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CAUSES OF VARIATIONS IN RADIOACTIVITY DATA.

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ABSTRACT. Because of the geochemical and geothermal importance of radioactivity data, a report is made of recent observations on the variations in the radioactivity of rocks. Variations by a factor of fifty or more are sometimes found in the radioactive content from specimen to specimen. The greatest differences occur in certain granitic rocks, the least in some sedimentary sections. Regional variations are not so pronounced, but relatively highly radioactive provinces are indicated in Colorado and Great Slave-Great Bear Lakes areas and relatively barren areas in parts of Ontario and Quebec. Some laws governing the distribution of radioactive elements are indicated by the discovery that the radioactive elements are more concentrated near the border than at the core of the Bourlamaque batholith, and by additional evidence of a relationship between radioactivity and proportion of accessory minerals, chiefly apatite and zircon. Variations in the radioactivity of granitic rocks, at least, may be due entirely to differences in the amounts of such minerals in which radioactive elements are concentrated. The need for more radioactivity data is emphasized.

INFORMATION concerning the distribution of radioactive elements in rocks is of considerable geochemical interest, but such knowledge is of greatest importance geophysically because of the influence of radiogenic heat on the geothermal history of the earth.

Nearly ninety per cent of the heat energy from radio-active disintegration in rocks is due to alpha-ray emission (most of the remainder due to beta- and gamma-rays is closely related by the expression $\frac{a+\beta+\gamma}{a} = 1.125$). Alpha-ray measurements, then, afford a direct means of determining H′, the rate at which radiogenic heat is being produced from the uranium and thorium series in rocks. For completeness, the small quantity of energy liberated by the beta-ray disintegration of potassium isotope K^{40} must also be considered; then the total rate of heat production,

$$H = 2.15\ a + 5\ K \text{ cals./gm./M.y.}$$

where M.y. = million years

a = activity = alpha-rays/mg./hour

K = grams of potassium per gram.

For practical purposes, however, an assumed value of the potassium-activity ratio, K/a = 2.06, introduces no significant error and the simple equation

$$H = 2.25\ a \text{ cals./gm./M.y.}$$

may be employed when the potassium content is not known.

Recently a preliminary survey of the heat produced in various rocks has been made using this method.[1]

For major intrusive bodies the results have indicated heat values somewhat lower than previous estimates made from rather meagre data. However, some alarming differences in radioactivity among specimens from the same rock formation, and even among separate samples from the same specimen, have suggested that a closer study be made of the distribution of radioactivity in rocks, and of the significance of sampling. Several investigations of the distribution of radioactivity among the different mineral constituents of rocks have already been made[2] and detailed studies of the distribution of radioactivity in granite and granodiorite batholiths are now in progress.

In this present paper some recent observations on variations in the radioactivity of rocks are made.

ACCURACY OF RADIOACTIVITY MEASUREMENTS.

Instruments for the detection of radioactive disintegrations have steadily improved with time, and concurrently advances in experimental technique have been made (Plate 1). It is therefore possible today to make more precise analytical measurements and to detect much smaller quantities of radioactive material than was possible in the past. A few years ago a series of intercalibrations and intercomparisons helped to establish the reproducibility and reliability of recent experimental methods,[3, 4] and to reveal discrepancies in earlier results.

[1] Keevil, N. B.: 1943, Radiogenic Heat in Rocks, Jour. Geol., Vol. 51.

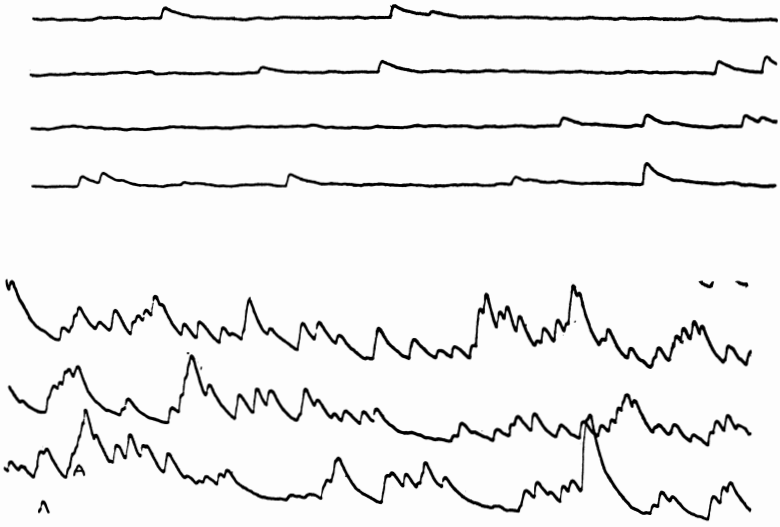
[2] Keevil, N. B.: 1938-1943, Amer. Jour. Sci.

[3] Evans, R. D., Goodman, C., Keevil, N. B., Lane, A. C., and Urry, W. D.: 1939, Intercalibration and Comparison in Two Laboratories of Measurements Incident to the Determination of the Geological Ages of Rocks. Phys. Rev. 55, 931-946.

[4] Evans, R. D. and Goodman, C.: 1941, Radioactivity Measurements of Rocks, Bull. G. S. A., Vol. 52, pp. 470-477.

Intercomparisons of analytical results have revealed differences as great as a factor of one hundred between different investigators. These have been attributed to various causes. Recent work has shown earlier results to have been frequently too high due to contamination by foreign radioactive material, to improper correction for extraneous electrical effects, and to inaccurate calibration. These difficulties seem to have been eliminated in present-day technique.

No more sensitive method of detection is possible than that of observing individual disintegrations of nuclei of radioactive atoms. Sections of continuous records of alpha-ray pulses, automatically and photographically recorded at the University of Toronto, are shown in Text Fig. 1.



Text Fig. 1. Upper: "Background" record obtained from a blank disc. Lower: Record after sample deposit is made on disc. At A, six pulses in rapid succession can be seen.

More than four thousand alpha-ray records (usually recorded for more than six hours) have been obtained in this laboratory. Such records are particularly useful in geological research because they record the rate of production of helium atoms and, for practical purposes, the rate of production of radiogenic heat.[1] The method also has the advantage of being independent of radioactive standards.[3] By determining the rate of alpha-ray emission from rock surfaces of known areas

it is possible to detect the equivalent of 10^{-13} gm. Ra per gm. and 10^{-7} gm. per gm. of UI and Th. Alpha-ray measurements on thoron and radon liberated from weakly active rocks permit the analysis of still smaller quantities: 10^{-15} gm. Ra, 10^{-8} gm. UI, and 10^{-8} gm. Th.

Due to the statistical nature of radioactive disintegration the accuracy of a determination by an alpha-counting method depends upon the length of observations. Another limitation to the accuracy obtainable in these geophysical problems is prescribed by the natural inhomogeneity of geological materials. For ordinary rocks five or more hours of recording of sample runs and blanks provide results with a probable error of about ten per cent, satisfactory for most purposes.

VARIATIONS IN RADIOACTIVITY DATA.

Examples of variations in the radioactive content of particular bodies are legion, and only a few examples will be given here. While duplicate determinations on rock samples frequently check remarkably well, small differences are usually found, and rarely, variations by a hundred per cent or more are observed. Extreme examples of differences noted for different samples from the same specimen are given in Table I.

TABLE I.

Extreme Examples of Variation in Radioactivity in Individual Specimens.

Rock	Source	Alpha-rays/mg./hr. 1st det.	2nd det.	3rd det.
Granite	Tanganyika	1.68	0.34	4.32
Porphyry	Dome Gold Mines, Ont.	0.08	0.81	0.27
Norite	Yellowstone Park	0.19	0.27	0.45
Hornblende concentrate	Red Lake, Ont.	1.01	0.13	0.26

The larger variations in granitic rocks may be due to irregular localization of radioactive elements in small crystals of accessory minerals along interstices in rocks, as suggested by Text Fig. 3.

The specific radioactivity may have even greater variance when several specimens are investigated. This discrepancy is most characteristic of specimens from large intrusive bodies, particularly granite batholiths. A few examples chosen because of their extreme variation are listed below (Table II).

TABLE II.

Local Variations in Radioactivity.

Rock	Source	Alphas/mg./hr. 1st spec.	2nd spec.	3rd spec.
Granites	Tanganyika	0.1	1.4	3.0
Syenites	Adirondacks, N. Y.	0.05	0.40	1.17
Granodiorite	Bourlamaque, Que.	0.05	0.23	1.33
Porphyry	Porcupine area, Ont.	0.09	0.19	0.78
Lava	Lake District, England	0.39	1.05	3.12
Limestone	Gilman, Colo.	0.07	0.6	5.6

These results are not to be considered typical. The variations are due to several factors, one of which is rock-type. Largest variations are found in the more active granitic rocks, smallest in less active basic rocks. For example, results reported for three groups of diabase samples from the Palisades of New York and New Jersey are as follows: (1) 0.52, 0.48, 0.51; (2) 0.38, 0.31, 0.31; (3) 0.44, 0.41, 0.37, 0.33 and 0.41. Results from an alkali riebeckite granite of moderate activity from Quincy, Massachusetts, were as follows: 1.60, 1.74, 1.82, 2.24, 2.06, 1.61, 2.12, 1.89, 2.04, 1.54, 1.45, 1.75, 1.08, 1.47, 1.90, 2.01, 1.34, 1.61, 1.37, 1.44, 1.48, 1.38, 1.18, 1.32, 1.21, 2.23, 1.46, 1.52, 1.47, 1.27, 1.27, 1.86, 1.29, 1.38, 1.39, 2.05, 1.31, 1.68, 1.50, 1.78, 1.74, 1.33, 1.40, 1.0, 1.0, 1.56, 1.18, 1.35, 2.14, 2.04, 1.92, 1.81, 1.20, 1.43, 1.37, 1.45, 1.29, 1.35, and 1.40; the latter half are the results of special tests on one sample.

The variations in this case and in several other rocks were found to be due in part to the contrasting activities of the constituent minerals,[2] confirming the non-uniform distribution of the radioactive elements. All of the above results, however, emphasize the caution to be exercised in interpreting isolated radioactivity results.

Regional variations, of more general geological import, appear to be less pronounced. Where sufficient data are available, local variations are less impressive when compared with the intermediate statistical (probable) value for the region. These probable values, however, suggest the existence of real differences in radioactivity of various regions. The results of a compilation by A. R. Keevil are tabulated in Table III.

No importance is attached to *small* differences in average or probable activities due to the fact that the limited number of

TABLE III.

Preliminary Survey of Regional Variations in Radioactivity.

Region	Rock Type	Limits of Activity	Average Activity	No. of Determinations	Probable Activity
Southern and Central British Columbia	Granitic	0.004–2.20	1.148	10	1.1 ± 0.5
	Other acidic	0.62 –2.76	1.78	5	1.78 ± 0.4
	Intermediate	0.01 –3.40	1.69	15	1.30 ± 0.7
	Basic	0.21 –0.85	0.37	8	0.3 ± 0.15
	Ultrabasic	0.00 –0.10	0.027	7	0.02 ± 0.01
North and East of Yellowknife, N. W. T.	Granitic	0.06 –3.77	1.947	18	2.5 ± 1.0
	Other acidic	0.83 –2.08	1.45	2	
	Intermediate		0.52	1	
	Basic	0.07 –0.59	0.27	10	0.25 ± 0.06
	Ultrabasic		0.00	1	
Saskatchewan	Granitic	0.877–1.56	1.127	3	1.0 ± 0.5
Manitoba	Granitic	0.18 –2.37	1.04	11	1.0 ± 0.5
	Intermediate	0.51 –0.61	0.56	2	0.56
	Basic	0.03 –0.04	0.03	3	0.03 ± 0.01
Ontario, West	Granitic	0.18 –0.86	0.52	2	0.5 ± 0.3
	Intermediate	0.13 –0.91	0.55	3	0.55 ± 0.1
	Basic	0.00 –0.99	0.46	5	0.46 ± 0.15
Ontario-Sudbury Area	Granitic	2.5 –2.95	2.72	2	2.72 ± 0.3
	Intermediate	1.19 –1.29	1.24	2	1.24 ± 0.1
	Basic	0.31 –2.10	0.818	10	0.70 ± 0.1
Ontario, East	Granitic	0.114–1.19	0.631	18	0.62 ± 0.25
	Other acidic	0.17 –1.34	0.44	25	0.40 ± 0.1
	Intermediate	0.00 –0.74	0.27	5	0.27 ± 0.1

Quebec, West	Granitic	0.08 –1.01	0.42	7	0.42 ± 0.25
	Other acidic		0.93	1	
	Intermediate	0.18 –0.40	0.36	4	0.36 ± 0.1
	Basic	0.15 –0.72	0.43	6	0.50 ± 0.1
	Ultrabasic	0.00 –0.20	0.05	5	0.05 ± 0.02
Newfoundland	Granitic	0.29 –2.31	1.54	4	1.54 ± 0.50
	Other acidic	0.88 –2.75	1.58	8	1.30 ± 0.5
	Intermediate	0.65 –1.96	1.28	4	1.28 ± 0.1
	Basic	0.32 –0.52	0.43	4	0.43 ± 0.02
Maritimes (N. B., N. S.)	Granitic	1.99 –3.30	2.43	3	2.40 ± 0.50
	Intermediate	0.34 –0.42	0.38	2	0.38 ± 0.05
	Basic	0.18 –0.89	0.60	18	0.60 ± 0.1
Eastern States—Me., N. J., N. Y. Penna., Mass., N. C., Tenn., Va.	Granitic	0.17 –7.82	2.02	18	1.8 ± 0.8
	Other acidic	0.18 –7.06	2.86	14	2.5 ± 1.5(erratic)
	Intermediate		1.19	1	
	Basic	0.02 –2.25	0.13	40	0.45 ± 0.20
	Ultrabasic		0.00	1	
Yellowstone Park	Granitic	2.8 –3.2	3.00	2	3.00 ± 0.1
	Other acidic	3.30 –3.60	3.45	3	3.45 ± 0.1
	Intermediate	1.15 –1.80	1.48	3	1.48 ± 0.10
	Basic	0.40 –1.60	0.79	13	0.70 ± 0.30
California and Nevada	Granitic	1.93 –1.97	1.95	2	1.95 ± 0.50
	Other acidic	0.77 –1.46	1.11	2	1.11 ± 0.05
	Intermediate	0.00 –1.79	0.84	9	0.95 ± 0.20
	Basic	0.56 –1.46	0.79	9	0.65 ± 0.05
Northern U. S. A., Michigan and Wisconsin	Basic	0.10 –2.40	0.67	35	0.25 ± 0.10
England, Scotland and Ireland	Other acidic		2.83	1	
	Intermediate		0.26	1	
	Basic	0.44 –1.92	0.98	10	0.78 ± 0.15
South Africa	Granitic	0.12 –3.10	1.58	4	1.58 ± 0.50
	Basic	0.27 –1.64	0.96	11	0.75 ± 0.2

samples studied thus far fails to provide low enough probable errors in many cases. The probable errors in the last column of Table III are intended to show the probable range of inaccuracy. In accordance with the usual definition of probable error, there is a fifty per cent chance that the quoted value lies within the specified limits. It is clear, however, that batholithic bodies in the vicinity of Yellowknife, Northwest Territories, are more radioactive than batholiths in southwestern Quebec. Summarizing, the general features of the distribution of radioactivity in igneous rocks indicated by the data in Table III are as follows:

Acidic intrusives in the Canadian Precambrian Shield show at least a five-fold variation, those near the western borders being more radioactive than those in Quebec and Ontario, which lie some distance within the Shield.

Granites and granodiorites from southwestern Quebec have the lowest activity found for these types of rocks.

Acidic rocks from California, British Columbia, Saskatchewan, Manitoba, Greenland, Newfoundland, Finland, and Tanganyika show intermediate values of activity, while Paleozoic igneous rocks along the eastern seaboard, intrusives in Colorado, some in Yellowstone Park and the Northwest Territories, show the highest content of radioactive elements, as determined by alpha-ray emission from the uranium, actino-uranium, and thorium series.

The contrasts were not so great in the average regional activities of more basic rocks, but in general, similar relationships are indicated. It is worthy of note that the contrast in radioactivity between basic and acidic rocks of a region appears to be smaller the smaller the alpha-ray activity of the rock. Similarly a lesser contrast in the distribution of radioactivity between mafic and felsic minerals was noted, the lower the activity of the rock as a whole. More detailed regional investigations are being made.

DISTRIBUTION OF RADIOACTIVITY IN SEDIMENTS.

Data on the radioactivity of sediments is meagre, and most of the work has been limited to radium alone. Rogers[5] has

[5] Rogers, G. S.: 1921, Helium-Bearing Natural Gas, U. S. Geol. Survey Professional Paper 121, p. 55.

TABLE IV.

Radioactivity of Sedimentary Rocks.

Rock	Source	Range in Activity	No. of Specimens	Average Value	Probable Value
Limestones	New Jersey		17	0.66	0.50 ± 0.20
Limestones	Virginia		3	0.30	
Limestone	Tennessee		3	(1.07)	
Limestone (Permo-Carb.)	Gilman, Colorado		1	(3.35)	
Norfolk limestone (Devonian)	Southwestern Ontario	0.24 –0.89	26	0.58	0.58 ± 0.08
Guelph-Lockport dolomite and limestone	Southwestern Ontario	0.07 –1.37	15	0.69	0.69 ± 0.20
Dolomite	Virginia		8	0.31	
Dolomite	Universal Exploration Mine, Tennessee		3	1.27	
Dolomite	Gilman, Colo.		11	1.26	
Bertie-Akron dolomite (Upper Silurian)	Southwestern Ontario	0.66 –1.59	5	0.95	
Salina shaly dolomite and dolomitic shale (Upper Silurian)	Southwestern Ontario	0.41 –1.38	26	0.88	0.87 ± 0.20
Rochester limy shale and Clinton dolomite (M. Silurian)	Southwestern Ontario	0.903–1.89	3	1.27	
Queenston shale Upper beds (U. Ordovician)	Southwestern Ontario	0.97 –1.85	8	1.42	1.42 ± 0.20
Medina sandy shale	Southwestern Ontario	0.89 –1.32	4	1.05	
Slightly dolomitic sandstone	Gilman, Colorado		1	0.97 ± 0.4	
Sandstone	Gilman, Colorado		1	0.93 ± 0.1	
Sandstone	Zion Canyon, Utah		1	0.80	
Quartzite	Magma Mine, Arizona		1	(2.45)	
Quartzite	Sterling Mine, N. J.		1	(0.67)	
Quartzite	Gilman, Colorado		5	2.65	
Arkose (Permo-Carb.)	Gilman, Colorado		1	(1.62)	
Conglomerate	Foster Lake, Saskatchewan		1	(1.30)	
Silicified sediments	Page Mine, Idaho		2	1.65	
Unconsolidated sediments	Southwestern Ontario	0.54 –1.79	14	1.03	1.07 ± 0.06

( ) Brackets indicate values obtained from records of only one hour duration.

summarized radium analyses made prior to 1921, and a more recent survey has been made by Bell et al.[6] Goodman and Evans[7] quote six complete analyses of sediments based upon radium by determinations by Evans and Raitt,[8] and later determinations of thorium content. Other workers[9] have directed their studies to investigation of the radium content of unconsolidated sediments.

Measurements of the radioactivity of a number of sediments have been made in the laboratory at the University of Toronto. These are listed in Table IV.

A particular study was made by G. P. Crombie of the radioactivity of the Paleozoic sediments of the southwestern peninsula of Ontario in the hope that correlation could be established by comparison of data. Cable-tool samples were examined from two wells about six miles apart in Malahide Township. The results were disappointingly uniform and low throughout Devonian, Silurian, and Upper Ordovician strata, as the profile (Text Fig. 2) shows. This uniformity is interpreted as a result of the conditions of sedimentation. During most of the Paleozoic era the Ontario peninsular area was transitional between two or more well defined basins of deposition (Michigan Basin, Appalachian geosyncline, and, to a lesser extent, the Arctic region). Other sedimentary studies in Silurian[10] and Devonian[11] strata confirm the opinion that in the Ontario peninsula repeated re-working of pre-existing sediments produced a sedimentary section having only minor variations in heavy mineral assemblages and hence in radioactivity. In this particular study the limit of error of the alpha-counting method was of the same order as the variation in values obtained.

[6] Bell, K. G., Goodman, C., and Whitehead, W. L.: 1940, Radioactivity of Sedimentary Rocks and Associated Petroleum. Bull. A. A. P. G., Vol. 24, No. 9, p. 1531.

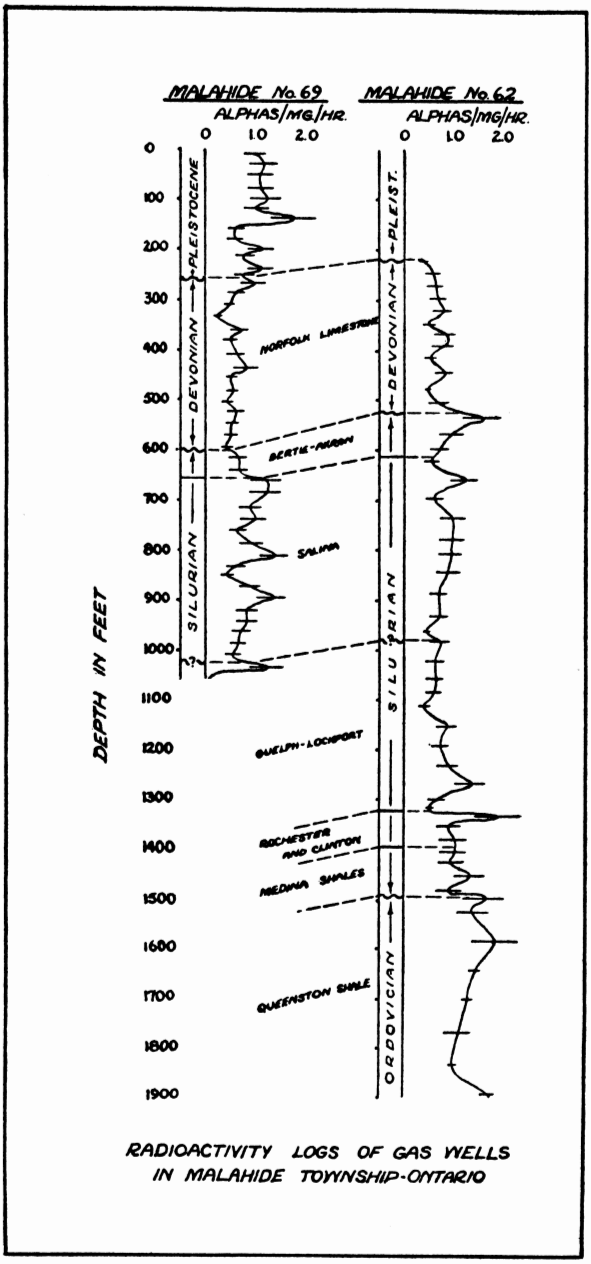
[7] Evans, R. D., and Goodman, C.: 1941, Radioactivity of Rocks. Bull. G. S. A., Vol. 52, p. 474, Table 9.

[8] Evans, R. D., and Raitt, R. W.: 1935, The Radioactivity of the Earth's Crust and Its Influence on Cosmic-Ray Electroscope Observations Made Near Ground Level. Phys. Review, Vol. 48, p. 71.

[9] Piggot, C. S.: 1933, Radium Content of Ocean Bottom Sediments. Amer. Jour. Sci., Vol. 25, p. 229. Gives further references.

[10] Holstein, A.: 1936, Unpublished Thesis, Department of Geology, University of Toronto.

[11] Crombie, G. P.: 1943, Thesis, Department of Geology, University of Toronto.



RADIOACTIVITY LOGS OF GAS WELLS
IN MALAHIDE TOWNSHIP-ONTARIO

Fig. 2.

The Queenston shale samples give values generally higher than those for overlying beds. This variation, while significant, cannot be attributed wholly to the particular source from which this detrital material came (Grabau places the source in the Appalachian highlands), because it is expected that shales will normally have a greater activity than other purer sediments such as sandstone or limestone. The Pleistocene unconsolidated sediments are relatively high in radioactivity.

RELATION BETWEEN RADIOACTIVITY AND MINERALIZATION.

Evidence has accumulated to support the idea of a radioactive aureole extending outward some distance from the loci of deposition of orebodies. Metamorphic aureoles are quite obvious, of course, in many cases, but some which are macroscopically indeterminate can be detected by microscopic study. The recognition of such effects may sometimes be carried further by sensitive radioactivity detection methods. Work of this kind has shown that some ore solutions contain quantities of radioactive elements which can diffuse through the surrounding rock for considerable distances. In many instances where the ore is relatively highly radioactive, rocks adjacent to ore are also high in radioactivity, the amount decreasing away from the ore. This effect was observed in the Page mine, Idaho, and in a suite of specimens from the Gilman mine, Colorado.

In the Coeur d'Alene district, ore from the Black Hawk Curlew vein, Page mine, was found to have an activity of 2.7, wall rock two feet from this vein in the footwall, 1.95, and thirty feet distant the wall rock activity had decreased to 1.25. Similarly in the Tony vein, the activity of ore was 1.38; wall rock two feet from the footwall, 1.25; and 10 feet distant, 1.0.

Several specimens and a suite of country rocks representing all of the geological formations at Gilman were investigated. A wide range of radioactivities was obtained for both country rock (0.00-8.20) and ore (0.20-98.6), the most striking result being the exceptional activity (a=98.6) for a sample of copper-silver ore from a pocket in the twentieth level. Some relationship between activity and mineralization was noted. For instance, the values obtained from Upper Leadville Zebra limestone (Mississippian) and Weber arkosic sandstone (Permo-Pennsylvanian), remote from ore, were 0.20 and 0.65 respectively, while in a section along an ore zone the corresponding

values were 5.80 and 4.25. Probable values for Gilman rock types are given in Table IV. Proof of a close relationship between activity and proximity to ore could not be expected from the material available, but most of the specimens of high activity showed evidence of mineralization or recrystallization.

PRELIMINARY STUDY OF A BATHOLITH.

As part of a systematic investigation of the distribution of radioactive elements in rocks a series of specimens from two batholiths were collected by W. N. Ingham. Examination of more than one hundred samples from the Bourlamaque intrusive mass has indicated the essential features of the distribution of radioactivity within that batholith (Text Fig. 3).

The Bourlamaque granodiorite covers an area of about 75 square miles and lies in the Dubuisson, Bourlamaque, Louvicourt, Pascalis, and Senneville townships east of Lake Dubuisson in Quebec, Canada. Results obtained thus far reveal the inadequacy of one specimen as an indicator of the specific radioactivity of the body (Table II) and it is clear that part of the variation in radioactivity of batholiths is due to conditions of emplacement. The outstanding feature of the preliminary results is the low activity of the central part of the exposed portion and the relatively high activity of the border zone. The average activity in the low central area, which comprises about one-fifth of the exposed area, is 0.14 as compared to 0.81 alphas/mg./hr. for the average activity of the border zone.

The distribution of radioactivity values in Text Fig. 3 shows the general tendency for decreasing radioactivity as the central portion is approached. There was, however, no progressive change from specimen to specimen along any profile. In fact, two high values were found northeast of Herbin lake at points distant from any known part of the outer contact of the intrusive. Examination of thin sections of the granodiorite from this locality suggests, however, that the activities are due to an abnormally high zircon content (Text Fig. 4). A few low values found near the border of the mass in the southeast corner may be attributed to the fact that here a more basic, hybrid phase of the granodiorite is developed adjacent to the invaded volcanics. It is possible that radioactive elements have migrated outward from the intrusive into the adjoining lavas at the time of emplacement of the magma. This concept finds

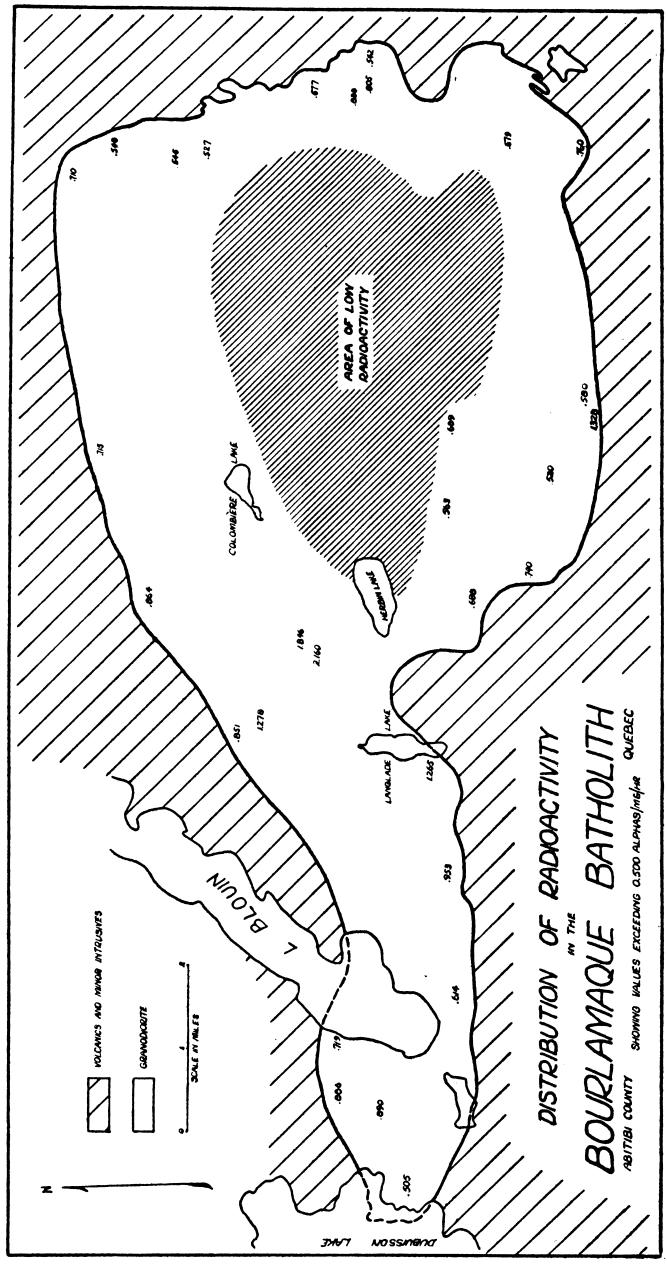

DISTRIBUTION OF RADIOACTIVITY
IN THE
BOURLAMAQUE BATHOLITH
ABITIBI COUNTY SHOWING VALUES EXCEEDING 0.500 ALPHAS/mg/hr QUEBEC
AREA OF LOW RADIOACTIVITY
VOLCANICS AND MINOR INTRUSIVES
GRANODIORITE
SCALE IN MILES
N
COLOMBIÈRE LAKE
LANDRIAULT LAKE
LANDLADE LAKE
DUBUISSON LAKE
L. BLOUIN

Fig. 3.

support not only in the exceptionally high radioactivity of the intruded contact rocks of this area, but also in the highly albitized and silicified condition of these rocks, which alteration may be attributed to diffusion of material from the batholith.

LOCALIZATION OF RADIOACTIVITY.

In the past there has been some question as to whether traces of radioactive elements in rocks were localized or nearly uniformly distributed. Observations of pleochroic halos and small crystals of radioactive minerals have shown a degree of localization in rocks of relatively high activity, but an approach toward uniformity was perceived as the specific radioactivity decreased. The striking results obtained by Larsen and Keevil[12] suggested, however, that radioactive elements may be localized in accessory minerals regardless of the specific activity of a rock. Careful experiments on the Lakeview tonalite, itself emitting less than one alpha-ray per milligram per hour on the average, disclosed that the accessory minerals, zircon, sphene, and apatite emitted 40, 260, and 56 alpha-rays/mg./hr. respectively, accounting for half the radioactivity of the rock. These data, together with earlier reports of petrographic and radioactive studies, suggested that a search be made for possible radioactive accessory minerals in rocks for which activity data and thin sections were available. The results of a preliminary study by A. R. Keevil are shown in Text Fig. 4. A definite relationship between radioactivity and concentration of accessories was found, particularly in acidic rocks. The petrographic descriptions of the samples examined in this series are listed below in the order of decreasing activity:

268-GGE—(5.13) Granite, Ivigtut, Greenland.

> Microperthite occupies 80 per cent of the slide. A little micrographic intergrowth occurs, and some free quartz. Saussurite and sericite are common, kaolinite less abundant. Sericite and muscovite together amount to about 5 per cent. Calcite and fluorite occur in one or two places but magnetite, a frequent associate of fluorite, is rare.
>
> Zircon occurs in one or two fairly large crystals and numerous smaller ones, usually showing characteristic physical properties.

[12] Larsen, E. S., and Keevil, N. B.: 1942, Amer. Jour. Sci., Vol. 240, pp. 204-215.

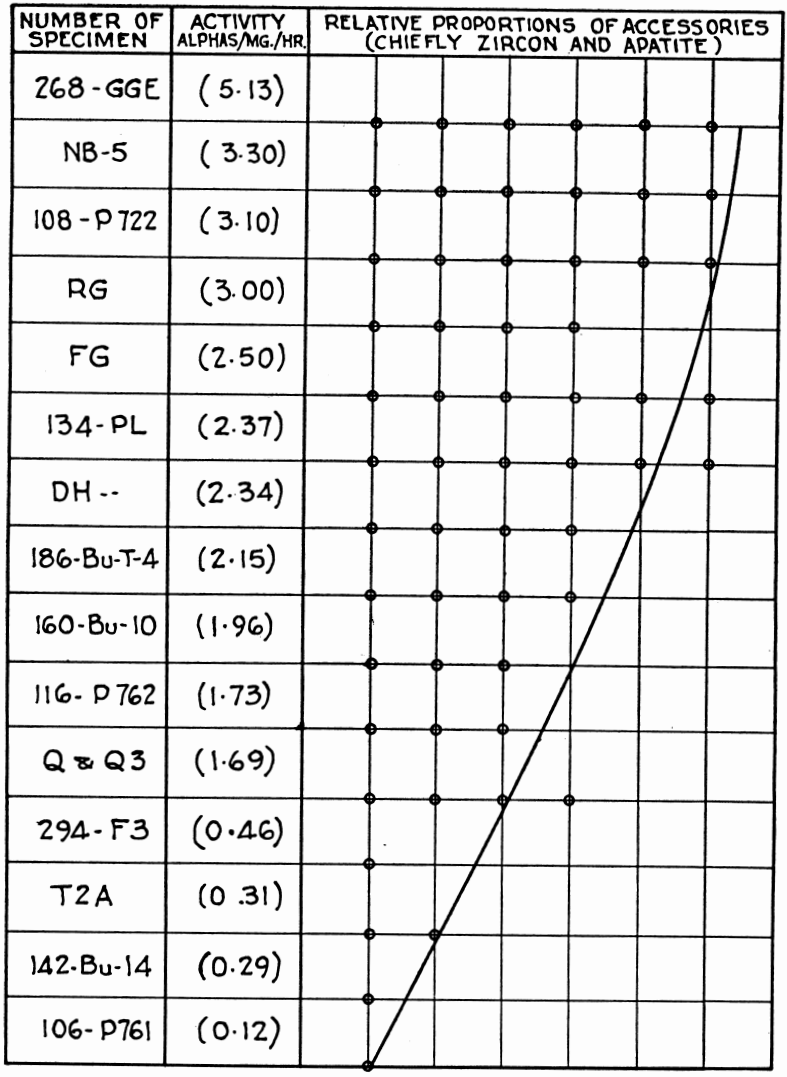
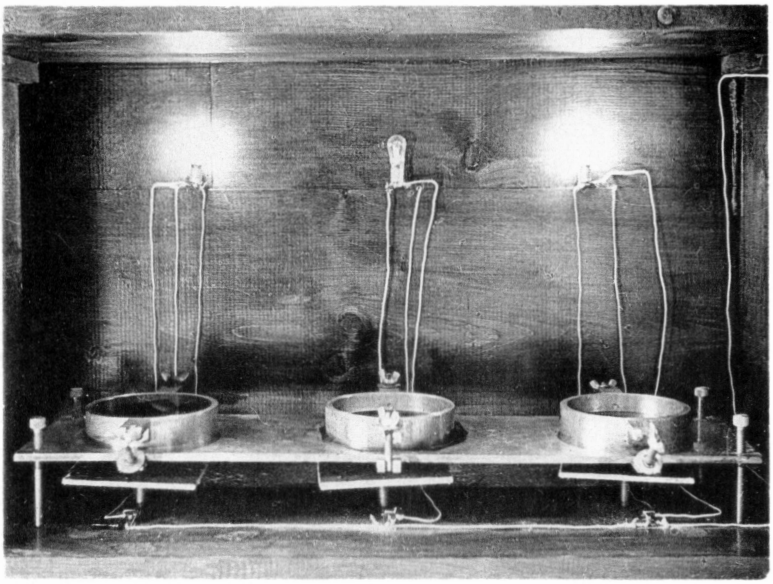


Fig. 4.

NB-5—(3.30) Granite, Hampstead, N. B.

There is 65 per cent zoned plagioclase (probably albite-oligoclase), 20 per cent quartz, 10 per cent biotite, and 3 per cent hornblende. The biotite is strongly pleochroic and shows a few halos. Saussurite and sericite replace some of the earliest formed feldspar.



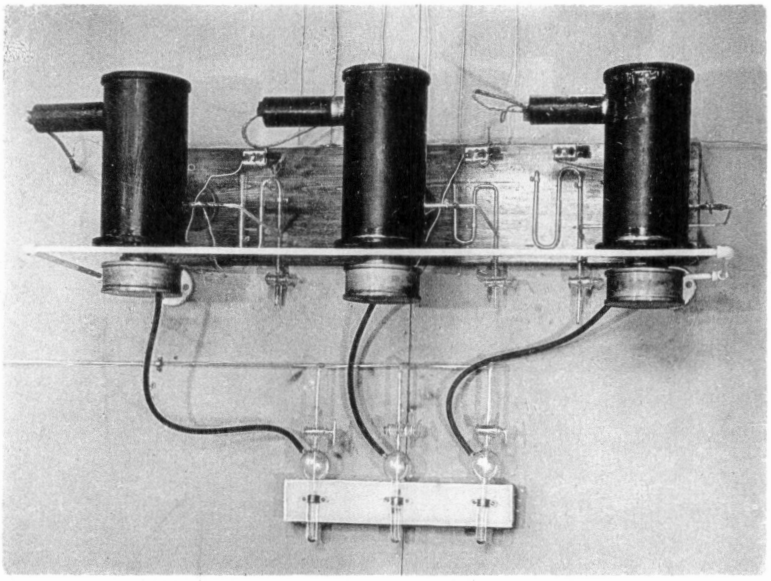


PLATE I

(Upper). Apparatus used in making rock deposits on copper discs.

(Lower). Chambers and vacuum-tube housings used in determining alpharay emission from rocks. Discs are placed in receptacles in the bottoms of the chambers.

Sphene is present as a deuteric alteration product. There is not enough to make an estimate of the percentage present. Apatite is fairly common in small, well-formed crystals. Magnetite, less than 1 per cent, usually occurs associated with biotite and hornblende. One good-sized crystal of zircon is present and shows a distinct halo effect on the biotite in contact with it.

108-P722—(3.10) Granite, Tanganyika.

Microcline and albite, slightly altered in places, make up about 50 per cent of the slide. Some zoned extensively altered plagioclase is present. Approximately 10 per cent is quartz and 5 to 10 per cent biotite, clustered irregularly in the feldspar.

Fairly small zircon crystals are numerous, and good halos are developed by those within biotite. There is as much zircon here as in slide 268-GGE. Sphene is as abundant as in slide NB-5, a little less than 1 per cent, but shows little or no radioactive effect in the biotite. Almost 1 per cent apatite occurs in well-formed crystals, often showing distinct halos in the biotite. Apatite exceeds zircon in amount. Magnetite, when present, is usually associated with the biotite and sphene.

R.G.—(3.00) Alkali granite, Cape Ann, Mass.

Microperthite, consisting of microcline and orthoclase intergrown with albite, makes up about 65 per cent of the slide. Thirty per cent quartz, less than 1 per cent biotite, and fluorite in irregular patches are present. Some hornblende occurs, but not as much as biotite.

A few small crystals of zircon are disseminated through the rock, showing distinct halos when enclosed in biotite. Primary magnetite is associated with the biotite. Practically no apatite is present.

F.G.—(2.50) Granite, Fitchburg, Mass.

The major constituent is 50-60 per cent potash feldspar (orthoclase and microcline). A few patches of myrmekite and some plagioclase are present. None of the feldspars are extensively altered. Muscovite occurs in a few large flakes. The amount of biotite here is approximately equal to that in slide 108-P722.

In and near the biotite crystals of zircon are locally abundant. Zircon and apatite in well-formed crystals show distinct halos in biotite, as in slide 108-P722. Magnetite in small amounts is usually associated with the earlier-formed biotite.

134-PL—(2.37) Granite, Petersen Lake, Man.

There is about 50 per cent quartz present. Plagioclase is zoned and altered somewhat to saussurite and sericite. Some sericite occurs concentrated along fractures in the rock. There is a little orthoclase and microcline, and about 1 per cent biotite in scattered flakes. Halos around zircon and possibly ilmenite are seen in places. Fluorite and carbonate, in patches, and hematite in streaks and fractures, are minor constituents. Leucoxene is associated with the ilmenite.

One good-sized crystal of zircon and a few smaller ones occur. There are also a few small crystals of apatite.

DH—(2.34) Alkali granite, Quincy, Mass.

This slide contains about 80 per cent microperthite, a little quartz, a few patches of fluorite and no more than 1 per cent hornblende. A good-sized piece of a variety of allanite was observed. It is pleochroic, red to yellow-brown. Epidote and zoisite occur around the plagioclase. Relatively few crystals of accessory minerals are present. Needles of apatite and a few zircon crystals are observable under high-power magnification. No zircons of appreciable size can be seen, but small ones lie in the vicinity of the ferromagnesians.

The allanite probably accounts for a major portion of the activity of this granite. Unfortunately no contact between allanite and biotite occurred and therefore its effect in producing radioactive halos could not be observed.

186-BuT-4—(2.15) Granite, Buchans, Newfoundland.

Plagioclase, amounting to about 70 per cent of the slide, is highly altered to saussurite and some sericite. There is approximately 25 per cent quartz and a few flakes of dark green biotite.

One cluster of sphene was observed. Good crystals of zircon occur in one or two places and these, when in biotite, have produced slight halos. Other small, more indefinite inclusions, are probably zircon. A few small crystals of apatite are present.

160-Bu-10—(1.96) Altered dacite, Buchans, Newfoundland.

This rock is highly altered and contains much chlorite. Only a few crystals of comparatively unaltered, zoned plagioclase occur. There are a few grains of quartz.

In the fine-grained part of the section some small crystals of zircon are visible. One or two well-formed, good-sized

crystals are present. The proportion of zircon is similar to that in slide 186-BuT-4. A few crystals of apatite are present.

116-P762—(1.73) Granite, Tanganyika.

There is 50 per cent quartz, 45 per cent or more microcline and some plagioclase in this slide. No ferromagnesian minerals are present, so that most of the radioactivity is probably due to the scattered accessories. This may not be a typical section of the rock.

Zircon occurs as short, tetragonal crystals sparsely distributed. They are in both the quartz and feldspar. A few crystals of apatite and a little magnetite are present.

Q-1—(1.69)

Sixty per cent of the section is microperthite, slightly altered to saussurite. A little plagioclase, suggesting albitization, and about 30 per cent quartz are present. Dark green hornblende. somewhat altered to serpentine and magnetite, makes up 7 per cent of the rock. Riebeckite in small amount is replaced in part by what appears to be sodic hornblende.

In the microperthite are numerous small inclusions arranged in definite lines. Some of these are zircon and others are undoubtedly apatite, which constitutes the majority of the inclusions. Fairly large crystals of zircon occurred in one place, but these are not so prominent as those seen in slides of higher activity. A little fluorite is present, some being included right in the hornblende. Sphene and epidote, associated with the feldspar, are found in small amounts.

Q-3—(1.69) Alkali granite, Quincy, Mass.

This slide also shows about 60 per cent microperthite, 30 per cent quartz, and a little plagioclase. There is 5 per cent of hornblende and riebeckite, the former replacing the latter in places. Saussuritization of the feldspar is advanced in places and quite a bit of epidote is present.

The accessories are much like those in slide Q-1. Sphene occurs in one large patch.

In general, except for one or two anomalous sections, the amount of accessory minerals present in the slides has gradually decreased as the activity decreased. Sphene does not show any direct relation to the activity of the rock. The activity of Q-3 is still fairly high when compared with some of the following slides:

149-Bu-3—(1.42), Porphyritic rhyolite, Buchans, Newfoundland; AR—(1.37), Rhyolite, Attleboro, Mass.; 285-FN-34—

(1.13), Granite, Finland; 267-GGW—(1.12), Granite, Ivigtut, Greenland; T1A—(1.01), Granite, Taschereau, Quebec; KD and KF3—(0.83), Granite, Barryfield Quarry, Ontario; and C1—(0.74), Granodiorite, LaMotte Tp., Quebec.

These slides were all examined in less detail to study the relationships between the activity and the amounts of accessories present.

The same decrease in accessories was noticed except in slide 285-FN-34, which showed an appreciable amount of zircon and some sphene. No other anomalies occurred and the amount of apatite and zircon is quite low in the slides of low activities.

294-F3—(0.46) Pochuck Gneiss, Franklin, N. J.

The principal constituents are 47 per cent plagioclase, 30 per cent microcline, 15 per cent quartz, and about 3 per cent biotite, lacking halos. Sericitization and saussuritization have slightly altered the plagioclase.

There is about 3 per cent magnetite in patches throughout the slide. A few crystals of apatite are present, but no zircon is visible.

T2A—(0.31) Granite, Taschereau, Quebec.

This slide contains nearly 50 per cent albite-oligoclase, 30 per cent quartz, a little potash feldspar, 5 per cent hornblende, about 10 per cent biotite, and some sericite and epidote. Plagioclase crystals are strongly zoned.

Small halos in the biotite surround zircon and apatite crystals, which are relatively few. Magnetite, in small amounts, is usually associated with the earlier-formed ferromagnesian minerals. Sphene, in patches, shows no halo effects when in contact with biotite.

142-Bu-14—(0.29) Granite, Victory Brook, Newfoundland.

The principal constituents are 50 per cent albite, 35 per cent quartz and about 5 per cent augite and hornblende. Sericite, epidote, and zoisite replace the feldspar, and the ferromagnesians are altered to chlorite in places. Very little potash feldspar is present.

A little magnetite shows sporadic distribution. There is less apatite than in slide T2A and no zircon is visible.

106-P761—(0.12) Granite, Tanganyika.

Orthoclase occupies about 50 per cent of this slide; 10 per cent zoned plagioclase, 20 per cent quartz, and 7 per cent biotite altered in part to chlorite make up the remainder, along

with some hypersthene, a few crystals of apatite, magnetite, and one crystal of zircon. Apatite is not as abundant as in slide 142-Bu-14.

The relationship between radioactivity and content of accessories was not entirely regular, but considering the errors involved in sampling and sectioning, and the variations in the specific activities of the accessory minerals themselves, this is not to be expected. Although no relationship between activity and sphene content was noted in this limited study, a definite increase of activity with increase of the amounts of zircon and apatite was found. A general tendency for the radioactivity to be concentrated in accessory minerals is indicated.

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CONCLUSIONS.

(1) Variation in specific radioactivity of a rock can be caused by:

a) inadequate sampling of the specimen or body;
b) irregular localization of radioactive elements in crystals of accessory minerals;
c) the effects of differentiation in the distribution of radioactive minerals within the intruded mass.

(2) There is further evidence for the belief that radioactivity is concentrated in zircon and apatite.

(3) A study of the Bourlamaque batholith suggests a concentration of radioactivity near the borders of the intrusive.

(4) Regional variations in radioactivity are apparent from examination of average and probable values for several geologic provinces.

(5) Mixing caused by sedimentation tends to produce a uniformity in radioactive content.

(6) Evidence for radioactive aureoles around some mineral deposits has been found.

(7) Additional data are needed to clarify the laws governing the distribution of radioactivity in rocks.

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