the total gamma exposure rate, and in the carbonates U may contribute more than 50%. This propensity of U to associate with the sedimentary rocks may be due to the element's mobility as U^{+6} in oxidizing environments, such as occur in shallow groundwater regimes in igneous terranes that may serve as source regions. U may then be deposited in reducing environments afforded by organic material and/or sulfide minerals in sedimentary rocks. K and Th, predominant in feldspar and accessory minerals, respectively, in igneous and sedimentary rocks, are much less mobile than U. Therefore, there is little difference between the relative contributions of K and Th to the total gamma exposure rates of sedimentary and igneous rocks.

The efficacy of the triangular diagram for displaying radioelement relationships is illustrated in Fig. 9, where median values of equivalent U, equivalent Th, and K in quadrangles from airborne gamma surveys (in conjunction with the National Uranium Resource Evaluation program) of Quaternary alluvium in Alaska are presented (data from Saunders and Potts, 1978, Table V-5). In this example, each point represents a combination of the median values for one map quadrangle; the diagram is truncated at the Th = 0.35 line. The data encompass the alluvia of four geologic provinces, and are thus considered to represent an integration of material from bedrock terranes. Though they plot relatively close together in the K "corner" of the triangle, the four provinces are clearly

distinguished by their radioelement relationships. Uranium appears to be somewhat more predominant over the other radioelements in the Bethel province than in the other three provinces, even though a tabulation of the aeroradiometric data shows that the alluvium of the Bethel province has lower absolute abundances of U. From these relationships and the aforementioned associations of radioelements with specific rock types, one can speculate that bedrock of the Bethel province contains more carbonate rock than does bedrock of the Yukon, or Holy Cross-Taylor Mountains provinces. An examination of the Geologic Map of Alaska (Beikman, 1980) suggests that the broad categories of rocks that contain carbonates are present in some of the drainage areas that provide material to the alluvium of the Bethel province. However, a more detailed examination of the geologic maps of individual quadrangles, comparing outcrop areas of the specific rock types, would have to be done to substantiate this speculation.

CONCLUSIONS

This compilation of natural radioelement concentrations of the various rock types has shown that:

1) The radioactivity (expressed as the gamma-ray exposure rate) and radiogenic heat production of the igneous rocks generally vary with the silica content of the rocks. Exceptions are the high-radioactivity alkali feldspathoidal rocks which are generally low in SiO_2 but high in Na and K.

2) With the exception of shale, sedimentary rocks generally have low K/U and K/Th ratios, compared to most igneous rocks.

3) The radioelement contents of metasedimentary and metaigneous rocks represent well the radioelement contents of their unmetamorphosed precursors.

4) The appreciable difference between the overall mean terrestrial gamma-ray exposure rate calculated from rock radioelement contents and the mean exposure rate from measurements over soil may be explained by effects of the differences in density of soil and rock, the moisture content of soil and the apparent depletion of U in unsaturated, near-surface soil.

5) One may differentiate between low-radioactivity terranes (carbonates, ultrabasics, and basic igneous rocks) by their K/U and K/Th ratios. High-radioactivity terranes (acid-igneous and alkali feldspathoidal rocks) may also be differentiated by their K/U and K/Th ratios.

6) Airborne gamma spectrometric surveys may be able to distinguish the general lithological character of overflown terranes by combining radioelement ratios and concentrations with relative total gamma radioactivity.

It is recommended that the data base be expanded, especially in the rock types where data are scarce: the ultrabasic and alkalic basic rocks, clay, and carbonate rocks where data on K are available. Conclusion #5 would be better tested and the radioelement ratio - rock type relationships more closely evaluated and refined by application of the large data base developed by the National Uranium Resource Evaluation project.

ACKNOWLEDGEMENTS

We are grateful for the help of Joan Fitzpatrick who initially assembled the data base and formulated the program DOSECAL. Expansion of the data base, operation of the program and compilation were ably carried on by Dee Di Somma and Beverly Strisower. We appreciate the comments and suggestions of Barbara Moed in reviewing a draft of this report.

This work was supported by the Aerial Measurements operations of EG&G/EM under a memorandum of understanding with the Lawrence Berkeley Laboratory, through U.S. Department of Energy Contract No. DE-AC03-76SF00098.

APPENDIX

Histograms and comments on the Individual Rock Categories

The distribution of radioactivity, expressed as total gamma-ray exposure rate, is indicated on the histograms, Fig. A-1 through A-15. The following comments apply to the individual histograms.

Acid Extrusives

The highest radioactivity entries, $>30\mu Rh^{-1}$ shown on the histogram in Figure A-1, represent samples of welded to partly welded ash-flow tuff of the Fish Creek Mountains, central Nevada (Wollenberg and others 1977). With the exception of these and the relatively low-radioactivity entries ($\sim 5\mu Rh^{-1}$), the population groups fairly coherently about the mean value of 16.2 μRh^{-1}.

Acid Intrusives

A well-defined log-normal distribution of radioactivity is evident on the histogram in Fig. A-2. The highest values represent entries of Precambrian granite and quartz monzonite from the southwestern U S. (Malan 1972).

Intermediate Extrusives

The bimodal nature of the distribution of radioactivities in the histogram, Fig. A-3, results from two distinctive populations. The lower-radioactivity population is predominantly hornblende andesite of the Cascade Range (White, 1979; Wollenberg

and others 1979), while the higher-radioactivity group, centered on $\sim 10\ \mu Rh^{-1}$, represents predominantly Oligocene andesite of the Basin and Range geomorphic province (unpublished data, Lawrence Berkeley Laboratory).

Intermediate Intrusives

As with the acid intrusives, a well-defined log-normal distribution of radioactivities is shown in the histogram, Fig. A-4. The few high values ($>30\ \mu Rh^{-1}$) represent Precambrian granitic rocks from Colorado and Wyoming (Morgan and others 1966; Malan and Sterling, 1970; Marjaniemi and Basler, 1972).

Basic Extrusives

The histogram shown in Fig. A-5 suggests a log-normal distribution of radioactivities in the basaltic rocks. The highest value, $\sim 9\ \mu Rh^{-1}$, represents an entry for basalt from southwestern Texas (Gottfried and others 1962a).

Basic Intrusives

The histogram for these predominantly gabbroic rocks (Fig. A-6) indicates a log-normal distribution of radioactivities. The highest values, $\sim 16\ \mu Rh^{-1}$, represent thorium-rich norite from Ontario (Keevil, 1944).

Ultrabasics

The rather meagre population whose distribution is indicated in the histogram, Fig. A-7, is comprised predominantly of peridotite and pyroxenite. The highest value (>4 μRh^{-1}) represents olivinite from the Eastern European Platform U.S.S.R. (Gonshakova and others 1972).

Alkali Feldspathoidal Intermediate Intrusives

A broad range of relatively high radioactivities in these rocks is indicated by the histogram in Fig. A-8. The predominant rock type in the data set, including the highest radioactivity values, is trachyte from the alkalic volcanic province of central Italy (Locardi and Mittempergher, 1967).

Alkali Feldspathoidal Intermediate Intrusives

The population shown in the histogram in Fig. A-9 is made up predominantly of syenite and nepheline syenite. The highest-radioactivity entries are lujavrite (a rare-earth thorium-rich nepheline syenite) from the Ilímaussaq intrusion, southwest Greenland (Sass and others 1972).

Alkalic Basic Intrusives

Since there are only eight entries for this category no histogram was drawn. The rocks are predominantly alkalic gabbro with the highest radioactivity entry being teschenite from Virginia (Gottfried, and others 1962b).

Alkalic Basic Extrusives

The rocks represented in the histogram in Fig. A-10 are predominantly alkalic basalt and limburgite of the Ukranian Shield, whose radioelement concentrations were reported by Gonshakova and others (1972). A prominent exception is relatively high-radioactivity tephrite (36.6 μRh^{-1}) from the Latera region, Italy, reported by Locardi and Mittempergher (1967).

Chemical Sedimentary Rocks (Including Carbonates)

Because of the scarcity of K-concentration data for these rocks, relatively few entries could be used to calculate total gamma-ray exposure rates. However, the histograms in Fig. A-11 and A-12 illustrate the broad range of radioactivities encompassed by the chemical sediments, in contrast to the much smaller range of the carbonates (which make up a substantial portion of the chemical sediments' data base). Distributions of the U and Th concentrations of both of these categories are strongly log-normal (illustrated Fig. A 11a, A 12a and A 12b) indicating that the distributions of their total gamma-ray exposure rates would follow suit. The highest radioactivity values of the chemical sediments, 35 to >45 μRh^{-1}, are representative of bauxite (Adams and Weaver, 1958), while those of the carbonate rocks, $\sim$6 to 6.5 μRh^{-1}, represent the Austin Chalk, Texas (Adams and Weaver, 1958) and an Arizona limestone (Malan and Sterling, 1969).

Detrital Sedimentary Rocks

As shown in the histogram, Fig. A-13, the distribution of radioactivity is fairly tightly confined, <15 μRh^{-1}, with the exception of a few high values representative of a California Eocene sandstone (Wollenberg and Dodge, 1973) and U and Th-rich sandstone from Utah (Murray and Adams, 1958). Other relatively high (>15 μRh^{-1}) radioactivity entries represent Devonian shale from the eastern U.S. (Leventhal et al., 1981).

Metamorphosed Igneous Rocks

The rocks represented on the histogram, Fig. A-14 are predominantly gneiss and orthogneiss. The high values (>30 μRh^{-1}) are for U- and Th rich Precambrian gneiss of the Front Range, Colorado, the McCullough Range, Nevada, and the Whetstone Range, Arizona (Malan and Sterling, 1970).

Metamorphosed Sedimentary Rocks

This category is made up primarily of slate, phyllite, schist and quartzite; predominantly of lower metamorphic grade than the metaigneous rocks. The highest values (>25 μRh^{-1}) shown in the histogram, Fig. A-15, are in Precambrian paragneiss, schist and quartzite of Arizona and California (Malan and Sterling 1970).

Figure Captions

1. Relative abundances of radioelements in different rock types, XBL 762-2189.

2. Gamma-ray exposure rates of igneous rocks; error bars express standard deviations of the means. XBL 846-9023.

3. Variation of gamma-ray exposure rate with silica content of the igneous rocks. A = Acidic rocks, B = Basic rocks, I = Intermediate rocks, UB = Ultrabasic rocks, AFI = Alkali - feldspathoidal intermediate rocks, AFB = Alkali feldspathoidal basic rocks. XBL 846-9018

4. Gamma-ray exposure rates of sedimentary and metamorphic rocks; error bars express standard deviations of the means. XBL 846-9022.

5. Mean values of K/U and K/Th of the various rock types (symbols correspond to those in Table 3), XBL 846-9021.

6. K/U and gamma-ray exposure rate (symbols correspond to those in Table 3), XBL 846-9020.

7. K/Th and gamma-ray exposure rate (symbols correspond to those in Table 3). XBL 846-9019.

8. The relative contributions of U, Th and K to terrestrial gamma-ray exposure rates (symbols correspond to those in Table 3), XBL 846-9024.

9. Relative U, Th and K abundances in alluvium of the Yukon (Y), Holy Cross (HC), Taylor Mountains (T) and Bethel (B) geologic provinces, Alaska, XBL 846-9025

Figure

A-1 Frequency distribution. total gamma-ray exposure rate. acid extrusive rocks XBL 784

A-2. Frequency distribution, total gamma-ray exposure rate acid intrusive rocks, XBL 784 1827A.

A-3. Frequency distribution, total gamma-ray exposure rate intermediate extrusive rocks, XBL 846 9013.

A-4. Frequency distribution, total gamma-ray exposure rate, intermediate intrusive rocks, XBL 784 1835A.

A-5. Frequency distribution. total gamma-ray exposure rate, basic extrusive rocks, XBL 784 1828A.

A-6. Frequency distribution. total gamma-ray exposure rate, basic intrusive rocks, XBL 784 1836A.

A-7. Frequency distribution, total gamma ray exposure rate, ultrabasic rocks, XBL 784 1829A.

A-8 Frequency distribution. total gamma-ray exposure rate, alkali feldspathoidal intermediate extrusive rocks, XBL 784 1833A.

A-9. Frequency distribution, total gamma-ray exposure rate, alkali feldspatoidal intermediate intrusive rocks. XBL 784 1834A.

A-10. Frequency distribution, total gamma ray exposure rate, alkali basic extrusive rocks, XBL 1824A.

A-11. Frequency distribution. total gamma ray exposure rate, chemical sedimentary rocks. XBL 784 1831A.

A-11a. Frequency distribution. uranium content, chemical sedimentary rocks, XBL 846-8821.

A-12. Frequency distribution, total gamma-ray exposure rate, carbonate rocks. XBL 784 1832A.

A-12a. Frequency distribution, uranium content, carbonate rocks, XBL 846-8820.

A-12b. Frequency distribution, thorium content, carbonate rocks, XBL 846-8822.

A-13. Frequency distribution, total gamma-ray exposure rate, detrital sedimentary rocks, XBL 784 1830A.

A-14. Frequency distribution, total gamma-ray exposure rate, metamorphosed igneous rocks, XBL 784 1825A.

A-15. Frequency distribution, total gamma-ray exposure rate, metamorphosed sedimentary rocks, XBL 784 1826A.

REFERENCES

Abramovich, I. I., 1959, Uranium and thorium in the intrusive rocks of central and western Tuva. Geochemistry n. 4, p. 442-50.

Adams, J. A. S. and C. E. Weaver, 1958, Thorium-to-uranium ratios as indicators of sedimentary processes: example of concept of geochemical facies. Bull AAPG v. 42, n. 2, p. 387-430.

Adams, J. A. S., W. M., Lowder, and T. F. Gesell, eds., 1972 "The Natural Radiation Environment, II", U.S. E.R.D.A. CON-720805-P1.

Bacon, C. R., R. MacDonald, R. L. Smith, and P. A. Baedecker, 1981, Pleistocene high-silica rhyolites of the Coso volcanic field, Inyo County. California, J. Geoph. Res.. v. 8b, n. B11. p. 100223-10241.

Baranov, V. I. A. B. Ronov, and K. G. Runashkova, 1956, Geochemistry of throium and uranium in clays and carbonate rocks of the Russian platform. Geochim. Icd. Akad. Nauk SSSR n 3, p. 3-8.

Barker, D. S., 1974, Alkaline rocks of North America in H. Sorensen, ed. "The Alkaline Rocks", John Wiley & Sons, New York.

Beck, H. and G. de Planque, 1968, The Radiation field in air due to distributed gamma-ray sources in the ground, Health and Safety Laboratory rept. HASL-195, U.S. Atomic Energy Commission.

Beikman, H. M. (compiler), 1980, Geologic map of Alaska; U.S. Geological Survey.

Bowman, H. R., F. Asaro and I. Perlman, 1972, On the uniformity of composition in obsidians and evidence for magmatic mixing, Lawrence Berkeley Lab. Rept. LBL-661.

Bunker, C., C. Bush, and R. Forbes, 1973, Radioelement distribution in the basement complex of the Yukon-Tanana upland, Eielson deep test hole. Alaska. J. Res. U.S. Geol. Surv., v. 1, n. 6, p. 659-663.

Cardinale, A., G. Cortellessa, F. Gera, O. Ilari, and G. Lembo, 1972, Distribution in the Italian population of the absorbed dose due to the natural background radiation, in "The Natural Radiation Environment II", J. A. S. Adams, W. M. Lowder and T. F. Gesell, eds, U.S.E.R.D.A. CONF-720805-P1.

Cioni, R., R. Clocchiatti, G. Di Paola, R. Santacroce, and S. Tonarini, 1983, Miocene calc-alkaline heritage in the Pliocene post-collisional volcanism of Monte Arci (Sardinia, Italy) J. Volc. Geothermal Res. v. 14, p. 133-167.

Crecraft, H. R., W. P. Nash, and S. H. Evans, Jr., 1981, Late Cenozoic Volcanism at Twin Peaks, Utah: geology and petrology J. Geoph. Res., v. 86 n. B11, p. 10303-10320.

Deruelle, B. 1982, Petrology of the Plio-quaternary vollcanism of the South-central and meridional Andes, J. Volc. Geothermal Res., v. 14, p. 77-124.

Dostal, J. and S. Capedri, 1978, Uranium in metamorphic rocks, Contrib. Mineral. Petrol. v. 66, p. 409-414.

Evans, R.D. and C. Goodman, 1941, Radioactivity of rocks, Geol. Soc. Am. Bull. v. 52, p. 459-490.

Gonshakova, V., V. Viktorov, S. Tseytlin, and N. Zhirova, 1972, Distribution of radioactive elements in platformal basites and ultrabasites. Int. Geol. Rev. v. 14, n. 7, p. 729-737

Gottfried, D., R. Moore, and E. Campbell 1962a, Thorium and uranium in some volcanic rocks from the circum-Pacific province, U.S. Geol. Surv. Prof. Paper 450-E, p. 85-88.

Gottfried, D., R. Moore and A. Caemmerer, 1962b, Thorium and uranium in some alkaline igneous rocks from Virginia and Texas, U.S. Geol. Surv. Prof. Paper 450-B, p. 70-72.

Grasty, R. L., J. M. Carson, B. W. Charbonneau, and P. Holman, B., 1983, Natural background radiation in Canada, Geol. Survey of Canada Bull. 366.

Heier, K. S. and J. Rogers, 1963, Radiometric determination of thorium, uranium and potassium in basalts and in two magmatic differentiation series, Geochim. Cosmochim. Acta v. 27 n. 2, p. 137-154.

Heier, K. S. and J. L. Carter, 1964, Uranium, thorium and potassium contents in basic rocks and their bearing on the nature of the upper mantle, in "The Natural Radiation Environment", University of Chicago Press, J. A. S. Adams and W. Lowder, eds.

Heier, K. S. and J. A. S. Adams 1965 Concentration of radioactive elements in deep crustall materials. Geochim. Cosmochim. Acta, v. 29, p. 53-61.

Jasinska, M., T. Niewiadomski, and J. Schwabenthan, 1980, On a new possibility of estimating population exposure to terrestrial sources, Health Physics, v. 38, p. 419-421.

Jupiter, C. and H. Wollenberg, 1974, Interim status of the Texas uranium survey experiment, EG&G Inc. Report EGG-1183-1630.

Keevil, N. B., 1944, Thorium-uranium ratios in rocks and minerals, Amer. J. Sci., v. 242, p. 309-321.

Kirkegaard, P. and L. Lovborg, 1980, Transport of Terrestial gamma radiation in plane semi-infinite geometry, J. Computational Physics, v. 36, p. 30-34.

Labhart, T. and L. Rybach, 1971 Abundance and distribution of uranium and thorium in the syenite of Piz Giuv (Aar Massif, Switzerland), Chem. Geol. v. 7, n. 4 p. 237-251.

Larsen, E. S. and G. Phair, 1954, The distribution of uranium and thorium in igneous rocks, in "Nuclear Geology" H. Faul, ed.

Larsen, E. S. and D. Gottfried, 1960a, Distribution of uranium in rocks and minerals of the western United States. U.S. Geol. Surv. Bull. 1070-C.

Larsen, E.S. and D. Gottfried, 1960b, Uranium and thorium in selected suites of igneous rocks, Am. J. Sci. v. 258-A pp. 151-169.

Leventhal, J. S., J. G. Crock, and M. J. Malcom, 1981, Geochemistry of trace elements and uranium in Devonian shales of the Appalachian Basin. U.S. Geol. Surv. open file Report 81-778.

Lindeken, C. L., K. R. Peterson, D. E. Jones, and R. E. McMillen, 1972, Geophysical variations in environmental radiation background in the United States, in "The Natural Radiation Environment II" J.A.S. Adams, W. M. Lowder and T. F. Gesell, eds., U.S.E.R.D.A. CONF. - 720805-P1.

Locardi, E. and M. Mittempergher, 1967, Relationship between some trace elements and magmatic processes. Geol. Rundschau, v. 57 p. 313-334.

Long, P. E. and R. D. Landon, 1981, Stratigraphy of the Grande Ronde basalt; chapter 4 in C. W. Myers and S. M. Price, eds, "Subsurface Geology of the Cold Creek Syncline" Rockwell Hanford Report, RHO-BWI-ST-14.

Lovborg, L., H. Wollenberg, H. Sorensen, and J. Hansen, 1971, Field determination of uranium and thorium by gamma ray spectrometry, exemplified by measurements in the Ilimaussaq intrusion, South Greenland. Econ. Geol. v. 66 n. 3., p.

Lyons J. B. 1964, Distribution of thorium and uranium in three early Paleozoic plutonic series of New Hampshire, USGS Bull. 1144-F.

Mahood, G. A. 1981, A summary of the geology and petrology of the Sierra La Primavera, Jalisco, Mexico. J. Geoph. Res., v. 86, no B11, p. 10137-10152.

Mahood, G. and W. Hildreth, 1983, Large partition coefficients for trace elements in high-silica rhyolites, Geochim. Cosmochim. Acta, v. 47, p. 11-30.

Malan, R. C. and D. A. Sterling, 1969a, An introduction to the distribution of uranium and thorium in Precambrian rocks, including the results of preliminary studies in the south-western United States. US Atomic Energy Comm. Rept. AEC-RD-9 open file.

Malan, R. C. and D. A. Sterling, 1969b, A Geologic Study of Uranium and Thorium in Precambrian Rocks of the Western U.S.-Distribution of Uranium and Thorium in Precambrian Rocks

of the Western Great Lakes Region. US Atomic Energy Comm. Rept. AEC-RD-10.

Malan, R. C. and D. A. Sterling, 1970, Distribution of uranium and thorium in the Precambrian of the west-central and northwest United States. US Atomic Energy Comm. Rept. AEC-RD-11 open file.

Malan, R. C., 1972, Summary report-distribution of uranium and thorium in the Precambrian of the western United States. U.S. Atomic Energy Comm. Rept. AEC-RD-12.

Marjianimi, D. K. and A. L. Basler, 1972, Geochemical investigations of plutonic rocks in the western United States for the purpose of determining favorability of vein-type uranium deposits. US Atomic Energy Comm. Rept. GJO-912-16.

McLennan, S. M. and S. R. Taylor, 1980, Th and U in sedimentary rocks· crustal evolution and sedimentary recycling, Nature, v. 285, p. 621-624.

Mishra, U. C., 1972, Natural and fallout gamma nuclides in Indian soils, in "The Natural Radiation Environment II" J.A.S. Adams, W. M. Lowder and T. F. Gesell, eds., U.S.E.R.D.A. CONF. - 720805-P1.

Morgan, J. W. and K. S. Heier, 1966, Uranium, thorium and potassium in six U.S.G.S. standard rocks. Earth Planet. Sci. Lett. v. 1, p. 158-160.

Murray, E. G. and J. A. S. Adams, 1958, Thorium, uranium and potassium in some sandstones, Geochim. Cosmochim Acta v. 13, p. 260-269.

Murphy, M., H. Wollenberg, B. Strisower, B. Bowman, S. Flexser, and I. Carmichael, 1978, Uranium in alkaline rocks, Lawrence Berkeley Lab. Rept. LBL-7029.

Noble, D. and H. Bowman, 1975, Unpublished chemical compositions of dacite, rhyodacite and quartz latite from central Peru. Lawrence Berkeley Lab.

Oakley, D. T. and D. W. Moeller, 1972, Estimates of terrestrial radiation exposure based upon aerial surveys, in "The Natural Radiation Environment II" J.A.S. Adams, W. M. Lowder and T. F. Gesell, eds., U.S.E.R.D.A. CONF. - 720805-P1.

Phair, G. and D. Gottfried, 1964, The Colorado Front Range, Colorado, USA, as a uranium and thorium province, in "The Natural Radiation Environment" J. A. S. Adams and W. Lowder, eds. U. Chicago Press.

Picciotto. E. E., 1950, Distribution de la radioactivite dans les roches eruptives. Societe Belge de Geologie, de Paleontologie et d'Hydrologie Bull. 59, p. 170-198.

Pliler, R. and J.A.S. Adams, 1962, The distribution of uranium and thorium in a Pennsylvanian weathering profile, Geoch. Cosmoch. Acta., v. 26, p. 1137-1146.

Rogers, J. 1964, Statistical tests of the homogeneity of radioactive components of granitic rocks in "The Natural Radiation Environment", J. A. S. Adams & W. Lowder, eds. U. Chicago Press.

Ronov, A. B., and A. A. Yaroshevskiy, 1967 Chemical Structure of the Earth's Crust, Geochemistry International, v. 4, no. 6, p. 1041-1066.

Sass, J, B. Nielsen, H. Wollenberg, and R. Munroe, 1972, Heat flow and surface racioactivity at two sites in south Greenland. J. Geoph. Res. v. 77 n. 32, p. 6435-44.

Saunders, D. F. and M. J. Potts, 1978, Manual for the Application of NURE 1974-1977 Aerial Gamma-Ray Spectrometer Data: U.S. D.O.E. Publication GTBX-12(78).

Smith, I. E. M. and R. W. Johnson, 1981, Contrasting rhyolite suites in the late Cenozoic of Papua New Guinea, J. Geop. Res., v. 86, no. B11, p. 10257-10272.

Smyslov, A. A. 1958, Radioactive elements in igneous rocks of northern Kazakhstan, Geochemistry n. 3, pp. 248-58.

Tilton, G. R, G. W. Wetherhill, L. T. Aldrich, G. L. Davis, and P. M. Jeffery, 1956, Geochemistry of uranium and lead, Carnegie Inst. Wash. Year Book, v. 55, p. 99-100.

Turovskii, S. D., 1957, Geochemistry of uranium and thorium: Distribution of the radioactive elements in intrusive rocks of northern Kirgizia, Geochemistry, n. 3, p. 119-215.

Vinogradov, A. P., 1961, The origin of the matter of the earth's crust, I. Geochemistry, n. 1, pp. 3-29.

Weng, P. S., C. M. Tsai, and T. C. Chu, 1972, Environmental radioactivity and radiation measurements in Taiwan Republic of China, in ""The Natural Radiation Environment II" J.A.S. Adams, W. M. Lowder and T. F. Gesell, eds., U.S.E.R.D.A. CONF. - 720805-P1.

White, C., 1979, Geology and Geochemistry of Mt. Hood, Oregon, in "Geothermal Resources Assessment of Mt. Hood", final

report, Department of Geology and Mineral Industries, State of Oregon, p. 78-136.

Williams, H., F. J. Turner, and C. M. Gilbert, 1954 Petrography, W. H. Freeman & Co., San Francisco.

Wollenberg, H. and A. R. Smith, 1964a, Radioactivity and radiogenic heat in Sierra Nevada plutons, J. Geoph. Res. v. 69, n. 16., p. 3471-3478.

Wollenberg, H. A. and A. R. Smith, 1964, Studies in terrestrial radiation in "The Natural Radiation Environment" J. A. S. Adams and W. Lowder eds. U. Chicago Press.

Wollenberg, H. A. and A. R. Smith, 1966, Radioactivity of Cement Raw Materials in Proc. Symposium on Geology of Cement Raw Materials, Indiana Geol. Survey, Indiana University.

Wollenberg, H. A., A. R. Smith, and E. H. Bailey, 1967, Radioactivity of upper Mesozoic greywackes in the Northern Coast Ranges, Ca., J. Geoph. Res. v. 72, n. 16, p. 4139-4150.

Wollenberg, H. A. and A. R. Smith, 1968, Radiogologic studies in the central part of the Sierra Nevada batholith, California. J. Geoph. Res. v. 73, n. 4., p. 1481-1495.

Wollenberg, H. A. and A. R. Smith, 1970, Radiogenic Heat Production in Prebatholithic Rocks of the Central Sierra Nevada, J. Geoph. Res. v. 75, n. 2 p. 431-438.

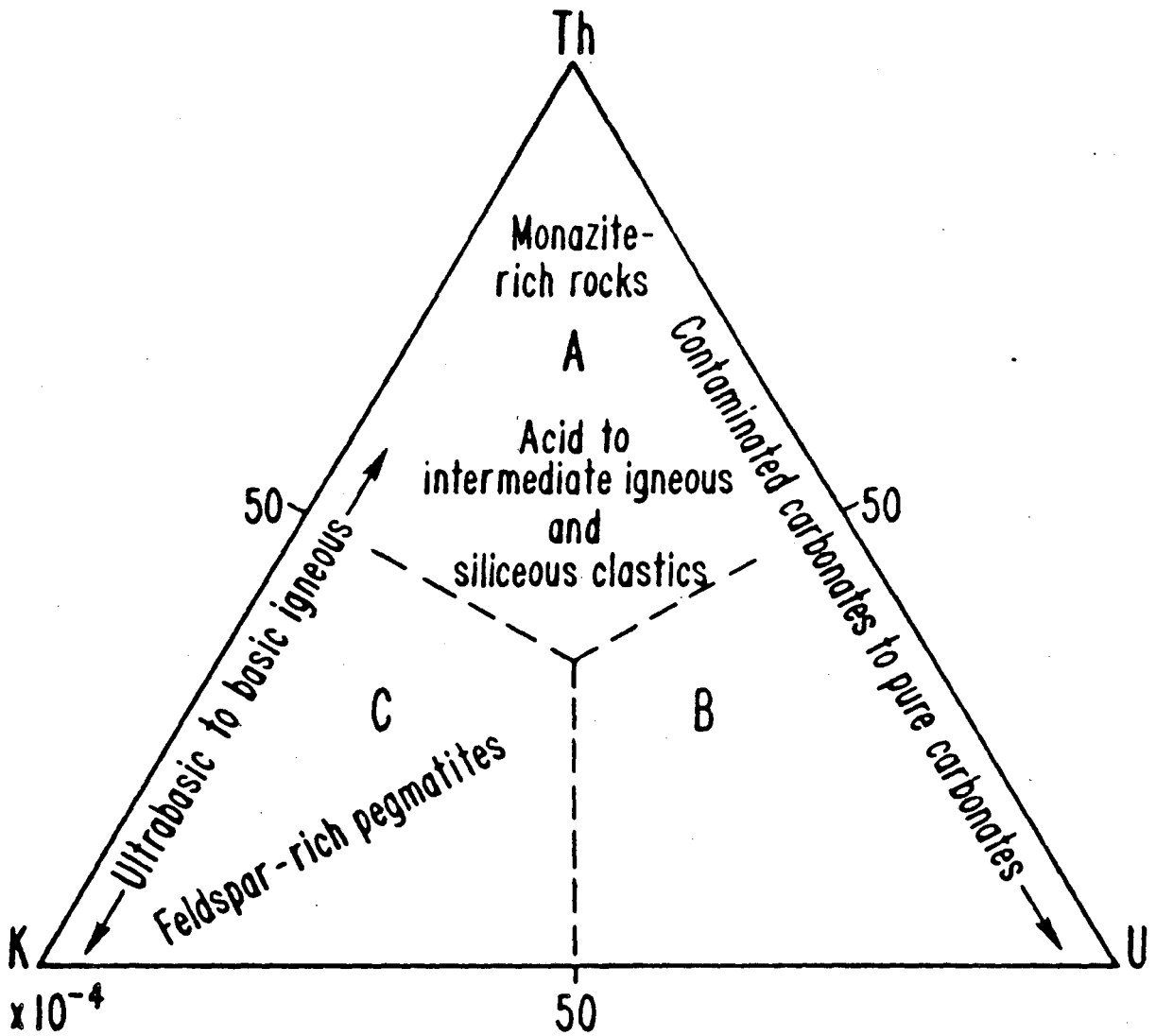
Wollenberg, H. A. and A. R. Smith, 1972, Geologic factors controlling terrestrial gamma-ray dose rates, in "The Natural Radiation Environment II", J. A. S. Adams, W. M. Lowder and T. F. Gesell eds., USERDA CONF-720805-P1.

Wollenberg, H. A. and F. C. W. Dodge, 1973, Radioelement and Trace-Element content of the Ione formation, central California U.S. Geol. Surv. Bull. 1382-B.

Wollenberg, H. A., H. Bowman, and F. Asaro, 1977, Geochemical studies at four northern Nevada hot spring areas, Lawrence Berkeley Lab. Rept. LBL-6808.

Wollenberg, H. A., R. Bowen, H. Bowman, and B. Strisower, 1979 Geochemical studies of rocks, water and gases at Mt. Hood, Oregon, Lawrence Berkeley Lab. Rept. LBL-7092.

Wollenberg, H. A., S. Flexser, and L. Andersson, 1981, Petrology and Radiogeology of the Stripa pluton. Lawrence Berkeley Lab. Rept. LBL-11654.



XBL 762-2189

Figure 1.

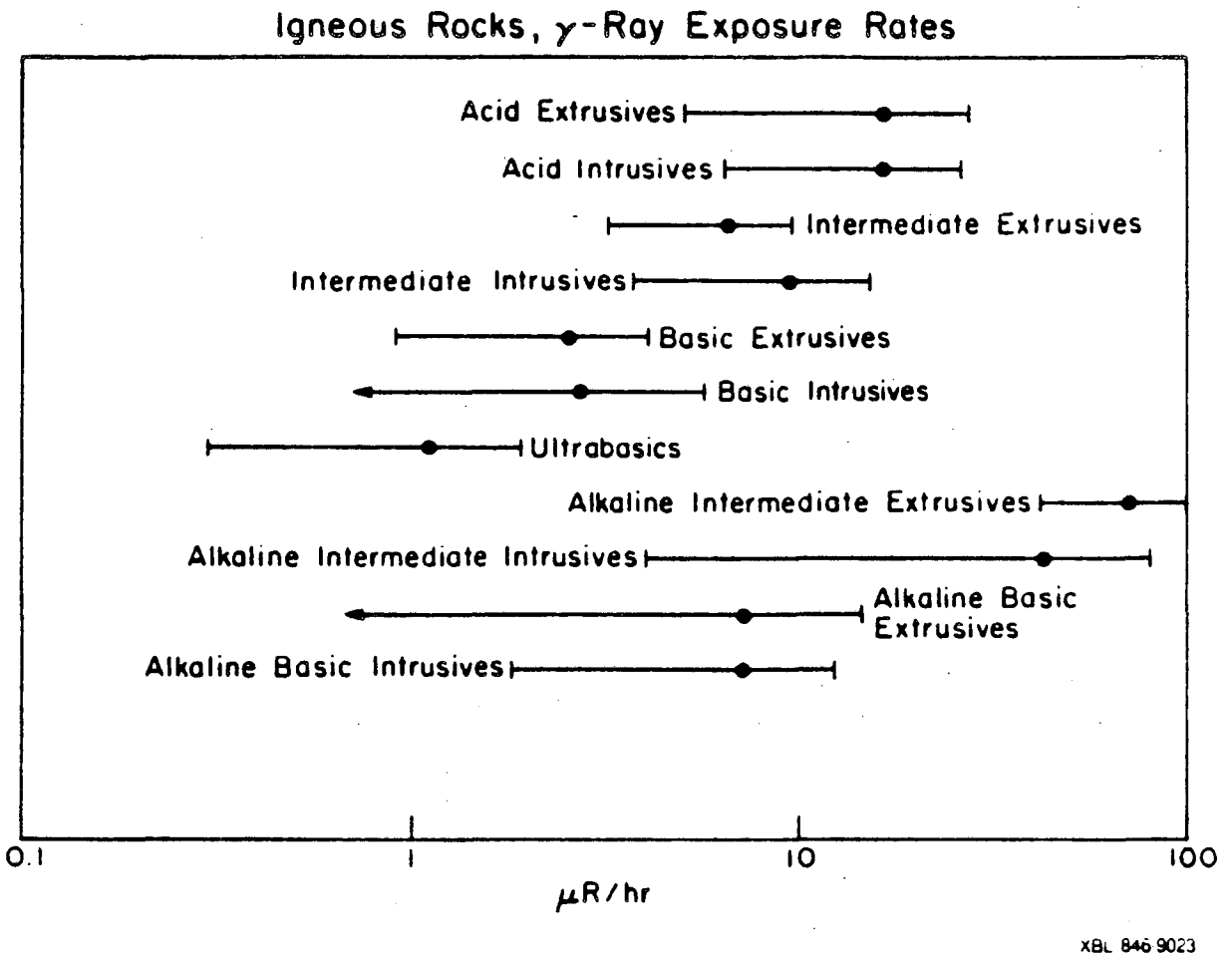
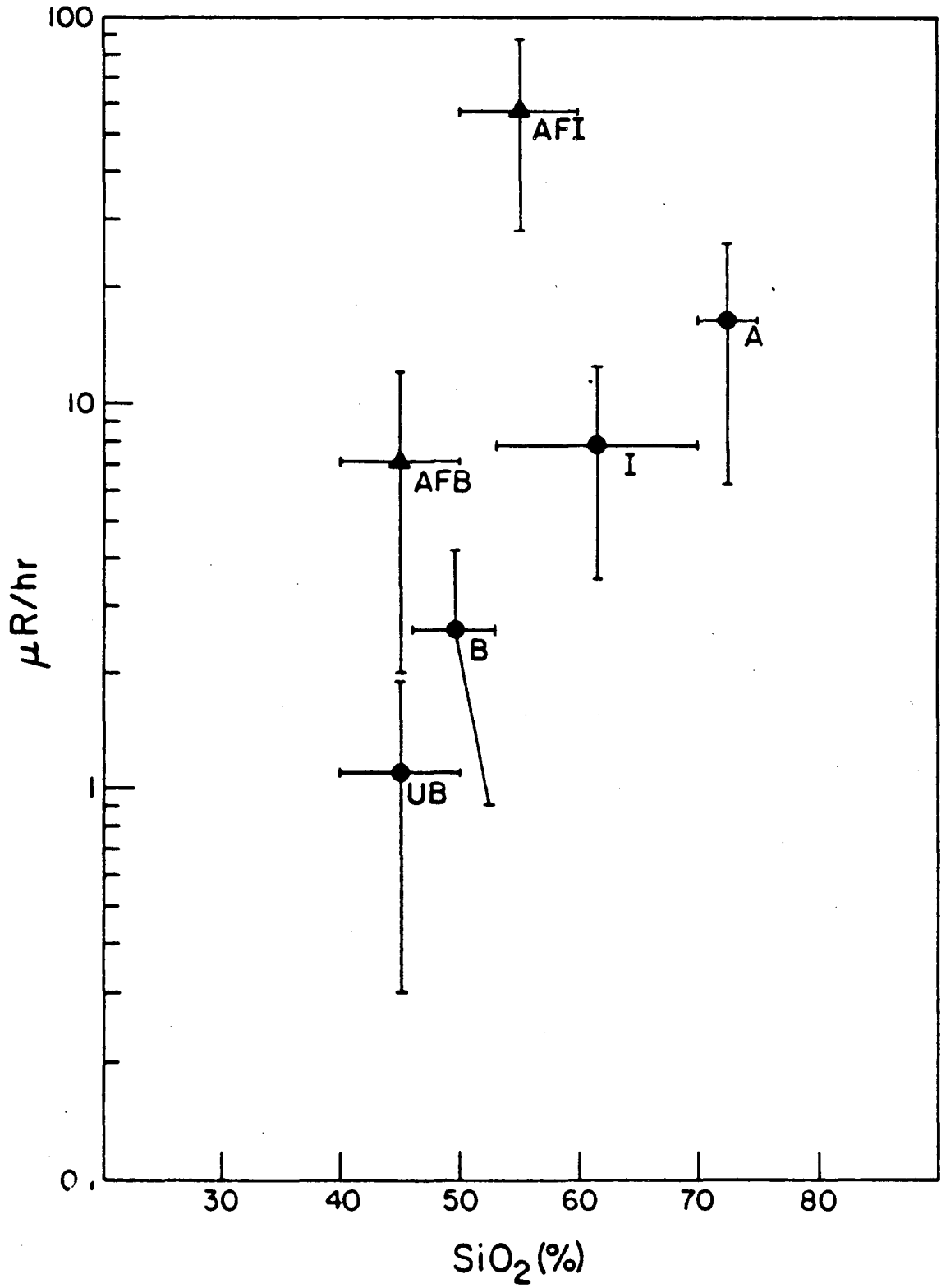
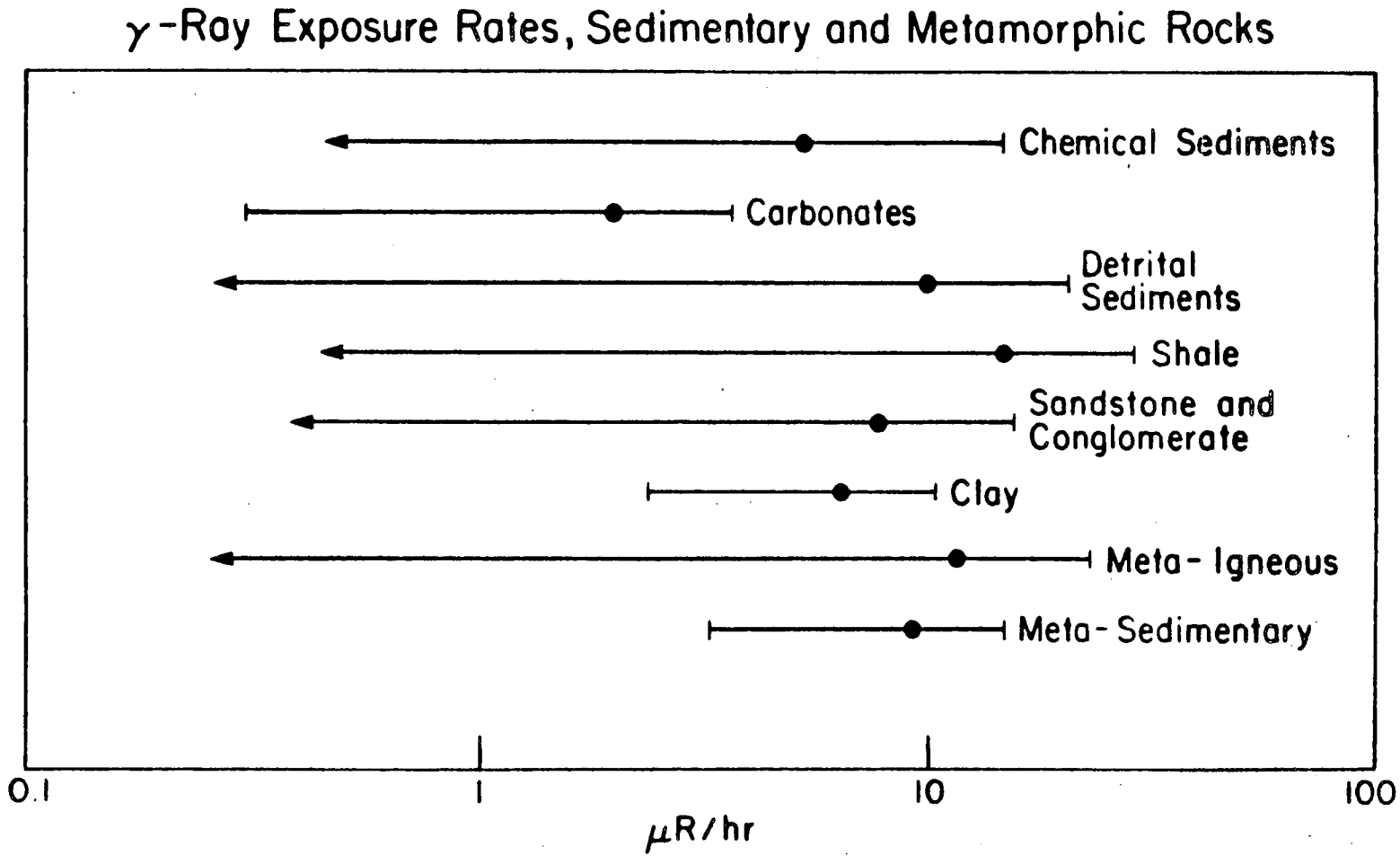

Igneous Rocks, γ-Ray Exposure Rates
Acid Extrusives
Acid Intrusives
Intermediate Extrusives
Intermediate Intrusives
Basic Extrusives
Basic Intrusives
Ultrabasics
Alkaline Intermediate Extrusives
Alkaline Intermediate Intrusives
Alkaline Basic Extrusives
Alkaline Basic Intrusives
0.1
1
10
100
μR/hr
XBL 846 9023

Figure 2.



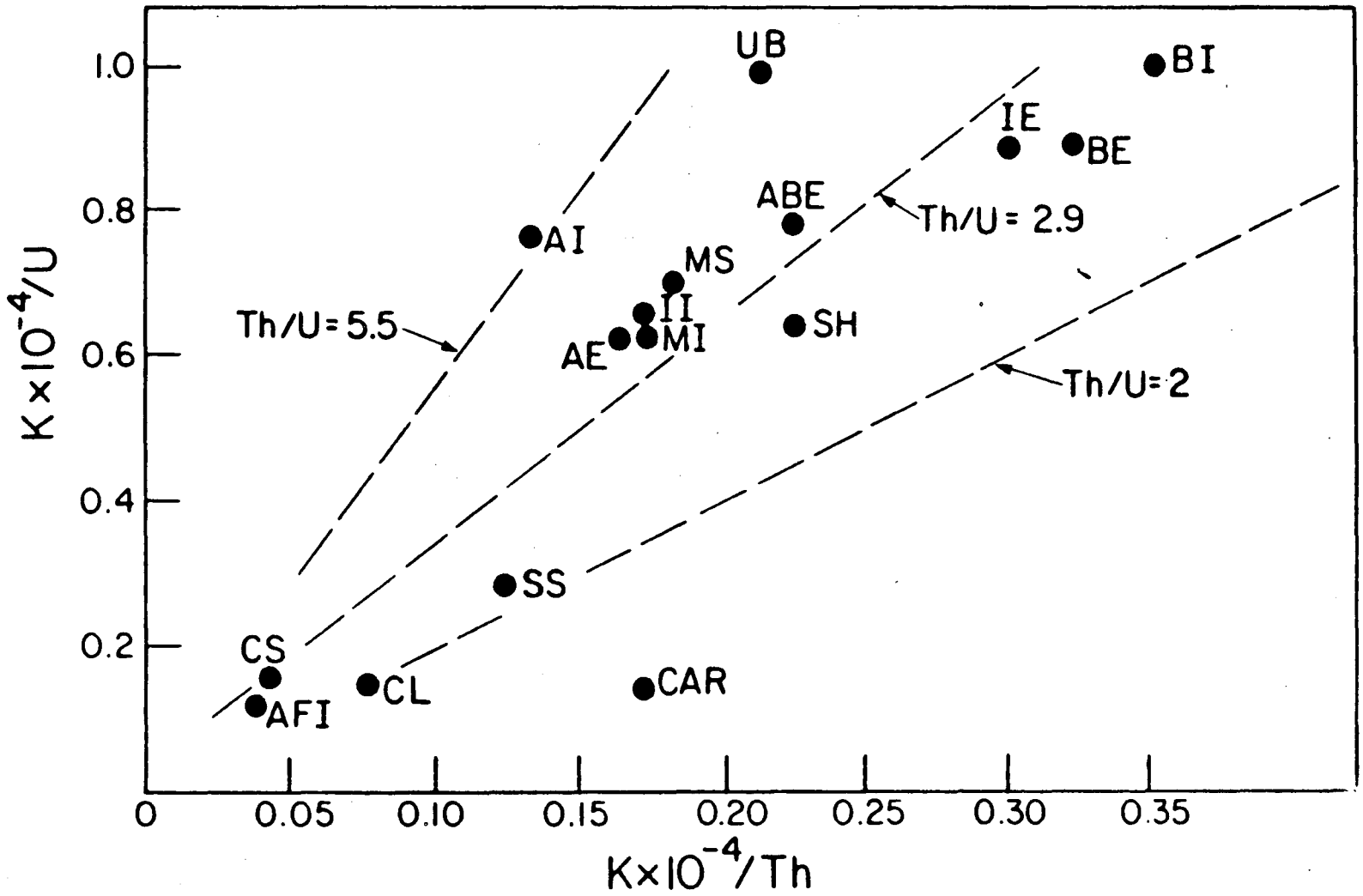
XBL 846-9018

Figure 3.



XBL 846-9022

Figure 4.



XBL 846-9021

Figure 5.

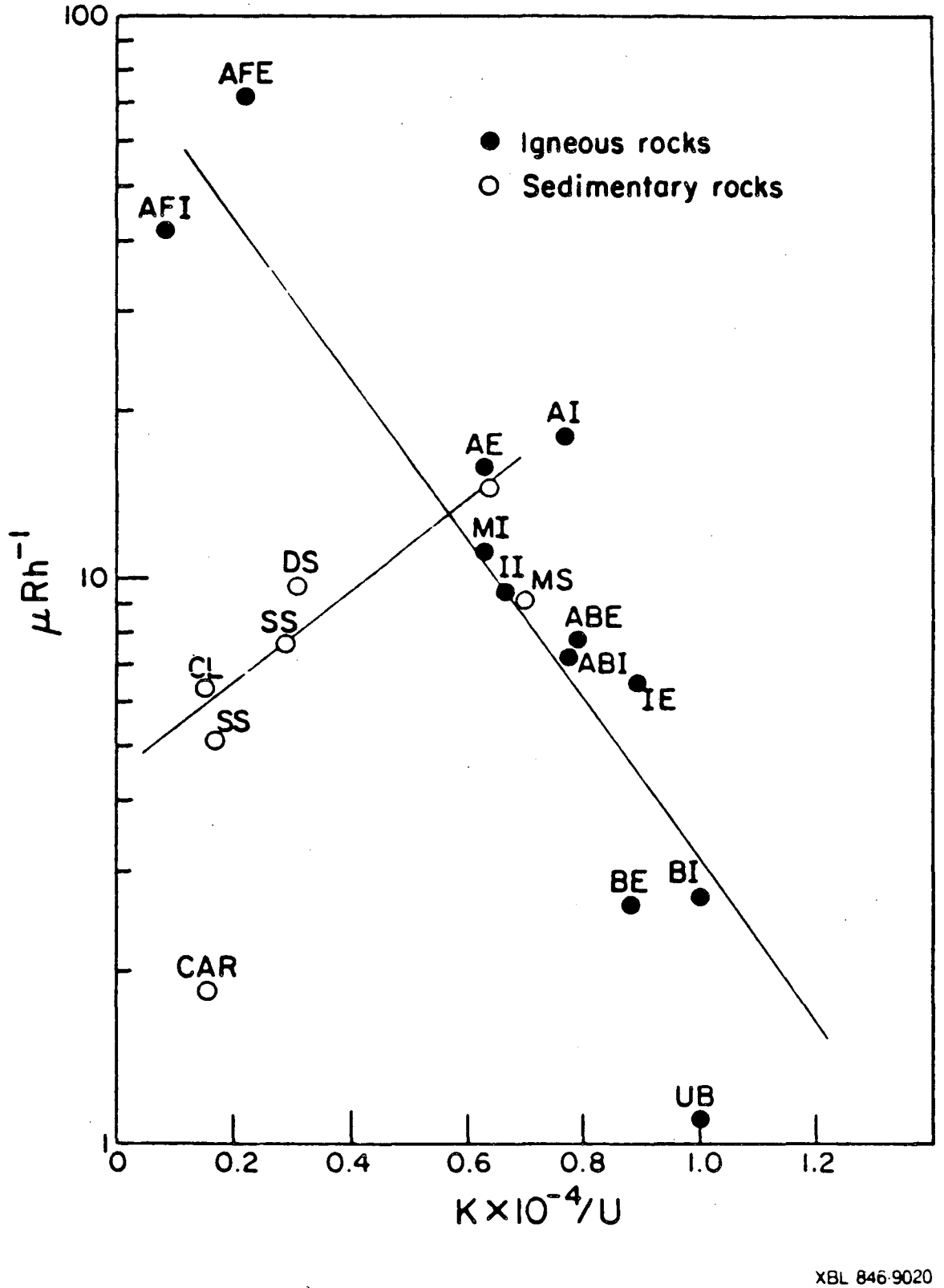

100
10
1
0
0.2
0.4
0.6
0.8
1.0
1.2
μRh^{-1}
$K \times 10^{-4}/U$
Igneous rocks
Sedimentary rocks
AFE
AFI
AI
AE
MI
II
MS
ABE
ABI
IE
BE
BI
UB
DS
SS
CI
SS
CAR
XBL 846-9020

Figure 6.

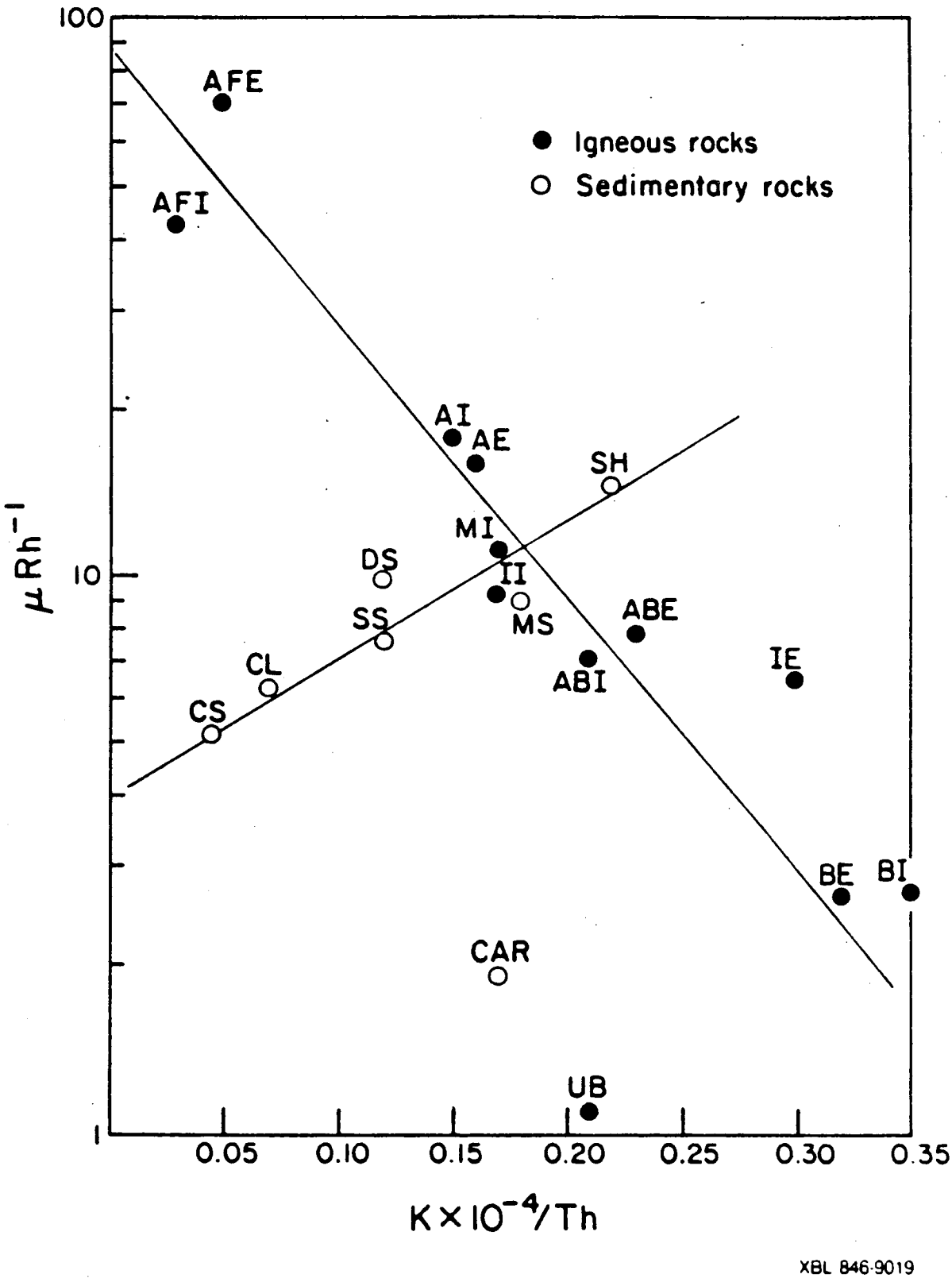

100
10
1
μRh⁻¹
0.05
0.10
0.15
0.20
0.25
0.30
0.35
K×10⁻⁴/Th
Igneous rocks
Sedimentary rocks
AFE
AFI
AI
AE
SH
MI
DS
II
MS
SS
ABE
CL
ABI
IE
CS
BE
BI
CAR
UB
XBL 846-9019

Figure 7.

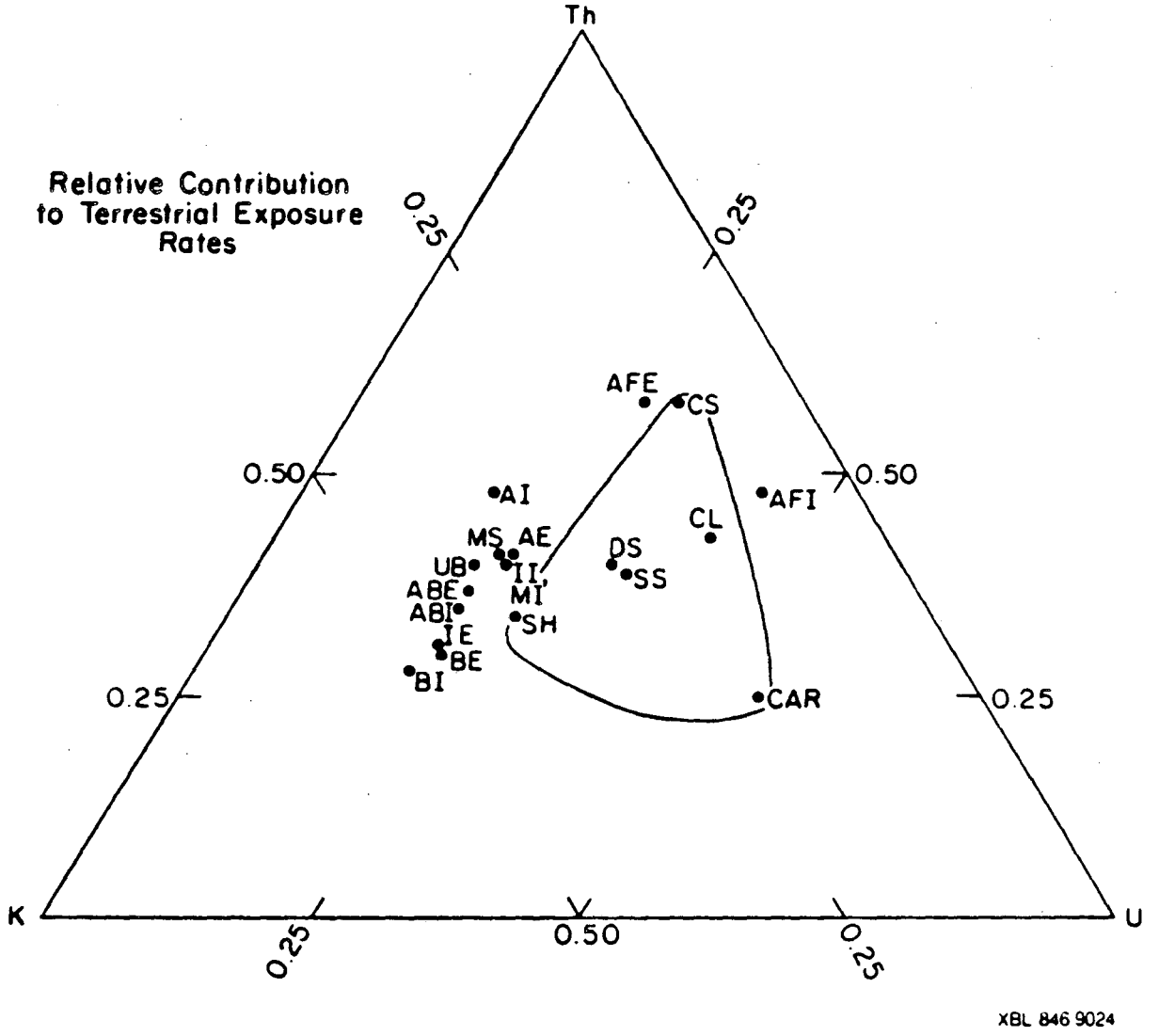

Relative Contribution
to Terrestrial Exposure
Rates
Th
K
U
0.25
0.50
0.25
0.25
0.50
0.25
0.25
0.50
0.25
AFE
CS
AI
AFI
CL
MS
AE
DS
UB
II
SS
ABE
MI
ABI
SH
IE
BE
BI
CAR
XBL 846 9024

Figure 8.

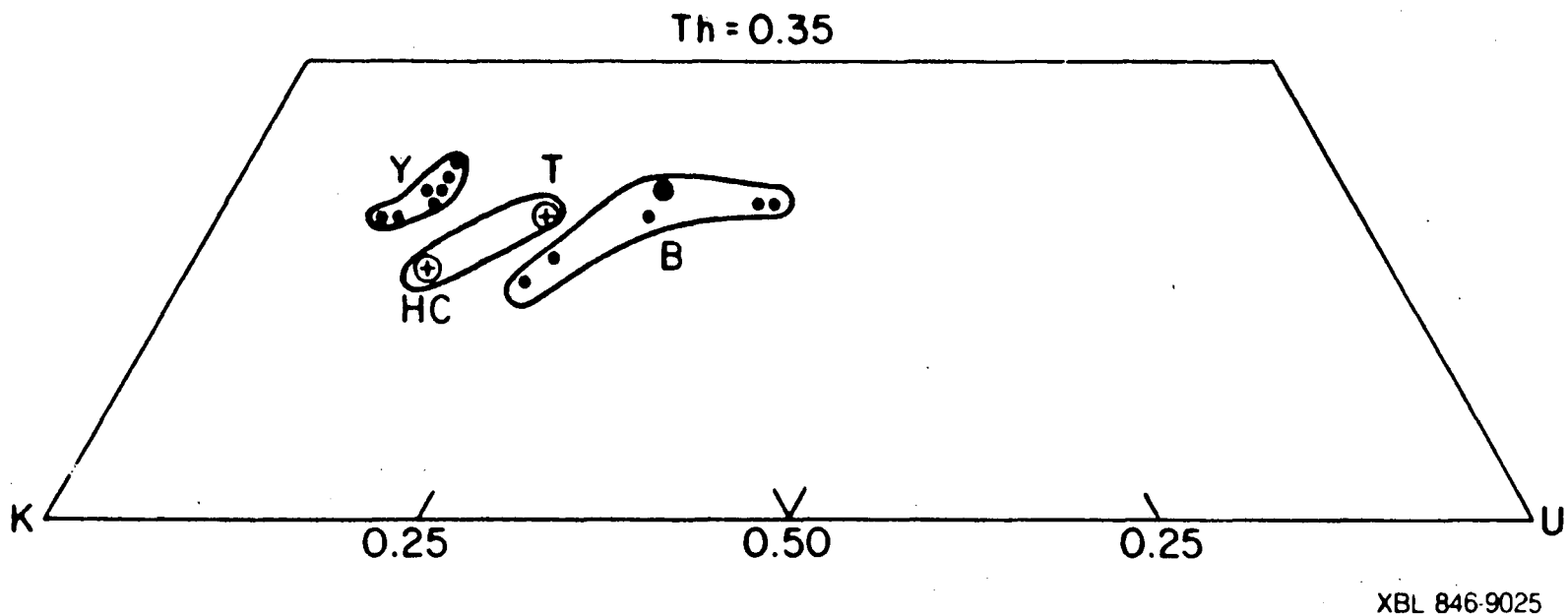


Figure 9.

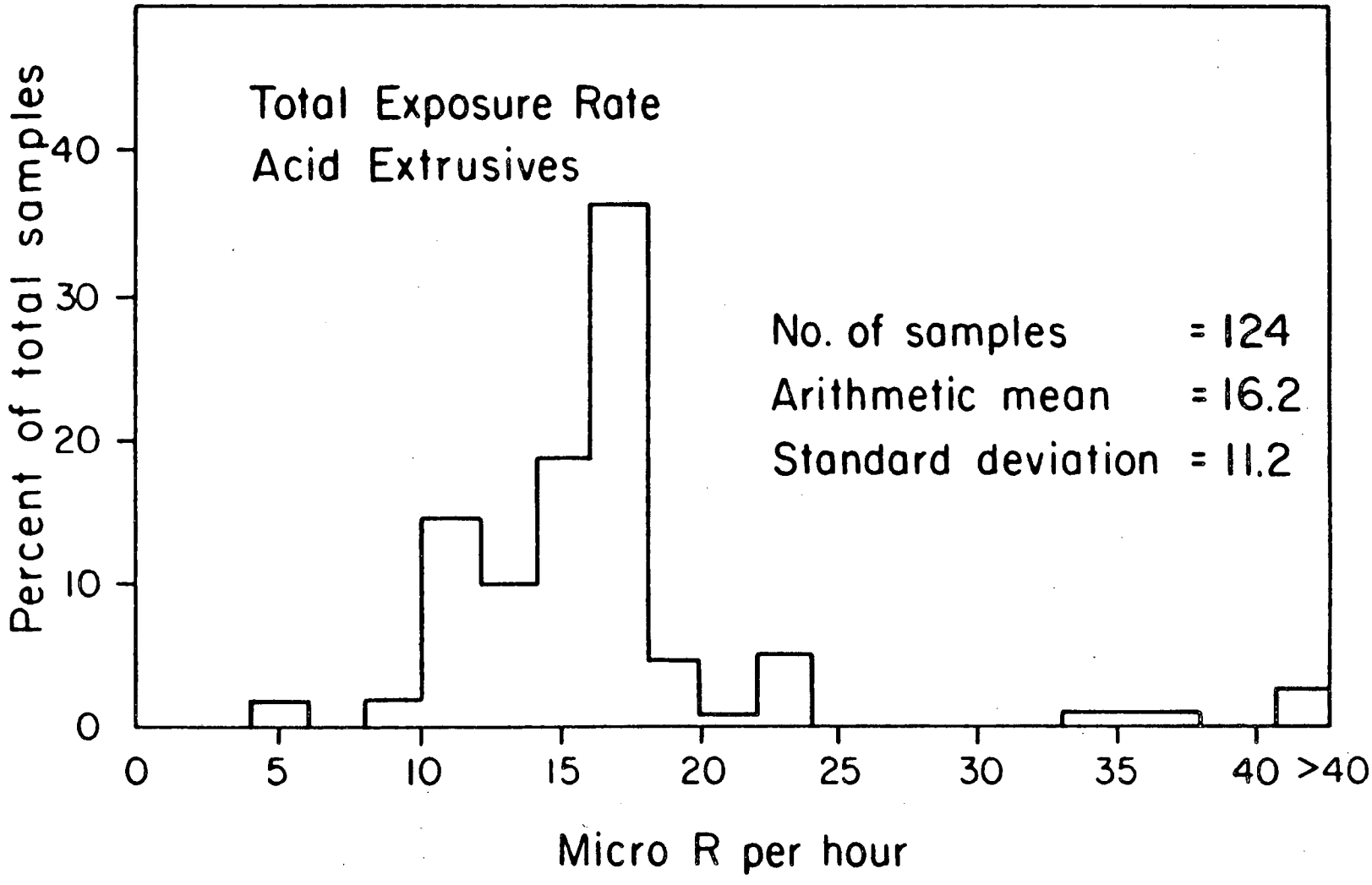


Figure A-1.

XBL 846-9017

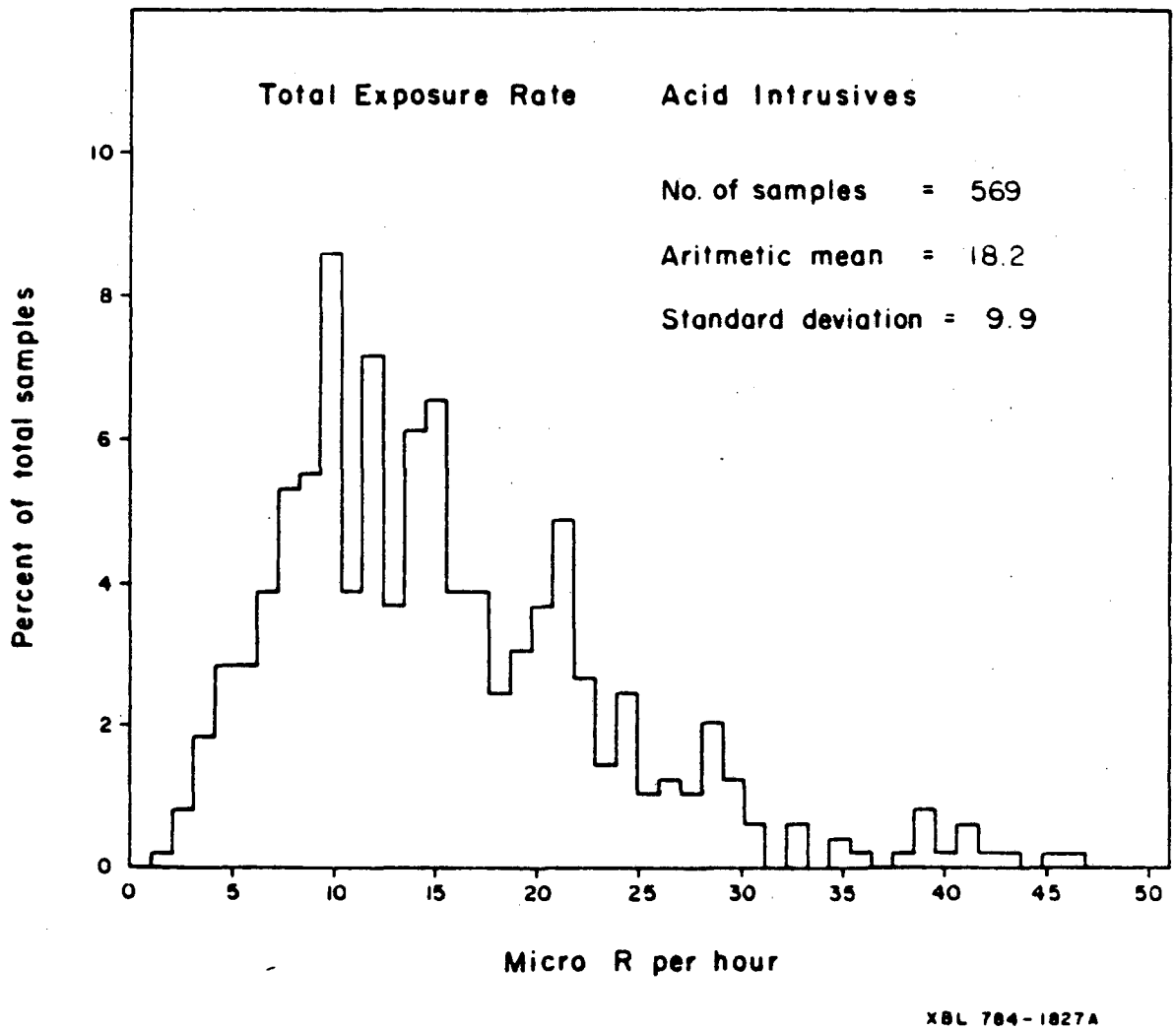
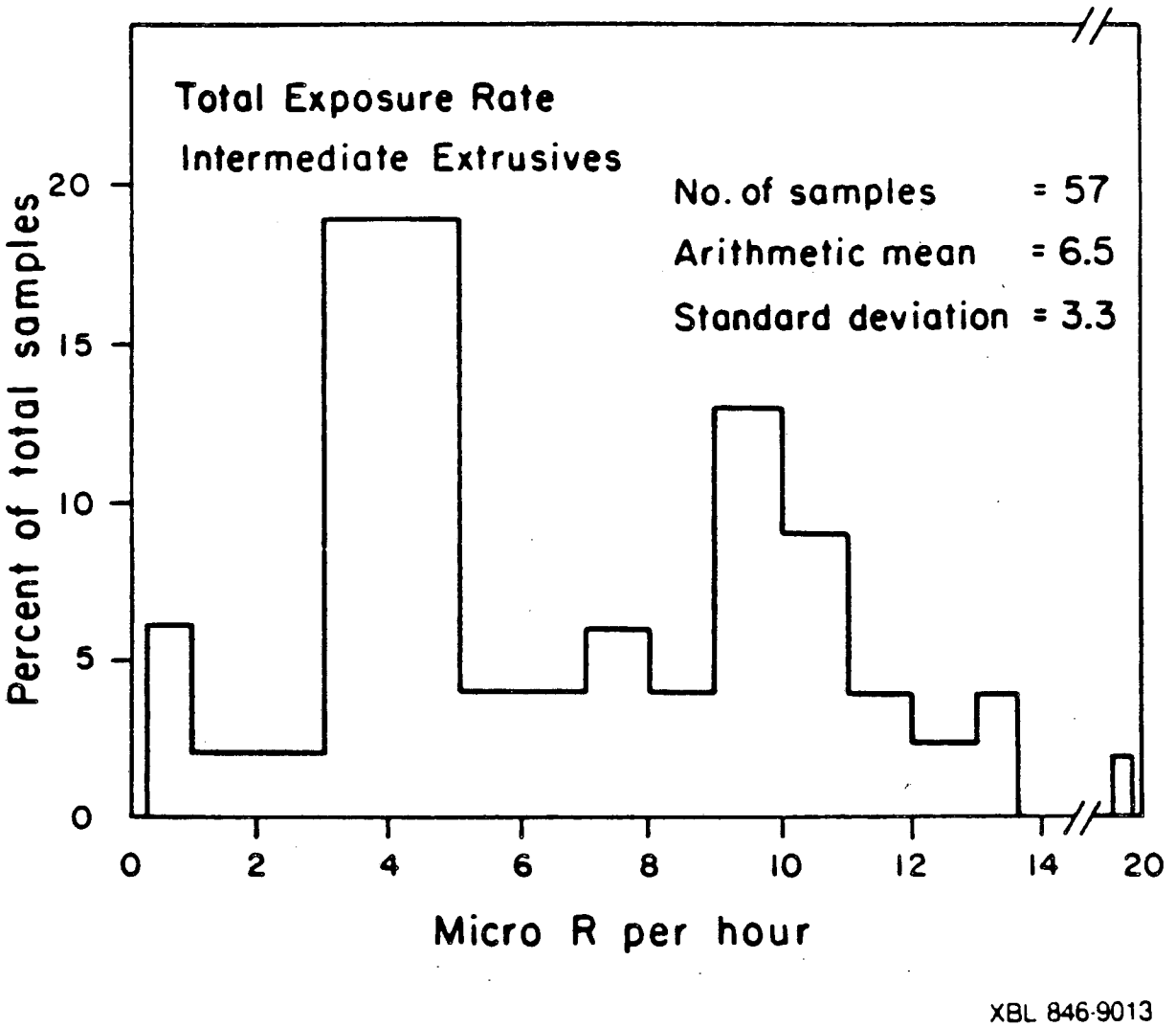

Total Exposure Rate
Acid Intrusives
No. of samples = 569
Aritmetic mean = 18.2
Standard deviation = 9.9
Percent of total samples
0
2
4
6
8
10
0
5
10
15
20
25
30
35
40
45
50
Micro R per hour
XBL 784-1827A

Figure A-2.



XBL 846-9013

Figure A3.

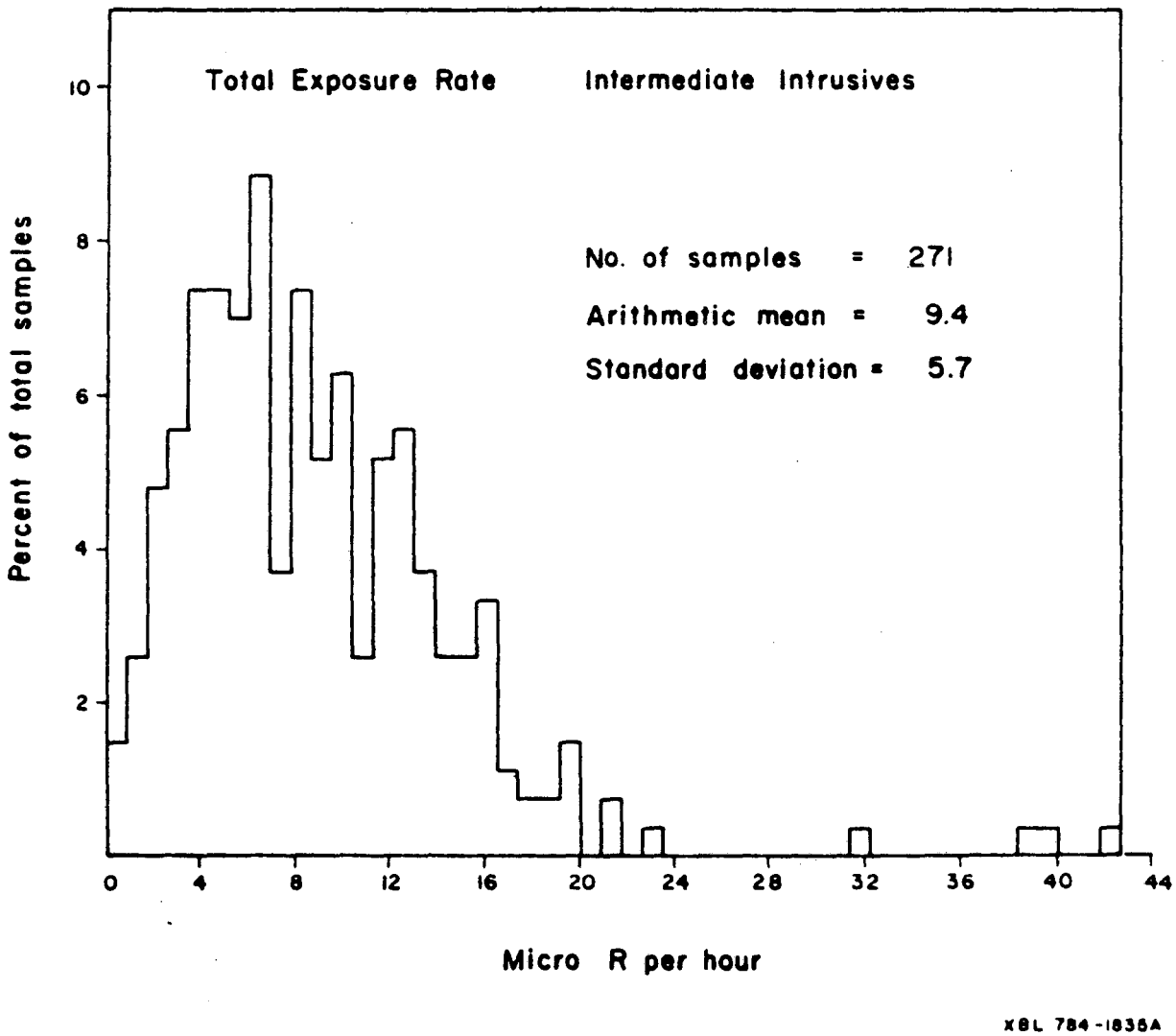
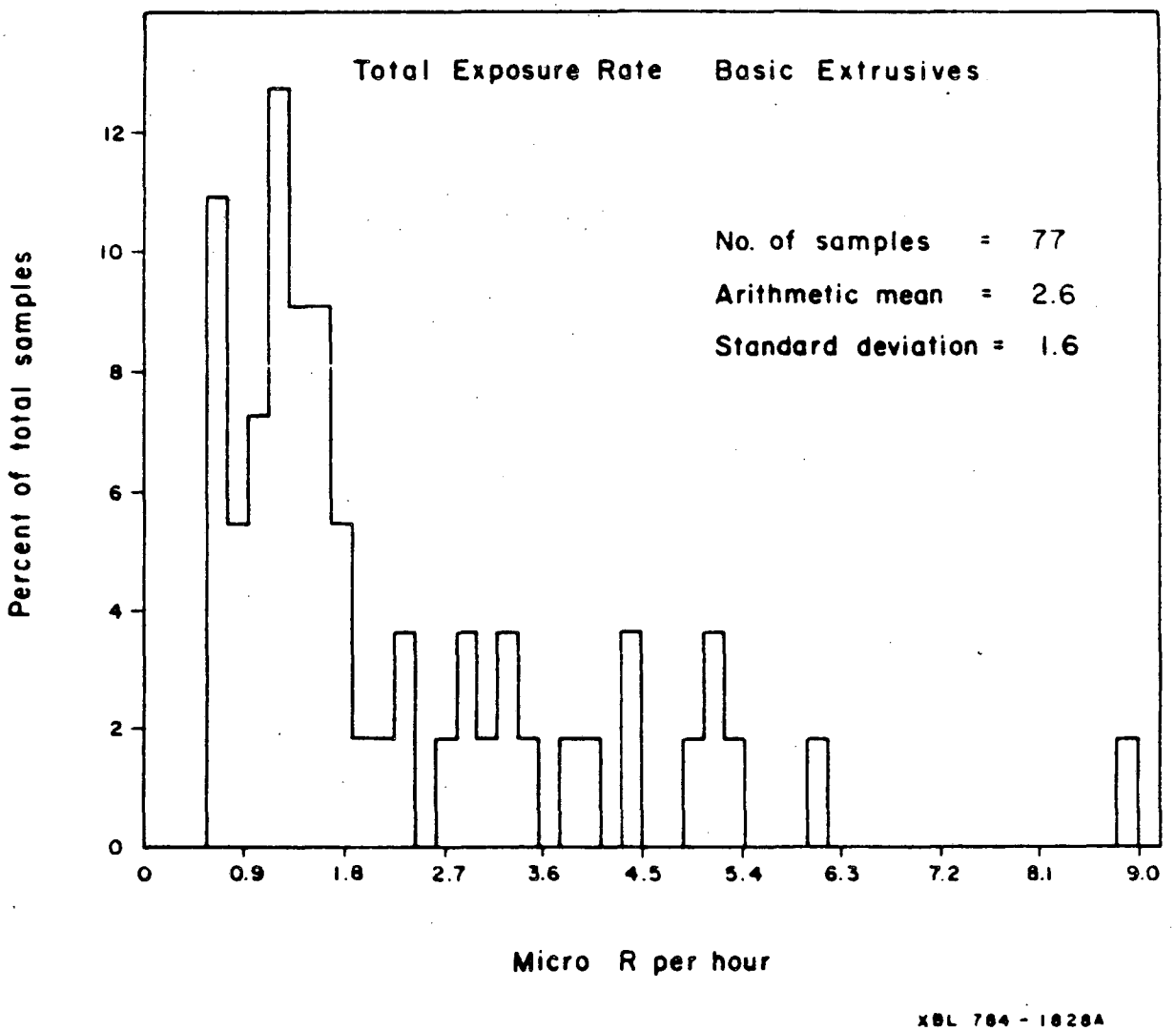

Total Exposure Rate
Intermediate Intrusives
No. of samples = 271
Arithmetic mean = 9.4
Standard deviation = 5.7
Percent of total samples
10
8
6
4
2
0
4
8
12
16
20
24
28
32
36
40
44
Micro R per hour
XBL 784-1835A

Figure A-4.



XBL 784 - 1828A

Figure A-5.

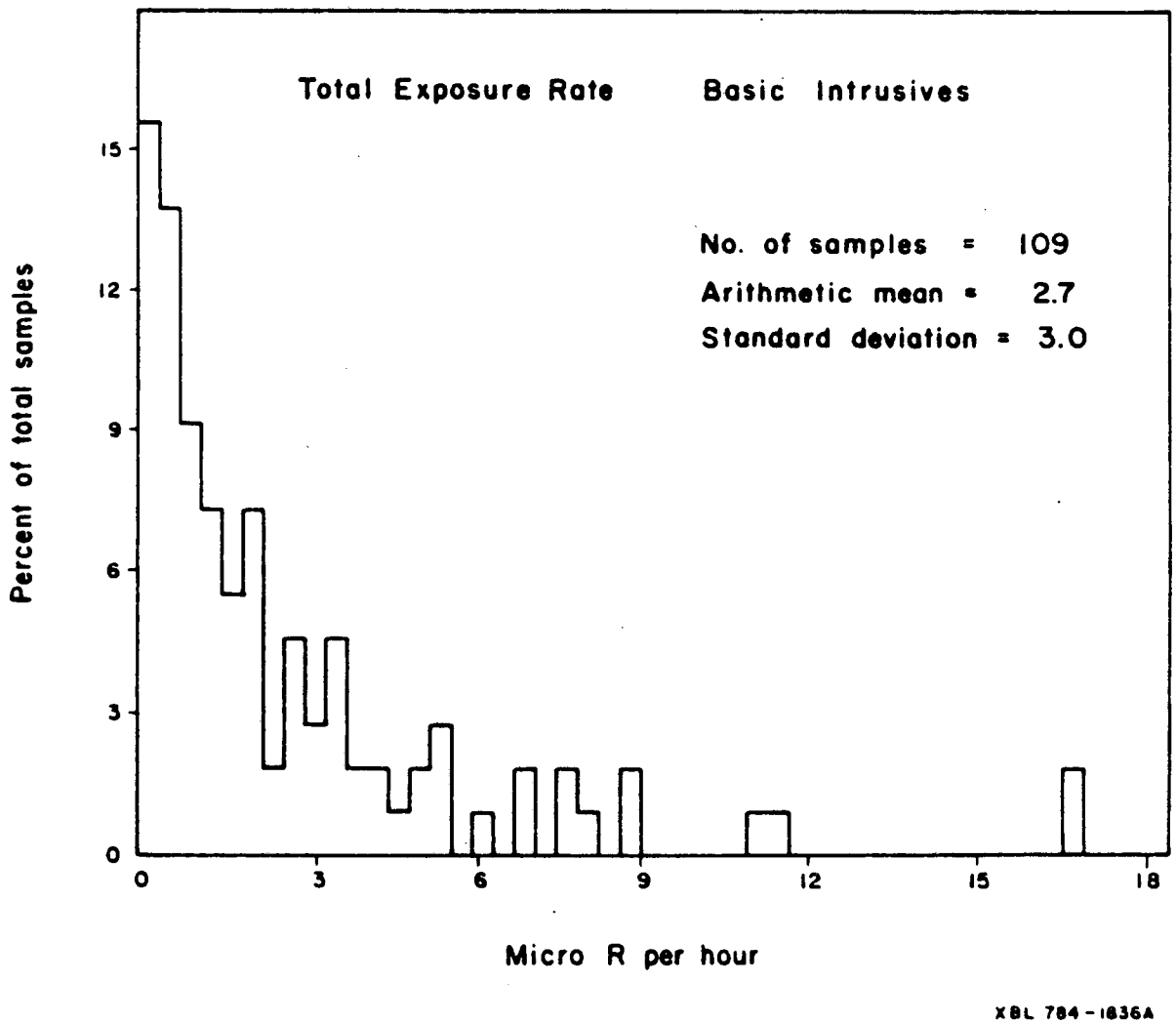

Total Exposure Rate
Basic Intrusives
No. of samples = 109
Arithmetic mean = 2.7
Standard deviation = 3.0
Percent of total samples
0
3
6
9
12
15
0
3
6
9
12
15
18
Micro R per hour
XBL 784-1836A

Figure A-6.

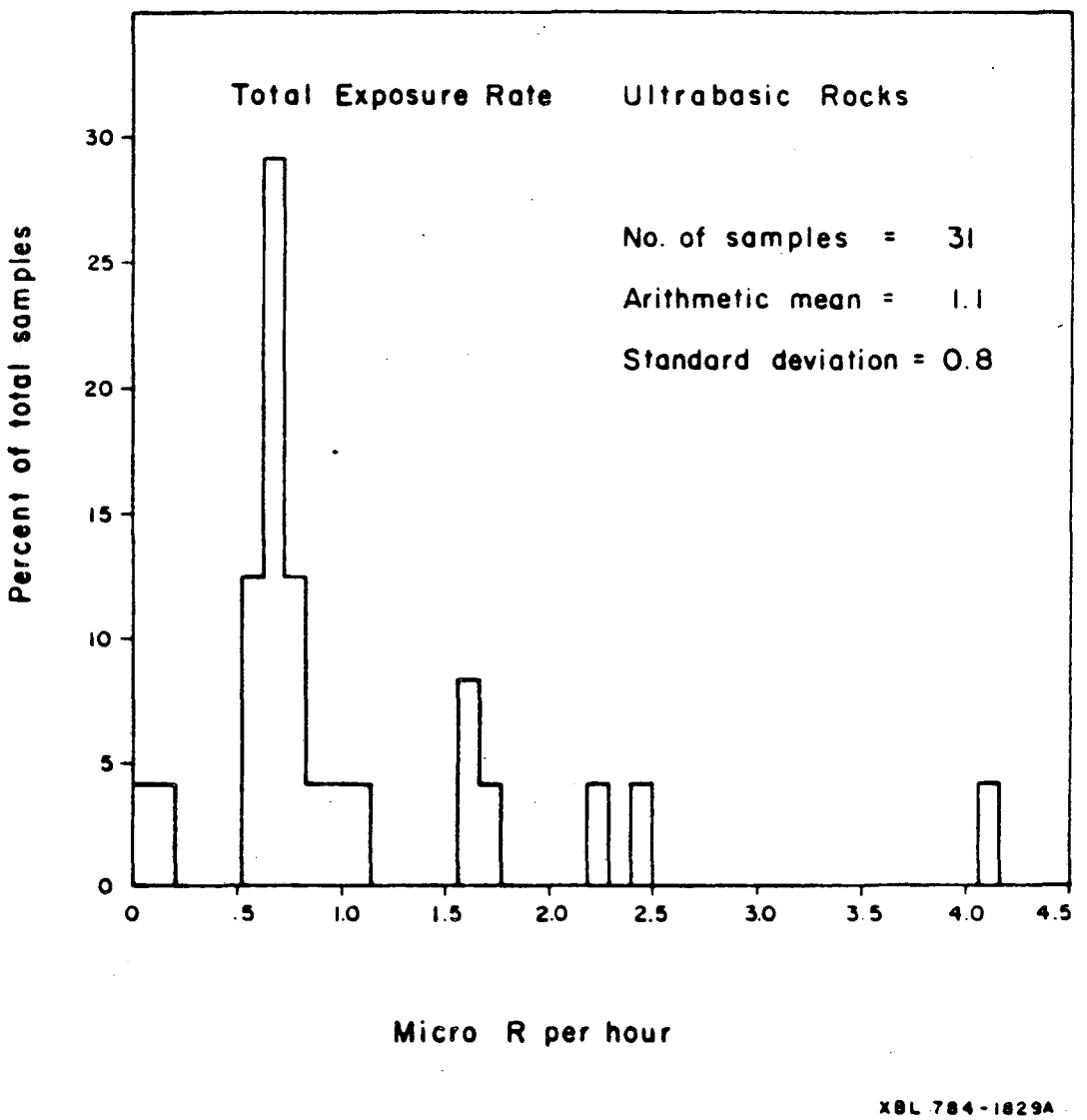
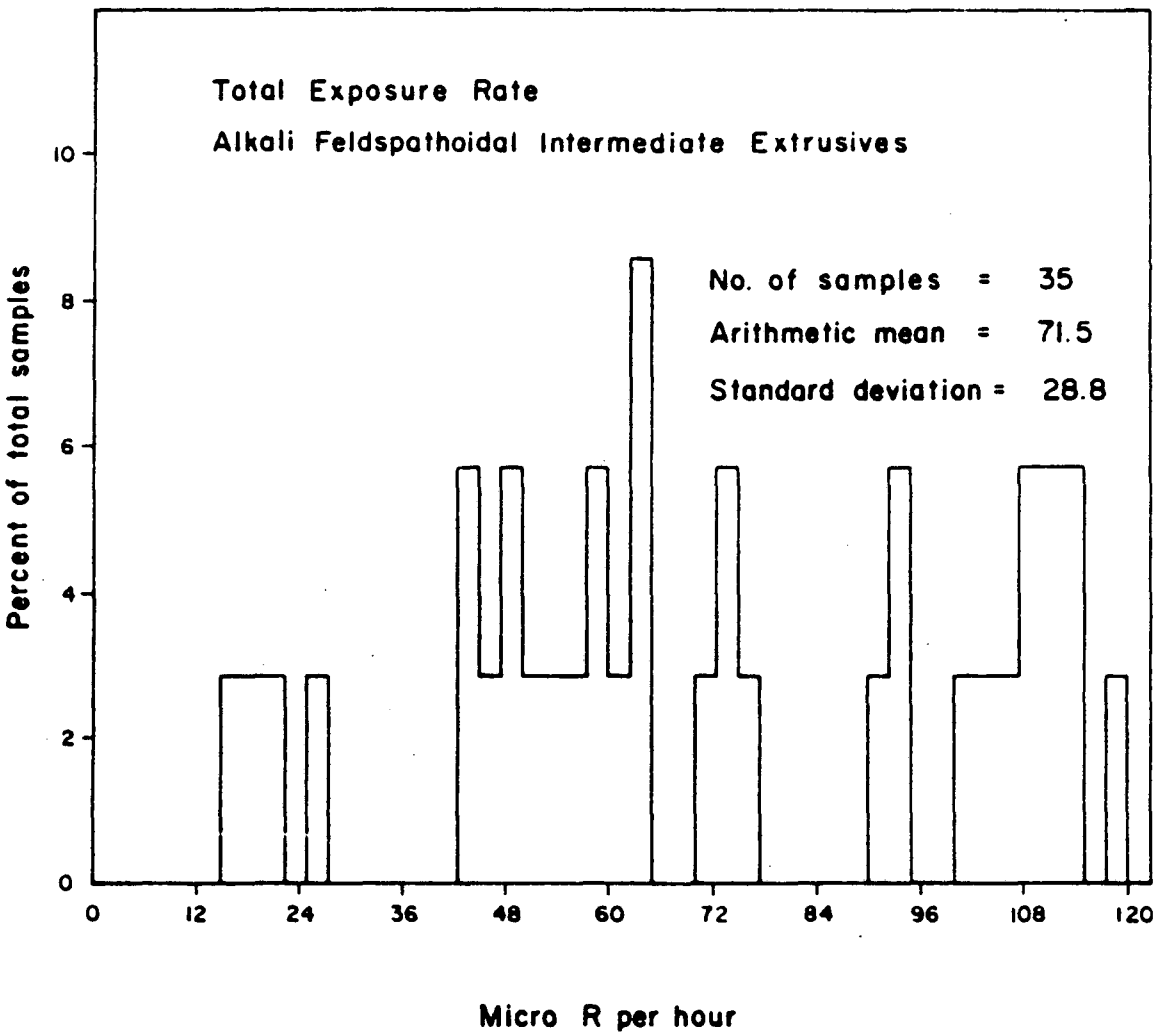
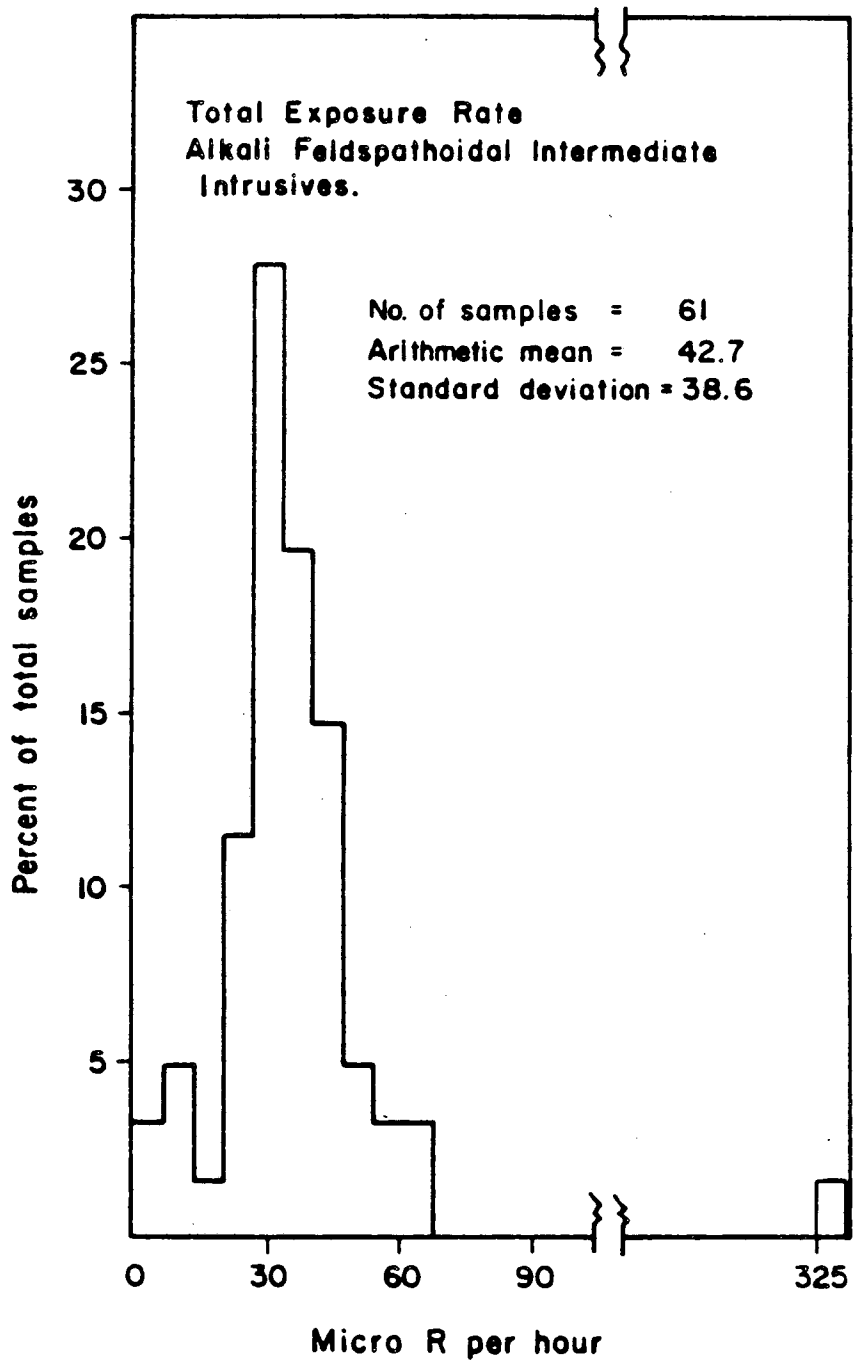

Total Exposure Rate
Ultrabasic Rocks
No. of samples = 31
Arithmetic mean = 1.1
Standard deviation = 0.8
Percent of total samples
30
25
20
15
10
5
0
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Micro R per hour
XBL 784-1829A

Figure A-7.



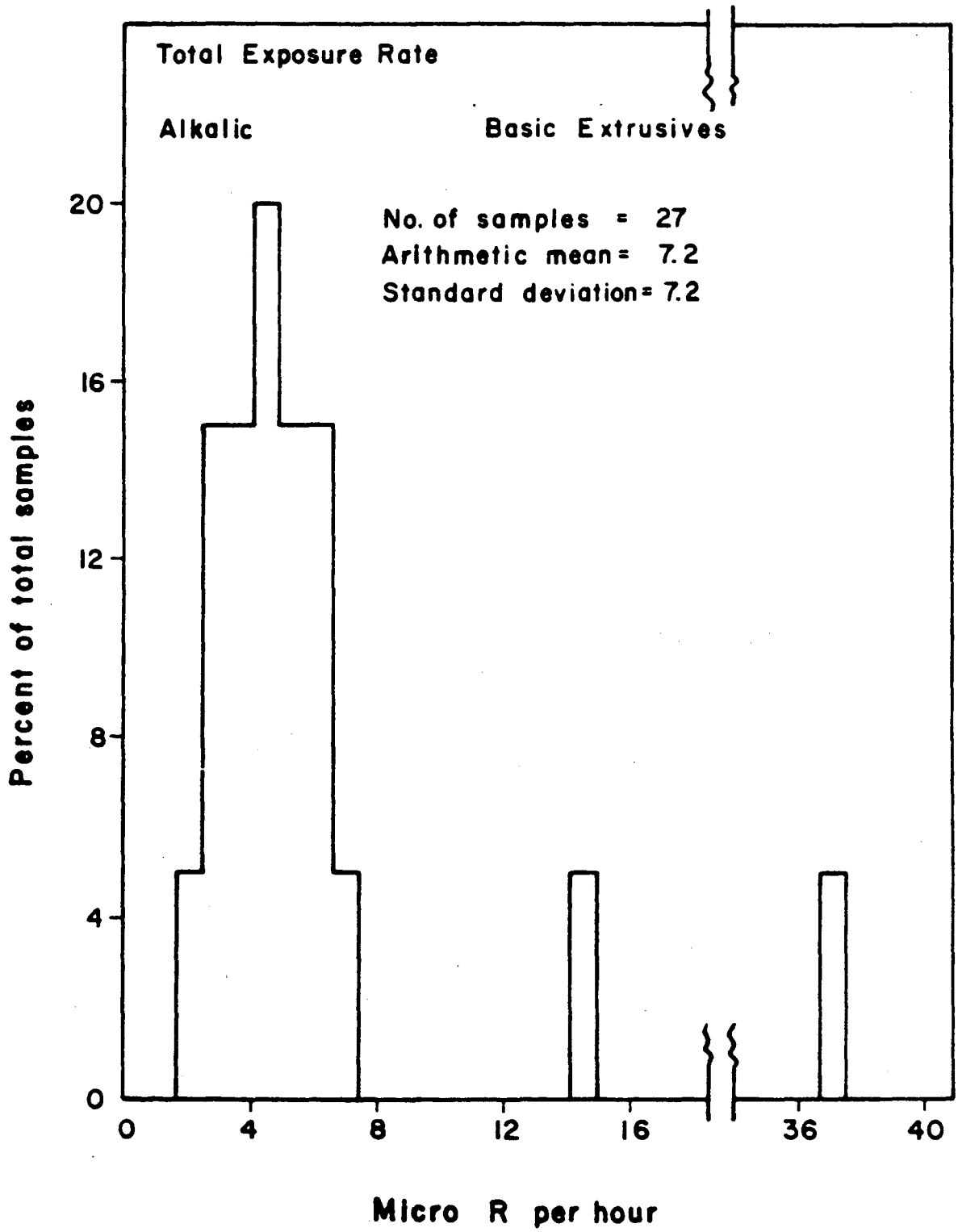
XBL 784-1833A

Figure A-8.



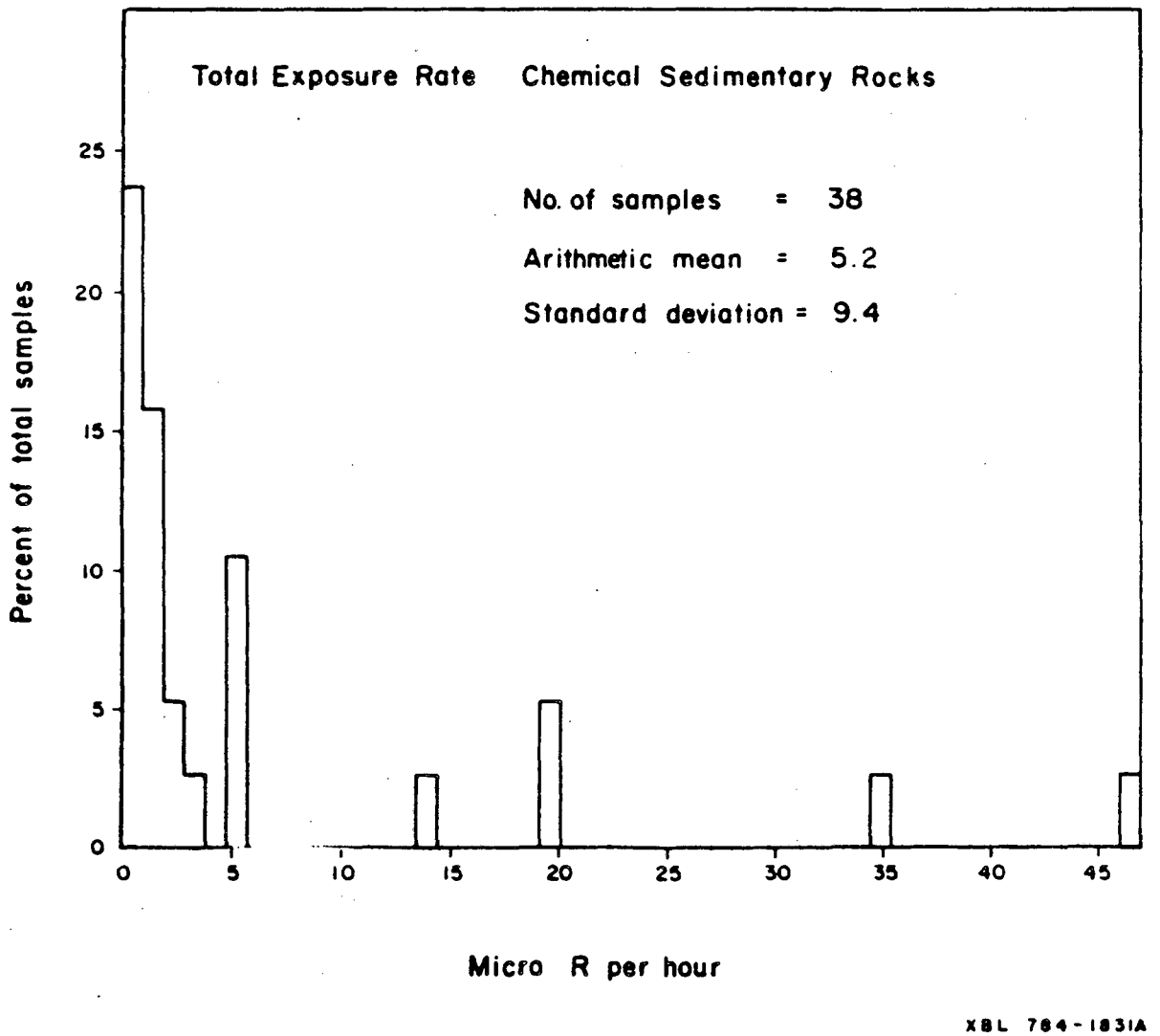
XBL 784-1834A

Figure A-9.



XBL 784 - 1824A

Figure A-10.



XBL 784-1831A

Figure A-11.

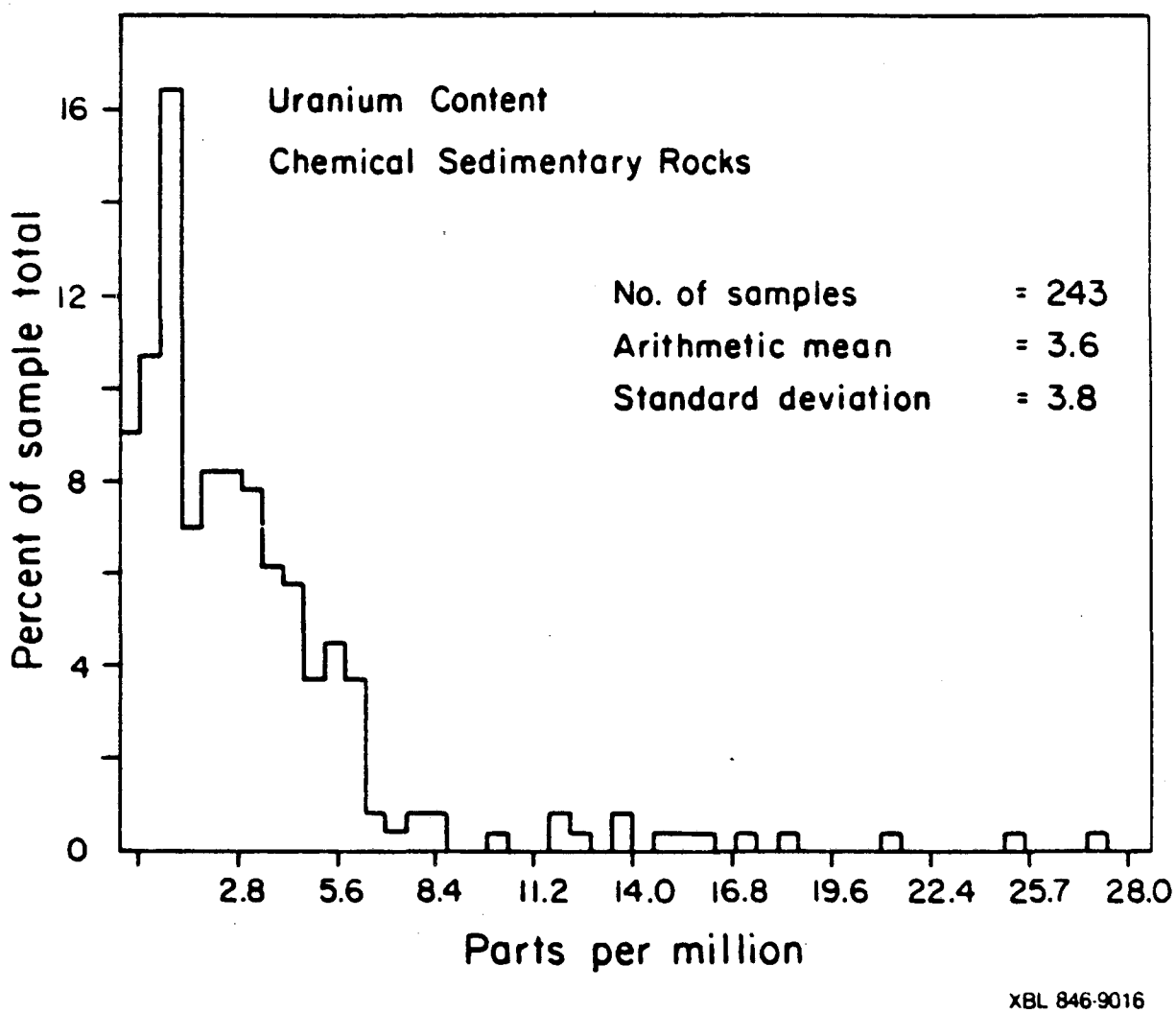

Uranium Content
Chemical Sedimentary Rocks
No. of samples = 243
Arithmetic mean = 3.6
Standard deviation = 3.8
Percent of sample total
0
4
8
12
16
2.8
5.6
8.4
11.2
14.0
16.8
19.6
22.4
25.7
28.0
Parts per million
XBL 846-9016

Figure A-11a.

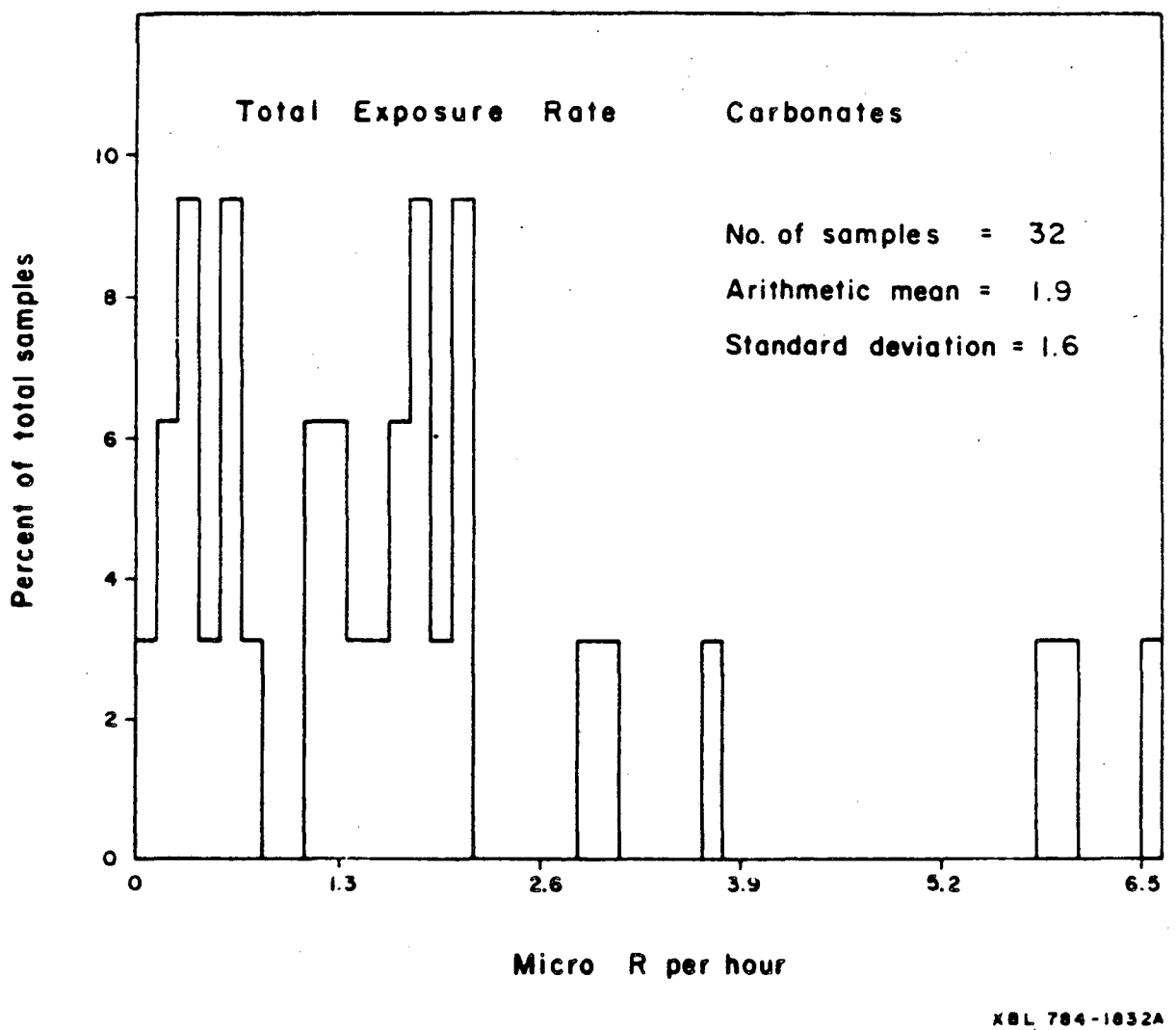

Total Exposure Rate
Carbonates
No. of samples = 32
Arithmetic mean = 1.9
Standard deviation = 1.6
Percent of total samples
0
2
4
6
8
10
0
1.3
2.6
3.9
5.2
6.5
Micro R per hour
XBL 784-1832A

Figure A-12.

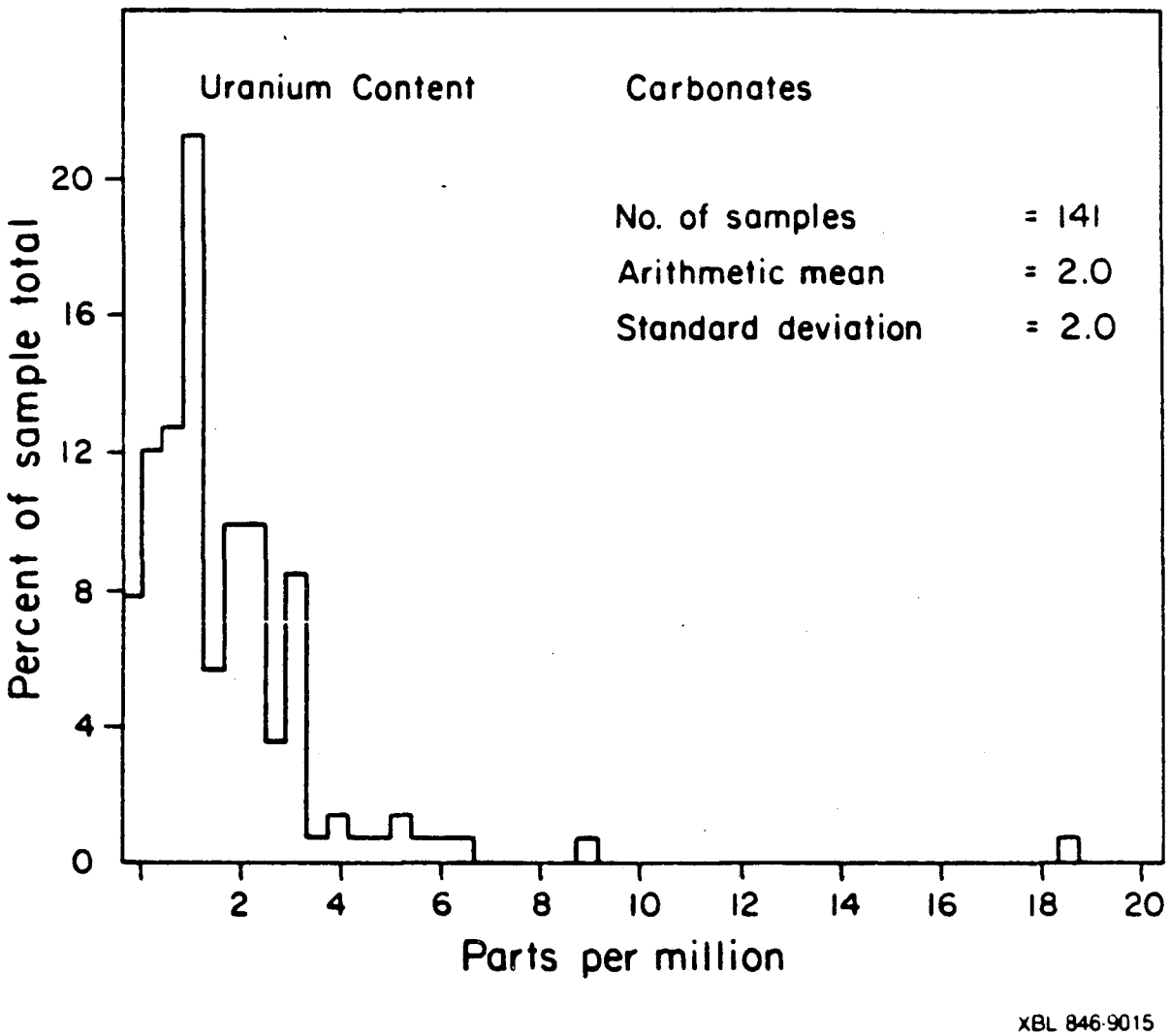

Uranium Content
Carbonates
No. of samples = 141
Arithmetic mean = 2.0
Standard deviation = 2.0
Percent of sample total
0
4
8
12
16
20
2
4
6
8
10
12
14
16
18
20
Parts per million
XBL 846-9015

Figure A-12a.

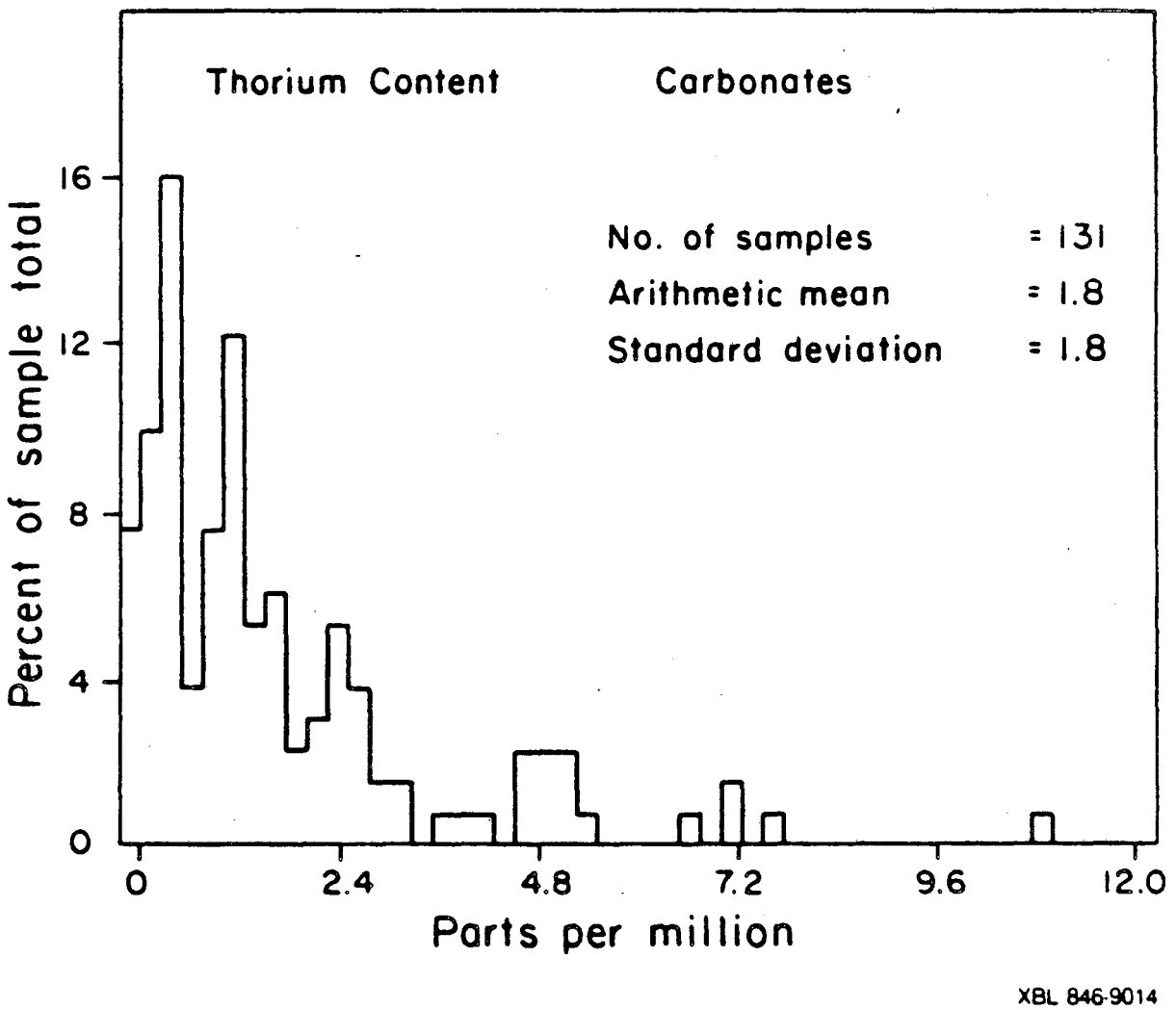
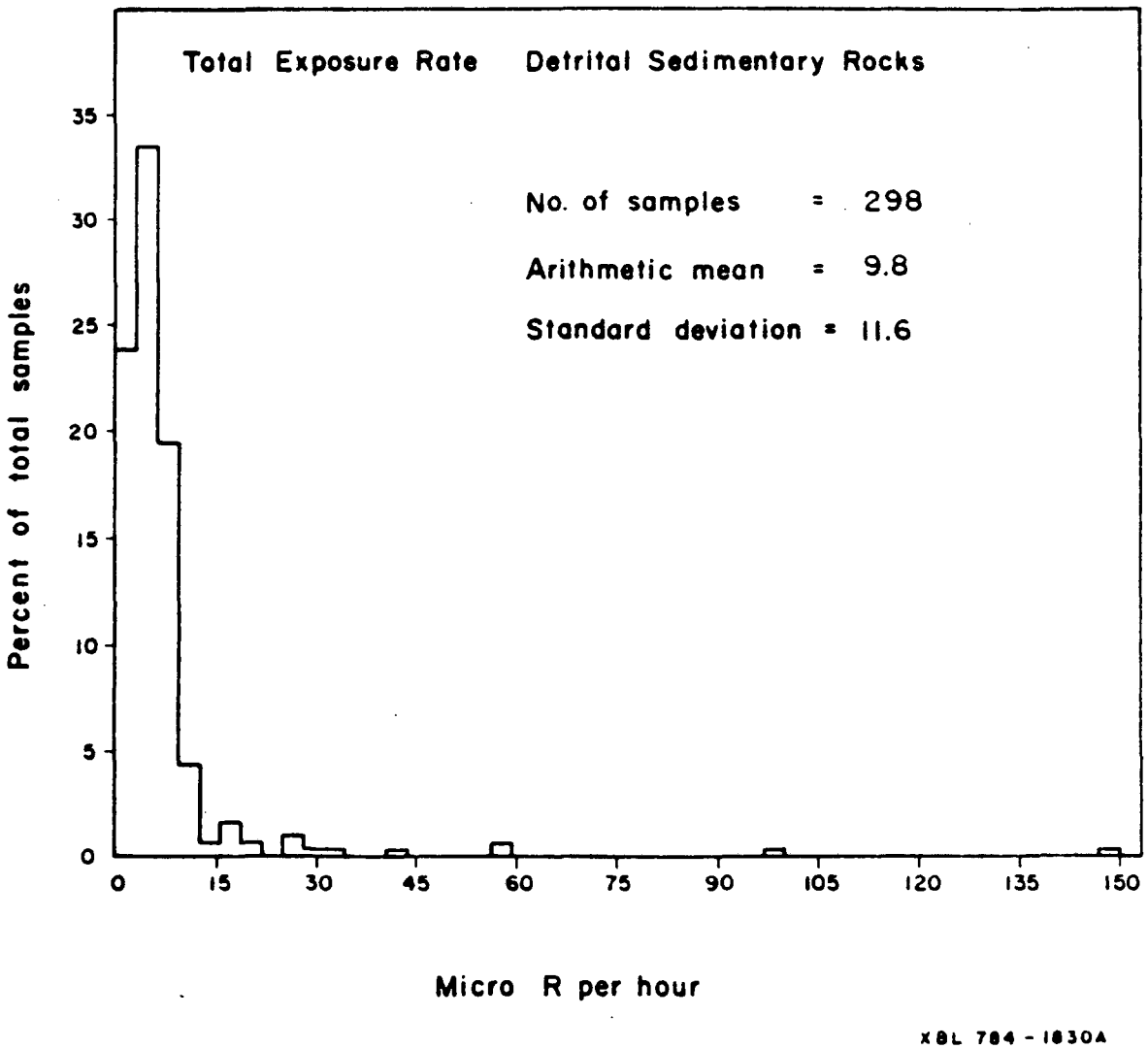

Thorium Content
Carbonates
No. of samples = 131
Arithmetic mean = 1.8
Standard deviation = 1.8
Percent of sample total
16
12
8
4
0
0
2.4
4.8
7.2
9.6
12.0
Parts per million
XBL 846-9014

Figure A-12b.



XBL 784-1830A

Figure A-13.

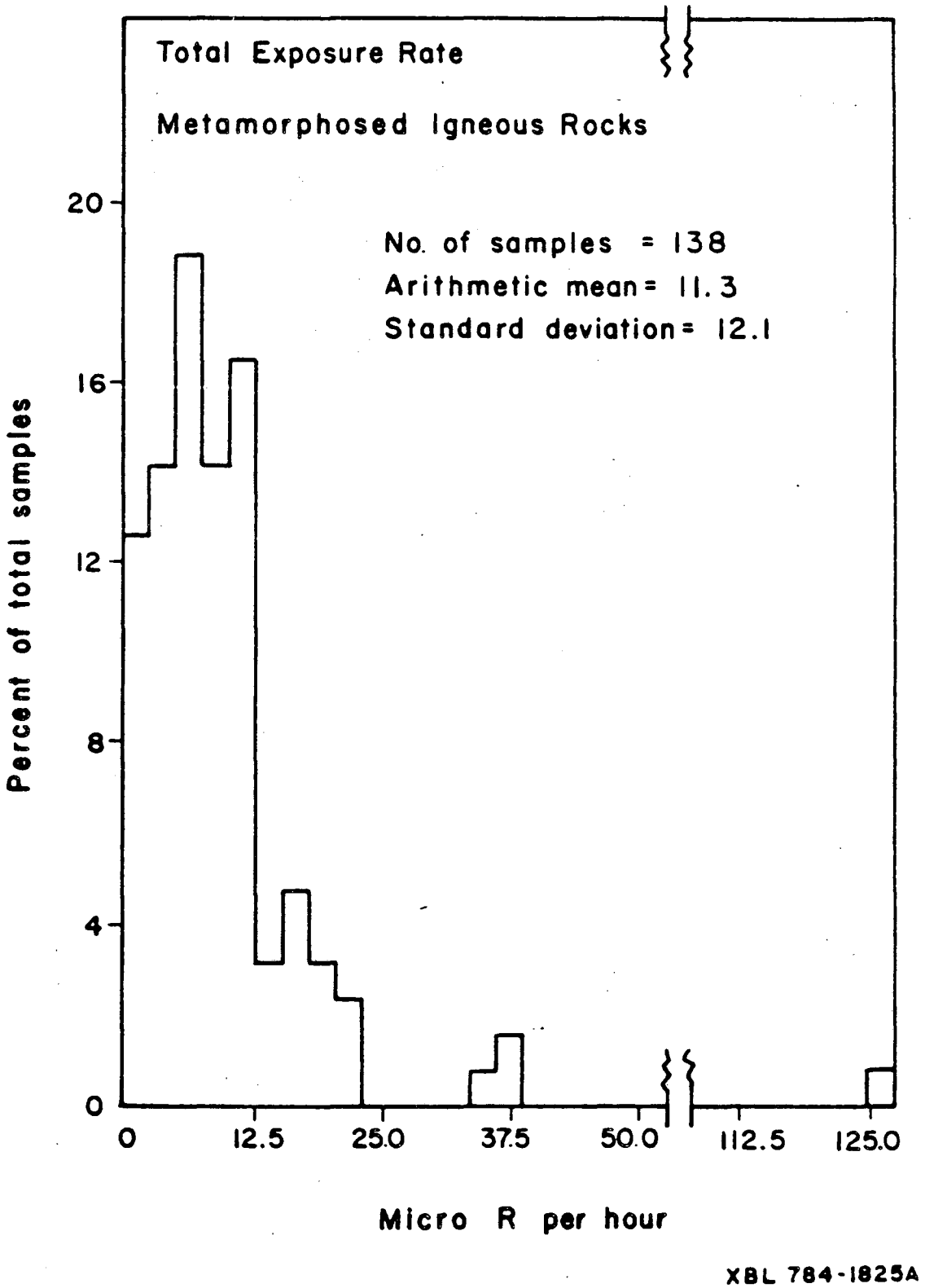

Total Exposure Rate
Metamorphosed Igneous Rocks
No. of samples = 138
Arithmetic mean = 11.3
Standard deviation = 12.1
Percent of total samples
20
16
12
8
4
0
0
12.5
25.0
37.5
50.0
112.5
125.0
Micro R per hour
XBL 784-1825A

Figure A-14.

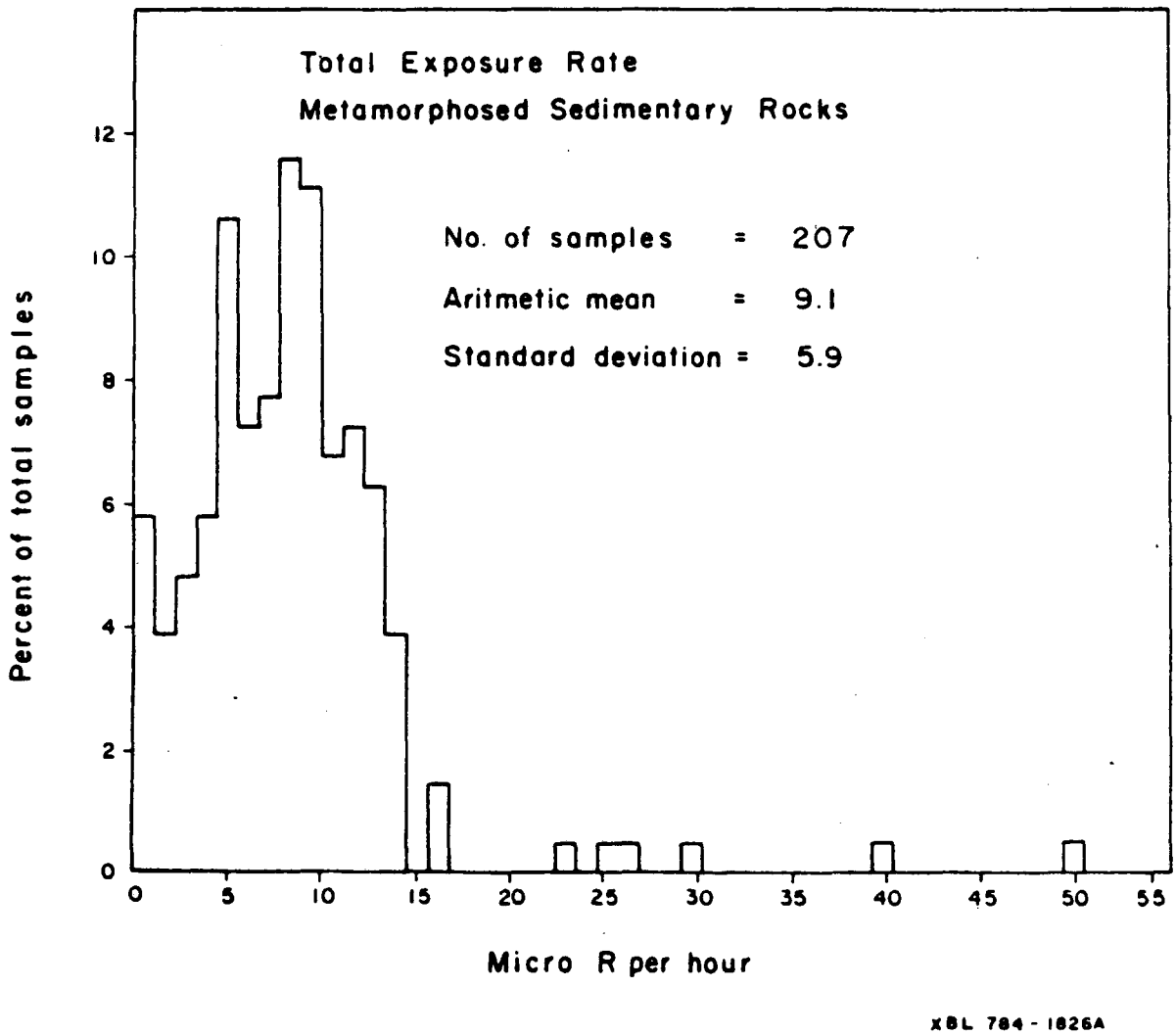

Total Exposure Rate
Metamorphosed Sedimentary Rocks
No. of samples = 207
Aritmetic mean = 9.1
Standard deviation = 5.9
Percent of total samples
0
2
4
6
8
10
12
0
5
10
15
20
25
30
35
40
45
50
55
Micro R per hour
XBL 784 - 1826A

Figure A-15.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720