RADIOACTIVITY OF ROCK FROM THE VAL VERDE TUNNEL

Thesis by

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Also to those others who have by word or deed given aid and advice, I express appreciation.

ABSTRACT

1. Suitable apparatus for the determination of the radioactivity of coarse-grained low activity samples was developed, and measurements of the alpha particle activity of 73 representative samples from in and around the Val Verde tunnel were made.

2. These measurements show:

a. Active substances are concentrated in grains distributed in such a way that for samples less than 175 - 210 mg the graininess is important. For 25-35 mg samples taken from a 65 gram mass of rock ground to 60 mesh and well mixed the average deviation from sample to sample is 18% while for 175 - 210 mg samples it is 4%.

b. Sampling around a point indicates that the majority of carefully chosen samples taken within a few feet of each other have fairly constant radioactivity.

c. The radioactivity increases in the western end of the tunnel and shows a strong secondary correlation both with the percentage and acidity of the plagioclase feldspar in the rock.

d. Measurements on 21 non-country rocks give a striking confirmation of the already observed variation of radioactivity with acidity among different rock types. Measurements also indicate that the inclusions came from the gabbro which definitely gives the order of intrusion of the successive magmas into the schist, and suggests that this may be a powerful method of studying the origin of

inclusions.

3. Radium determinations were made on 6 samples of tonalite and combination of these with counter measurements gives:

a. An average radium content of 0.47×10^{-12} grams/gram of rock.

b. A surprisingly constant Th/U ratio of average value 3.69.

c. An average content of $.53 \times 10^{-5}$ grams of thorium per gram of rock.

RADIOACTIVITY OF ROCKS FROM THE VAL VERDE TUNNEL

I

INTRODUCTION

Many measurements of the radium and thorium contents of rocks have been made. These measurements go back almost to the date of the discovery of the activity of uranium by Becquerel in 1896, and from them the variation in radioactivity of the chief rock types is known(1). However, very few data are at hand which give the variation within a given type and especially the variation within a given batholith. It is to be expected that when more information of this kind is available, supplemented by careful studies by the geologist, the part which radioactivity has played in the segregation of igneous rock types and in the thermal and chronological history of the earth will be more perfectly understood.

There have been, as far as I am aware, only three tunnels studied in which the lengths were at all comparable to that of the Val Verde tunnel. Two of these, the Simplon and the St. Gothard in Europe, are discussed by Joly(2); and the radioactivity of the third, the Transandine in South America, is discussed by Fletcher(3). In all three of these the composition of the rock and the geology

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(1) Kirsch, "Die Radioaktivitat der Erde" Handbuck der Experimental Physik (Wein-Harms) Vol XXV pt. 2: 37, (1931).
(2) Joly, "Radioactivity and Geology" Dublin Univ. Press (1909).
(3) Fletcher, "On the Radioactivity of Rocks of the Transandine Tunnel" Phil. mag. 20: 36-45, (1910).

are markedly different from that of the Val Verde tunnel, so it was felt at the outset of this investigation that much might be learned by applying the modern techniques of petrography and radioactive measurements to the rocks from this tunnel. Since the members of each of the three radioactive series are in equilibrium and the disintegration constants are known, the amount of any member of a series can be found if the quantity of any one member is known. The heating effect can be calculated, and the age will be known if additional measurements are made of the end products--helium and lead.

In order to measure the radioactivity of a rock, it is necessary to measure its radium and thorium content (von Grosse[4] has shown that the actinium series has a constant activity with respect to the uranium series). But since direct measurement of the thorium content of weak sources is both involved and subject to error, the total alpha particle activity was measured by a counter method, the radium content by the direct fusion emanation method, and the thorium content was then obtained by subtracting the effect due to the uranium and actinium series from the total. This procedure was carried through on 6 representative samples of the 73 whose total activity we have measured, and it is planned to make more radium determinations at a future date.

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(4) von Grosse, Phys. Rev. 42: 565, (1932).

II

APPARATUS AND TECHNIQUE OF MEASUREMENT

A- COUNTING APPARATUS:

Apparatus for counting the total number of alpha particles emitted from a small sample of rock (10-30 mg) was developed by Raitt[5] and at Dr. Millikan's suggestion we attempted to use it in the present problem. However it was necessary to modify his technique considerably to take account of the larger crystal size and activity of our samples. The apparatus finally used is similar in many respects to that discussed by Finney and Evans[6].

Since an alpha particle of average range will produce about 10^5 ions along its path in oxygen, and since an average igneous rock emits about 10^3 alpha particles/g/hr, the problem of designing a counter is reduced to finding the most efficient means of collecting these ions (1.67×10^{-14} coulombs) and of amplifying and recording this very minute charge. A suitable method for doing this is to place the prepared rock sample in an ionization chamber, one electrode of which is connected to the control grid of a General Electric FP-54 low plate voltage and filament current vacuum tube. The balanced amplifying circuit of Du Bridge and Brown[7], with only minor modifications (Fig. 1), satisfied the amplification needs.

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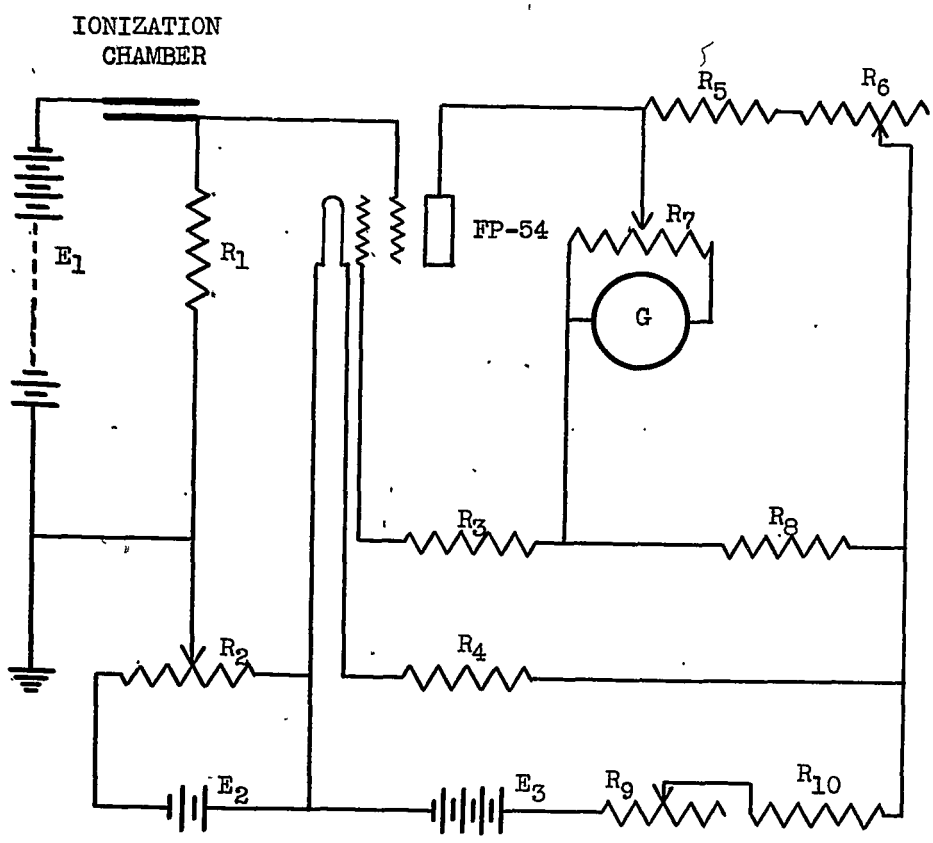
(5) C. I. T. Thesis - (1935).
(6) Finney and Evans "Radioactivity of Solids Determined by Alpha Particle Counting" Phys. Rev. 48: 503-511, (1935).
(7) Du Bridge and Brown, Rev. Sci. Inst. 4: 532, (1933).



R_1-5.3 x 10^{11} ohms	R_6- 200 ohms	E_1- 23.2 volts
R_2- 1000 ohms	R_7- 10,000 ohms	E_2- 4 volts
R_3- 10,000 ohms	R_8- 2,000 ohms	E_3- 8 volts
R_4- 40 ohms	R_9- 12 ohms	G-Leeds & Northrup 2285-C Galvanometer. Sensitivity 1.1 x 10^{-10} amp/mm. Period 11 sec.
R_5- 3,500 ohms	R_{10}- 10 ohms	

Fig.1 Circuit Diagram of Counting Apparatus.

The tube was placed in an evacuated brass housing and all parts of the circuit were carefully shielded. The output galvanometer was an L & N 2285C (period 12 sec., sensitivity 1.1×10^{-10} amps/mm at one meter), whose deflections were continuously recorded photographically on Eastman P. M. C. No. 2 contrast, smooth paper which was placed on the telechron driven drum of a camera. To obtain the proper drift rate for the spot of light along the drum, the circuit was at first slightly unbalanced so that the spot drifted according to the discharge rate of the batteries. But when new constant voltage nine plate Exide storage batteries were obtained the galvanometer lamp was shifted by a relay at the end of each revolution and the circuit left always balanced. The drum was 36 cm in circumference and turned at the rate of one revolution in 80 minutes which was fast enough to show all the detail in the deflection. The deflections (Fig. 2b,c) show a steep initial slope corresponding to the ballistic period of the galvanometer and a more gradual decline, an analysis of which gives 30 cm. for the capacity of the final chamber. The height of the kick is proportional to the range of the alpha particle in the chamber. A fifteen hour record taken with the chamber evacuated (Fig. 2a) shows that the circuit fluctuations due to random emission of electrons from the filament, temperature fluctuations, etc., are of the order of .5 to 1 mm. A limit of 1.5 mm was chosen above which all kicks were counted. This same

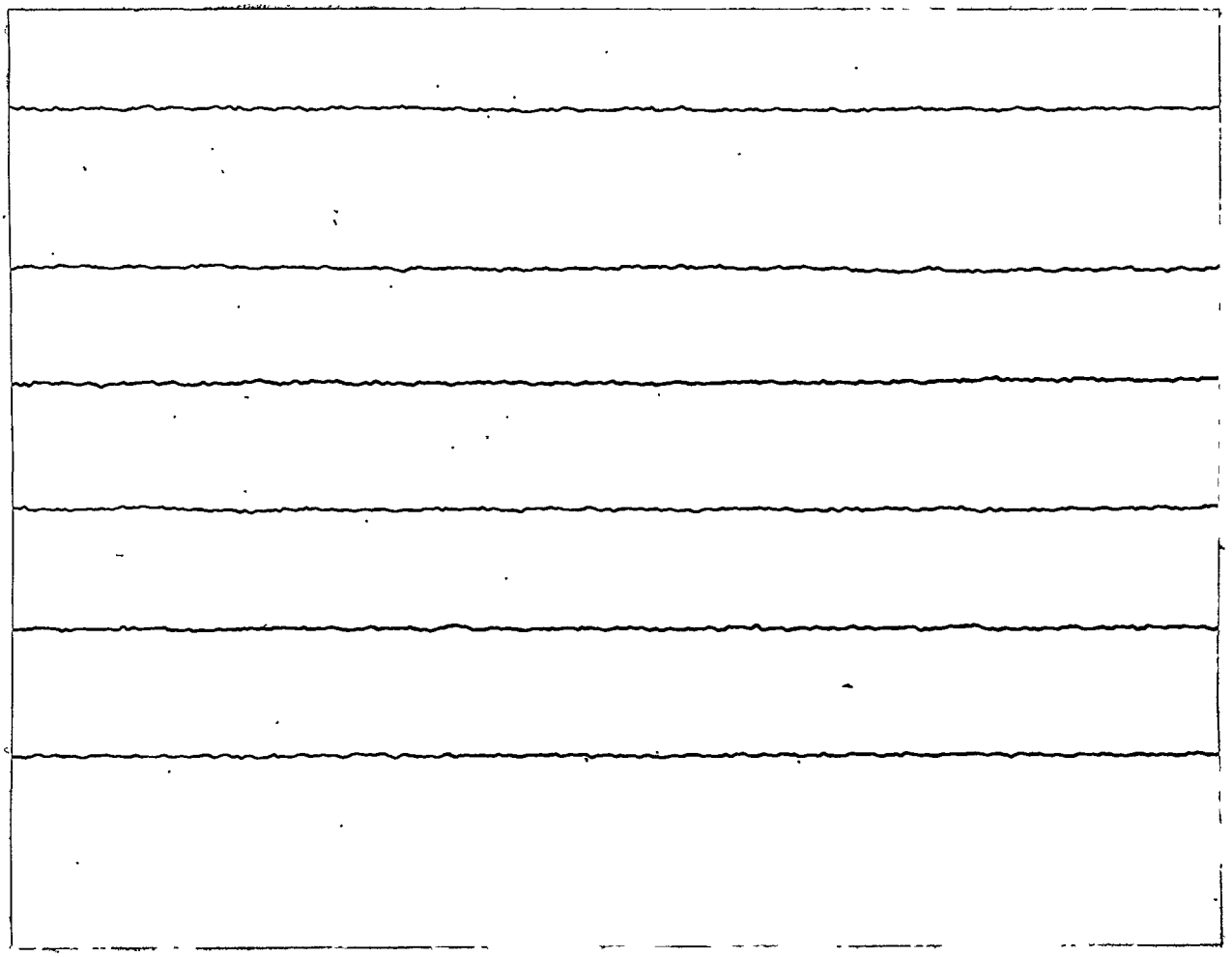


Fig. 2a -- Section of a fifteen hour record taken with flat chamber evacuated.

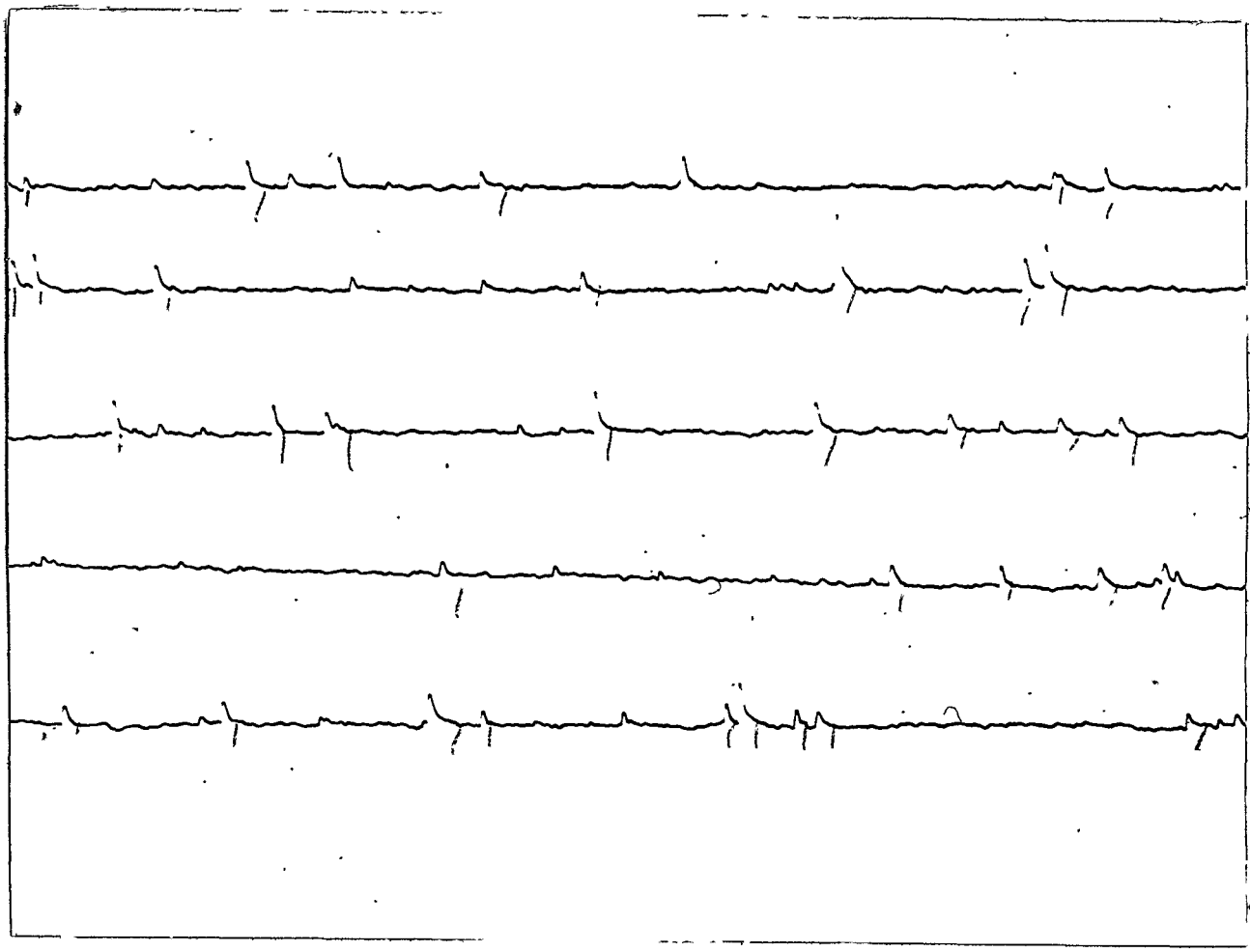


Fig. 2b -- Typical background record

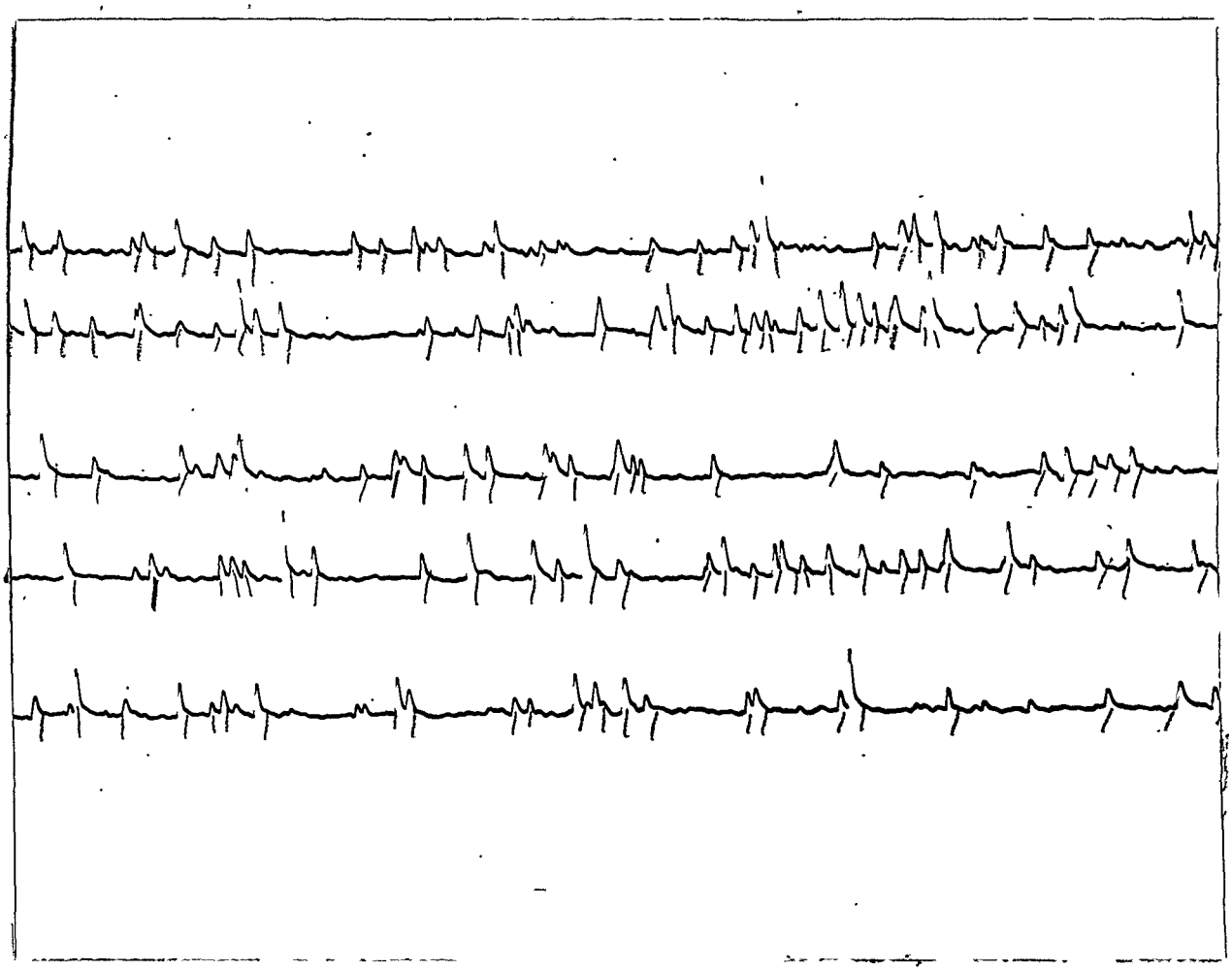


Fig. 2c -- Typical record with sample (#2b) in chamber

calibration was used for each of the ionization chambers constructed.

With gas in the chamber, great care was exercised to keep the background low and constant. Radioactively dead nitrogen and later oxygen were used; a record of the background was made before every sample measurement to eliminate the effect of contamination, and it was found that by careful cleaning the background fluctuations were very close to those calculated theoretically.

The resolving time of the circuit places a limit of 270 counts per revolution of the drum, but in spite of this disadvantage the present circuit was used because of the great advantage over the linear amplifier in regard to stability.

The factors which enter into the sensitivity of the counter circuit have been discussed [8,9]. The resolving time of the present counter circuit might be decreased by substituting a galvanometer of lower sensitivity and shorter period, since the present galvanometer is always used with an ayrton shunt set at 0.1; then if the value of the grid leak was decreased somewhat, possibly a factor of three could be gained in the sensitivity. Satisfactory results were obtained, so these changes were not made.

The relative merits of the three types of ionization

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(8) Hafstad, Phys. Rev. 40: 1044, (1932); Phys. Rev. 44: 201, (1933)
(9) Wyn-Williams and Ward, Proc. Roy. Soc. 131A: 391, (1931).

chambers which we used are worthy of some discussion. The first, a cylindrical type of chamber, was designed and used by Raitt[5]. It consisted of a brass cylindrical box of 5 cm in diameter and 2 cm in height, with a detachable lid on which the sample was placed and a hole in the bottom through which protruded a piece of 40 mil steel wire which formed one electrode and was carried through an insulator to the grid below. The capacity of this chamber is low, and as a result the resolving time is mostly dependent on the galvanometer period. A potential of 315 volts was found to collect virtually all of the ions formed by the alpha particles in the gas at atmospheric pressure. This box was enclosed in an iron shield of 1 1/2 in. minimum thickness which reduced the background to the cosmic ray level. The sample was a layer so thin that an alpha particle could pass through it and not be completely absorbed. In the case of granite this means a thickness of less than .0013 cm (less than 3 mg per cm^2 of source, or less than 50 mg for the total source). Raitt's method of obtaining a thin layer was ingenious but very laborious: a sample of 20 to 30 mg was taken from a larger sample, ground to 60 mesh, well mixed, then pulverized in an agate mortar until the largest grains were less than 10 microns in diameter. Direct tests have shown that a negligible amount of emanation escapes. The finely ground sample was thoroughly dispersed in 1.5 cc of amyl acetate and finally the suspension was picked up in a medicine dropper and ejected onto

the carefully leveled and weighed recessed lid. After drying and weighing, it was placed in the chamber.

A thin source has inherently one advantage: the correction for absorption in the source is small. Thus, accurate knowledge of the stopping power of the rock and of the limiting range is not necessary. One therefore can arrive at the true count without recourse to a standard. Its disadvantage is that convection currents in the evaporating liquid form ridges in the layer. This introduces an uncertainty in the absorption correction.

Some eighteen samples were measured in Raitt's chamber. Check runs on 8 of these (Table IV) showed that the distribution of radioactivity is such that for 30 mg samples taken from a 65 gram pile of rock ground to pass a 60 mesh screen, well mixed and finely ground as above, the count is almost random.

A larger source was needed, so a second chamber was built along the same lines as the first except that it was in the shape of a hexagonal prism so that rock could be deposited on the walls as well as the top. This increased the "thin" sample area from 18.0 cm^2 to over 100 cm^2 and the variation between runs on the same sample dropped in nearly the same proportion. This chamber was then workable and had the additional advantage that the ratio of background to sample was low. But the amount of time (of the order of ten hours) necessary to pulverize 150 to

200 mg of rock and get it on in a uniform layer, and then to make a run was prohibitive when contemplated as a routine procedure.

We turned now to a consideration of thick sources, the advantage being that ultra fine grinding is not necessary and weighing errors are eliminated. Moreover since our especial interest in this problem was to get at the relative distribution, and since the rocks which we wished to measure have very nearly uniform stopping power, the advantages of the thin source are only apparent. The third and final chamber was particularly adapted to the use of coarsely ground samples. Fig. 3 is a section of it. It consists of a parallel plate condenser, the lower plate of which is recessed to hold the sample. This plate is supported on a 40 mil copper wire held by a snugly fitting brass socket which runs through an amber bushing and is fastened directly to the grid. The capacitance to ground and thus the sensitivity of the counter is a fairly sensitive function of the length of the copper wire, and so we were careful to maintain its length constant throughout the experiments. The upper plate is held at a distance of 2.5 cm from the lower one by a cylindrical redmanol shell. On its upper surface is a post, the top of which forms a solder covered platform. This connects by means of a phosphor bronze spring to a hard rubber enclosed brass rod which in turn is connected to the collecting potential. The counting chamber is surrounded by

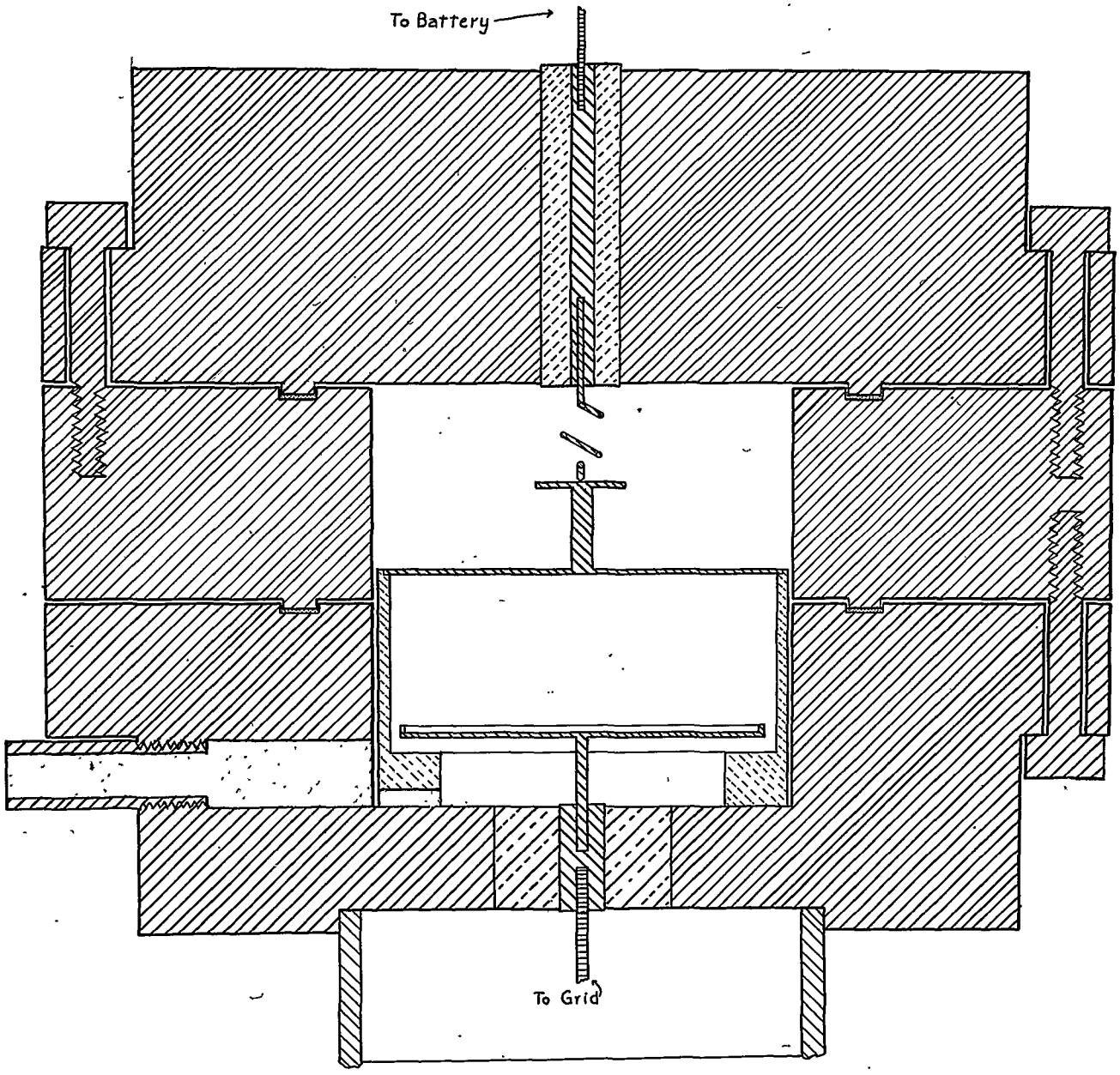

Fig. 3 Diagram of Counter Chamber

a 1 1/2 inch thick iron shield which, when bolted in place with rubber gaskets, is vacuum tight except for the 1/4 inch copper pipe through which the oxygen can be withdrawn or introduced.

The source was prepared as follows: approximately 65 grams was chipped from a 1 to 5 pound hand specimen which had been carefully chosen to represent the rock in its immediate vicinity. The chips were placed in an iron mortar especially designed to handle this large amount, and ground until all of it passed through a 60 mesh screen. This was thoroughly mixed with a spoon--direct tests showing that the sampling error was no greater by this method than when a more elaborate sample splitter from the Geology Department was used. Six grams of this representative sample was poured onto the lower plate and a smooth surface obtained by passing a glass straight edge across the top. The sample plate was now carefully put into place and after assembling and flushing the chamber with radioactively dead oxygen a run was taken, usually of from 6 to 7 hours, this giving sufficient counts to negate the effects of random emissions.

The whole assembly is shown in Fig. 4. The iron-shielded ionization chamber supported by a metal stand, with the evacuated tube chamber below, was mounted on a separate cement pier so that in handling the heavy shielding the galvanometer would not be damaged by sudden jars. Then from left to right is seen: the double-walled, heat insulated, copper shielded storage

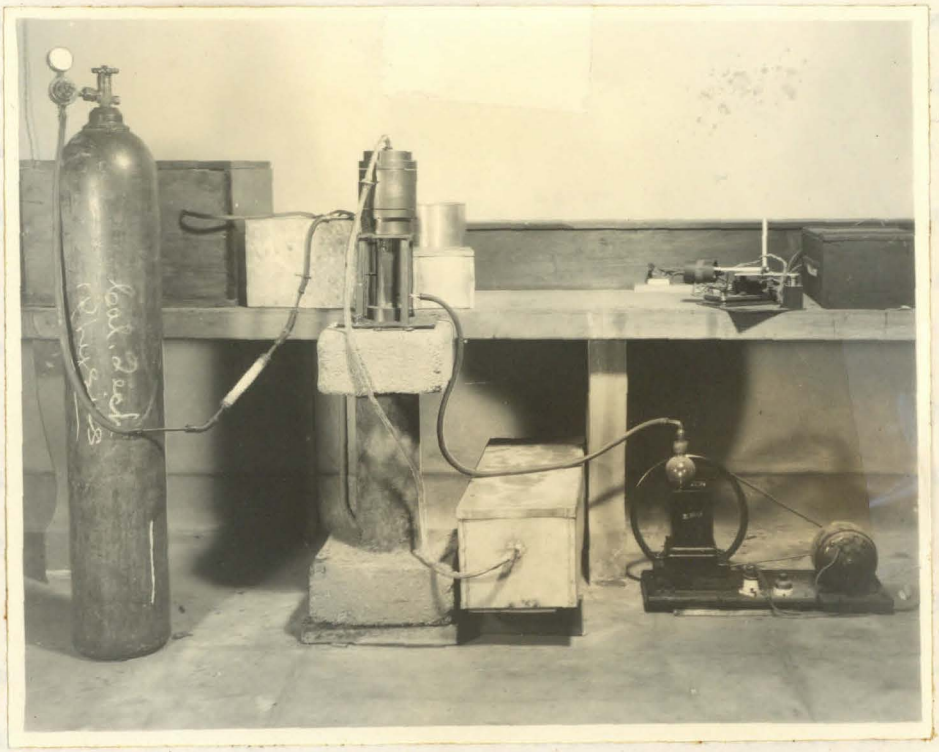

Fig. 4 -- Picture of apparatus for determining alpha particle emission rate of rocks

battery case; the tank of oxygen with glass wool, Ca Cl_2 trap attached; the metal enclosed circuit control box; the collecting chamber; the aryton shunt with galvanometer directly behind; the metal battery box below with the pump; the low friction, positive action, relay driven, galvanometer lamp support; and finally the telechron driven camera with its 10 inch long slit pointed toward the galvanometer. The battery boxes and circuit apparatus were constructed by Raitt[5]. This setup has been in satisfactory operation for some 3,000 hours, and outside of once changing the tube, it has only required minor adjustments to maintain it in satisfactory electrical operation.

To arrive at the true rate of emission from the observed rate requires several corrections. Raitt[5] has discussed some of the errors which enter into the observed rate:

(1) Edge effect and absorption in a thin source. The true rate is obtained by dividing the observed rate by (.904--.0053m), where m is the weight of rock in a circular source 18.1 cm^2.

(2) Coincidences. Since there is a finite probability of more than one particle entering the chamber in a time less than one-half the galvanometer period the observed rate in counts/rev must be multiplied by (1 +.00059 k) where k is in counts per revolution.

(3) Short lived alpha particle emitters. There are two alpha particle emitters--one in the thorium series and one in the

actinium series which have very short half-lives and whose parents also emit alpha particles. These will be counted only half the time, so the observed rate must be multiplied by 12/11 in the case of thorium series and 7/6 in the case of the actinium series. Assuming unity for the Th/U ratio and von Grosse's value of .04 for the ratio of the activities of the actinium and uranium series the correction is 1.04.

These corrections were applied to all the thin source data; number (2) was applied to the thick source data. Absorption in a thick source, neglecting edge effects, has been completely calculated by Evans[6] who finds for the observed rate: $n = (82.1\ U + 27.0\ Th)\ 10^3 \mu\ d$ where U and Th are the uranium and thorium content in grams, μ is the reciprocal of the stopping power, and d, the density. Thus by knowing μ and d, and measuring U and n separately, Th can be calculated. The difficulty lies in assigning a value to μ in the case of an inhomogeneous source. In actual practice it is better to eliminate μ by making measurements before and after contaminating the source with a known amount of thorium. In the present paper we arrived at a rough value of the true rate by using rock which had been measured by Raitt using a thin source. This has in it the error of the thin source method, but since the emphasis is on relative distribution, it is good enough for the present.

The observed background rate must also be corrected

because when the source is present no emission from the lower brass electrode is recorded. To get a value for this correction the source dish was covered with a disk of redmanol and a count made. From this the activities of the brass and redmanol were calculated. The Bragg-Kleeman rule[10] was found to hold very closely, so using it to determine the ratio of the activities of brass and rock, the correct background is found by multiplying that observed by .8. The background which was subtracted was obtained by averaging all of the backgrounds which were taken with a particular configuration. This reduced the uncertainty of the background of the flat chamber to 0.6% (See Table I).

The law for calculating the error in a count due to the random emission of the source has been given by Bateman[11], by Evans and Neher[12], and by others. This law states that if with the source in the chamber, the count for T hours is at an average rate of N counts per hour then the total count and error are:

$$NT \pm .67\ (NT)^{1/2} \qquad \text{or} \qquad N \pm .67\left(\frac{N}{T}\right)^{1/2}$$

Similarly if we count the background for T hours at an average rate of B counts per hour, then we have

$$BT \pm .67\ (NT)^{1/2} \qquad \text{or} \qquad B \pm .67\left(\frac{B}{T}\right)^{1/2}$$

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(10) Rutherford, Chadwick, and Ellis "Radiations from Radioactive Substances" Cambridge Press 1930.
(11) H. Bateman, Phil. Mag. 20: 704, (1910).
(12) Evans and Neher, Phys. Rev. 45: 144, (1934).

Then the effect of the source is

$$NT \pm .67\ (NT)^{1/2} - (BT \pm .67\ (BT)^{1/2})$$

This gives

$$(N-B)T \pm .67\ (N+B)^{1/2}\ T^{1/2} \quad \text{or} \quad N-B \pm .67\left(\frac{N}{T} + \frac{B}{T}\right)^{1/2}$$

Since the uncertainty in the background is small the errors given are calculated as $.67\ (N/T)^{1/2}$.

Table I is an analysis of all the backgrounds which were taken with the flat chamber, except for perhaps ten which were taken after these computations had been made. To save space and avoid excessive computation the background runs are taken ten at a time, with no attempt being made to influence the grouping. These are given in column one, and in column two are the corresponding times. In column three are the averages and the corresponding uncertainties; and in column four are the actual deviations from the mean. The table shows that there were 10,304 counts recorded in 660 revolutions (880 hrs.). This yields as the average background 15.6 counts, and correcting for coincidence gives 15.7 ± .1 K/rev. Then the background to be subtracted is .8 x 15.7 = 12.6 K/rev. The mean of column three is 15.8 and the mean of the probable errors is ± .40 while from column four the mean probable error is ± .81. From this we can conclude that contamination is a minor factor.

The first runs which were made are given in Table II.

TABLE I

BACKGROUND ANALYSIS

Total Observed Counts	Revs 1 rev = 80 min.	K/rev	Deviation from Mean
769	45	17.1 ± .41	1.3
831	49	17.0 ± .40	1.2
824	48	17.2 ± .40	1.4
714	48	14.9 ± .37	.9
835	53	15.8 ± .37	.0
777	54	14.4 ± .35	1.4
763	45	16.9 ± .41	1.1
686	44	15.6 ± .40	.2
835	50	16.7 ± .39	.9
670	45	14.9 ± .39	.9
811	59	13.8 ± .32	2.0
733	50	14.7 ± .36	1.1
680	42	16.2 ± .42	.4
376	23	16.4 ± .57	.6

Mean = 15.8 $\pm \frac{.40}{2.5\%}$

Mean = .96
Prob. error =
.96x.85 = .81 = 5%

TABLE II

TEST OF FLAT CHAMBER USING THICK SOURCE

Sample	Back-ground K/rev	Total K/rev	Net K/rev	Average	Dev. from Mean	Average Dev.
1 b	27.5	111	96	101.0	5	3.3=3.3%
		118	104		3	
		117	103		2	
1 f	28	96	79	84.3	4.7	3.1=3.7%
		101	85		.7	
	24	99	83		1.3	
		106	90		5.7	

Average background = 22.0 K/rev

It is seen that the checks are more consistent than those of the same rocks (Table IV) using a thin source, the average deviation in this case being 18% while in the case of the thick source it was 3.3% and 3.7% respectively for the samples checked. This chamber is therefore well suited to measure the variation of radioactivity, and its simplicity gives confidence in the results obtained.

B- APPARATUS FOR DETERMINATION OF RADIUM CONTENT OF ROCKS.

Determinations of the radium content of rocks by measuring the equilibrium amount of radon were made as early as (1905)[13] and this method has remained, up to the present, the best. However, the technique of removing radon and of measuring its activity has undergone almost as many innovations as the automobile or radio, and each man swears by his own apparatus and technique. Thus Piggot[14], Joly[15], and Poole[16] and others have used successfully for years flux furnace and electroscope methods while Evans[17] and others have used the direct fusion furnace, string electrometer method.

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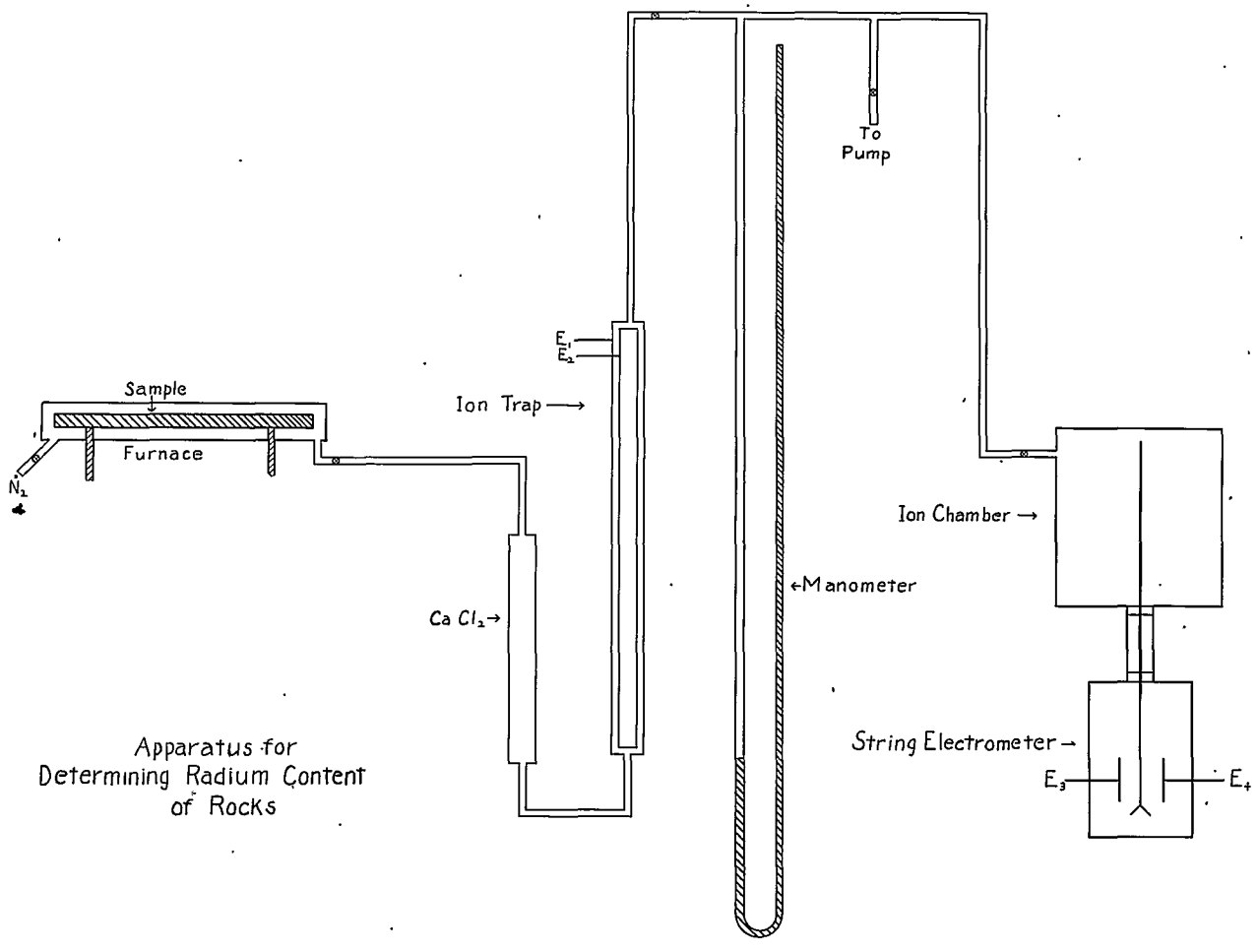
(13) Strutt, R. J.: (Lord Rayleigh), Proc. Roy. Soc. 77A: 472-485, (1905).
(14) Piggot, Am. Jour. Sci. XVII: 14-34, (1929).
(15) Joly, Phil. Mag. 23: 201, (1912).
(16) Poole, Phil. Mag. 29: 483, (1915) and 48: 819, (1924).
(17) Evans, C. I. T. Thesis (1932) Rev. Sci. Inst. 6:99, (1935).

The apparatus which we used is shown in Figs. 5 and 6. Since it is described by Evans[17], it will only be necessary to go into sufficient detail to make the method and our modifications clear.

Rock prepared as previously described is placed in the carbon crucible of the 7 KVA water cooled furnace. After evacuation the stopcock to the pump is closed and the rock boiled for 2 1/2 minutes at 1800°C to release the radon. Then radioactively dead nitrogen is blown into the furnace, carrying the radon through drying and ion traps into a large ionization chamber. When the pressure as read on the manometer has reached that of the atmosphere the ionization chamber is sealed off and the rate of decay of the radon measured by the discharge rate of a string electrometer. The setup is different from that used by Evans (and by Raitt) in that in conformity with later practice the path taken by the radon is entirely through metal or glass, all rubber tubing, which is known to be an absorber, being replaced. A single ionization chamber is used rather than two as in the balanced chamber method of Evans, because the background fluctuations are $\sqrt{2}$ more with two chambers, and with one chamber there is only half the worry about insulation leakage, evacuation, etc.

The operation of the furnace was carried out as described by Evans in his thesis. A potential difference of 315 volts was applied to the electrodes of the ion trap and ionization chamber,



Apparatus for
Determining Radium Content
of Rocks

Fig. 5

Fig. 6 -- Picture of apparatus for determination of radium content of rocks

this being shown to be sufficient to collect the ions formed. The electrometer plates were held at 90 volts with respect to each other, or with respect to the case they were each at 45 volts. Eight medium Eveready B batteries were the source of the potential and have given good service for more than a year and one-half. Long backgrounds were taken and were found to remain constant over the period of the experiment. The sensitivity of the electrometer was always held near to 3.25 divisions per volt, giving a rate of 2.75 volts/hour for the background and from twice to five times this value when the sample was being measured. The leakage with the chamber evacuated was of the order of .07 volts per hour; and though it varied somewhat with the humidity of the room, these variations were held to within .03 volts per hour by enclosing the electrometer in a box in which fresh $CaCl_2$ was kept. The charging switch could be operated from the outside. This box with the ionization chamber on top, and window in front, is shown in Fig. 6.

In order to get the results into grams of radium per gram of rock, samples of rock were measured, the radium content of which had been determined by Evans whose apparatus was calibrated with a standard radium solution checked by the Bureau of Standards.

The following table gives the calibration measurements. Using Evans' C13 as best, the calibration constant is:

$$1 \text{ volt/hr/gram} = .765 \times 10^{-12} \text{ grams Ra/gram rock}$$

TABLE III

RADIUM APPARATUS CALIBRATION MEASUREMENTS

Rock No.	Ra in g/g x 10^{12} by Evans	Ra in g/g x 10^{12} by Raitt	Ra in g/g x 10^{12} by Clarke
C_7	1.52	1.25	1.37 ± .1
C_{13}	1.83	1.88	1.97 ± .13 1.79 ± .04
C_9	1.34	1.23	1.33 ± .11

The calibration error is probably less than 7%, the chief error being in the sampling.

III

DESCRIPTION OF THE ROCK FROM WHICH THE SAMPLES WERE TAKEN

For the past two years a great aqueduct has been under construction which is to bring water from Parker Dam in Arizona to the various valleys of Los Angeles County. In order to complete this project a number of long tunnels have been bored. The Val Verde tunnel, located 13 miles southeast of Riverside, California, is one of these tunnels. This tunnel is made unusual by the fact that for five out of its seven miles of length the rock is very uniform and all a part of one tonalite batholith. Also, being 16 feet in diameter, an unusually large surface of exposed rock

is available. Problems of composition, flow structure, crystal orientation, and other phases are being studied by Osborn[18] and a study of the heavy accessory minerals has been made by Wilson[19]. The study of the variation of radioactivity and correlations was suggested by Dr. Ian Campbell, and is a part of this same program. The tunnel is shown in Fig. 7, the length, location of sample, and earth surface features, being drawn accurately to scale. All that is actually known is what can be seen in the tunnel, as the surface of the ground has no outcrops available; but from the intrusive and fault surfaces, we believe the picture to be substantially correct. The distances are in hundreds of feet from a bench mark at Parker Dam. It is seen that the tonalite is intruded into biotite schist and the western end is faulted in such a way that there is exposed a section of schist followed by more tonalite, then grano-diorite and granite. We have samples also from the basic dike rocks which were intruded into the tonalite near the middle of the tunnel, subsequent to the intrusion of the biotite schist by the tonalite. Osborn describes the tonalite as follows:

"The tonalite is a coarse grained rock, medium dark in color, and varying only slightly in composition throughout the district. The rock contains 50 to 60% andesine, 15 to 30% quartz, and 15 to 30% biotite and hornblende, the biotite commonly being more abundant than hornblende. Occasionally a very small

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(18) Osborn, E. F., C. I. T. Thesis (1937, now being written).
(19) Wilson, R. W., C. I. T. Thesis (1936) and Am. Min. 22: 122-131, (1937).

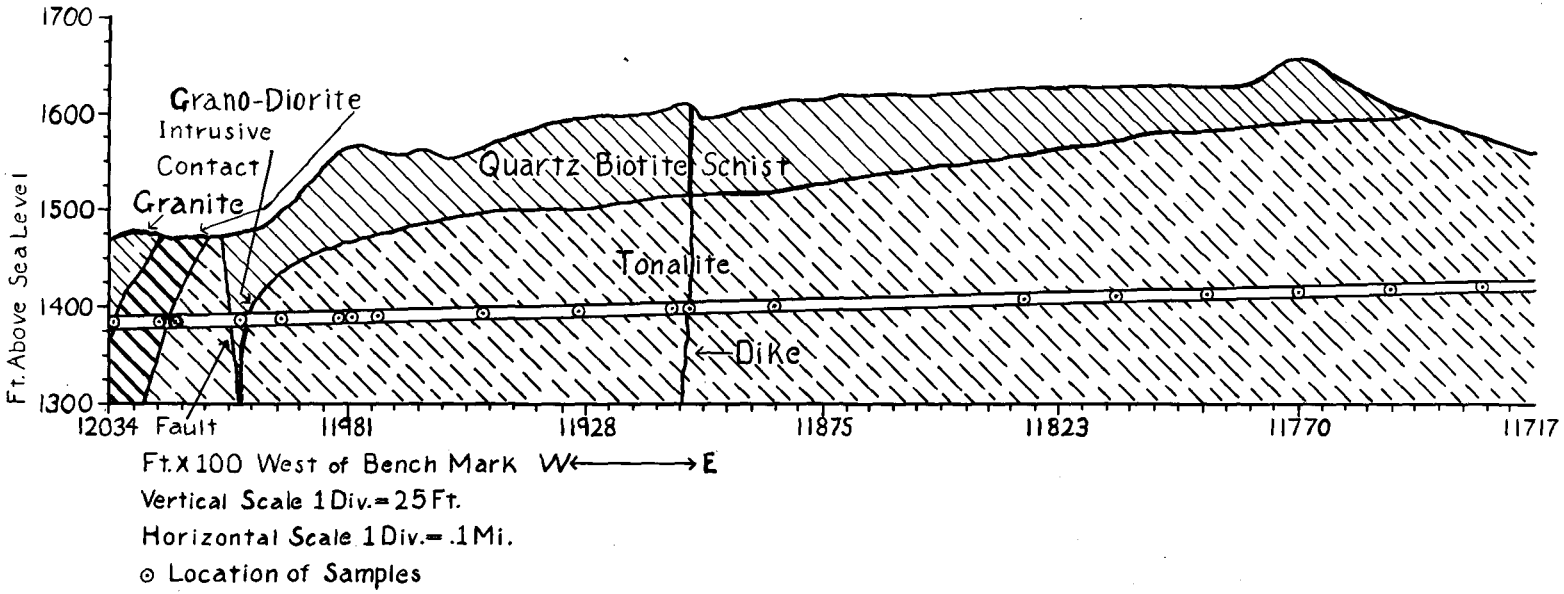


Fig. 7 Diagram of Val Verde Tunnel

percentage of orthoclase is present. Magnetite, sphene, apatite, and zircon are the common accessory minerals.

"A constant, conspicious feature of the tonalite is the presence of abundant dark, fine-grained, rounded inclusions. These vary from a few inches to several feet in diameter, but the average is about one foot across. In a few places the inclusions are practically absent and in others, occur in swarms, making 50% or more of the rock. In the latter instance they are more angular and more tabular in form and have a common orientation striking northwesterly and dipping steeply."

The composition of a typical tonalite (#12022 + 47 Series 2) is:

plagioclase feldspar	62%
quartz	15%
orthoclase feldspar	3%
biotite	9%
hornblende	11%

Ten samples were taken at approximately 2,000 foot intervals in the main body of the tonalite and later we procured six groups of about six samples each from points in the western section. Figures 8 and 9 are photographs of typical specimens of tonalite and inclusion. From them may be had some idea of the grain size and of the uniformity and general appearance of the rock.

IV

DISTRIBUTION OF RADIOACTIVITY IN TONALITE

A- DISTRIBUTION IN A 30 MG SAMPLE FROM 65 GRAMS OF ROCK GROUND TO PASS A 60 MESH SCREEN AND WELL MIXED.

Approximately 65 grams was chipped from a hand sample and ground to pass a 60 mesh screen. This was then stirred mechanically and shaken in a bottle as previously described, until it was

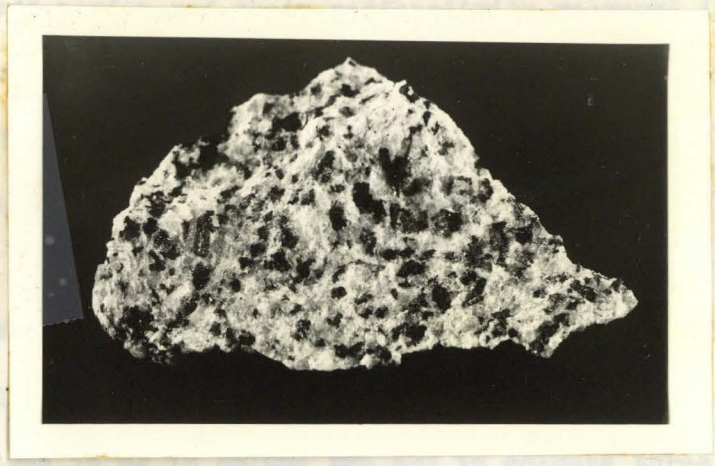


Fig. 8 -- A typical specimen of tonalite

Fig. 9 -- A typical inclusion

well mixed. Samples of about 30 mg each were now taken from this thoroughly mixed powder and their radioactivity measured in Raitt's "thin sample chamber." Runs and check runs were made on eight hand samples as shown in Table IV.

Table IV is to be read as follows: The rocks 1a, 1b,----1h, were taken at certain distances (which will be given later) from a point located 1,202,400 ± 50 ft. from a bench mark at Parker Dam. The samples $1d_1$ and $1d_2$ were taken from the same hand specimen. The weights are given in mg in column two and in columns three to six are given the observed background and sample counts with the corresponding number of 80 minute intervals. The calculated effects of the samples, together with the counting errors to be expected are given in column seven--the corrections and error calculations were made as already described--and in the final three columns are given the averages, the average deviations, and the average percentage deviations respectively. (The extreme sample was omitted in the twelve runs on 1f).

The deviations vary from 2% for 1b to 30% for 1g with a mean of 18% for all eight; thus the variation from one 30 mg sample to the next is of the same order as the variation between the different rocks. In order to check whether this variation was due to the rock not having been ground finely enough before mixing, the first eight runs on 1f were made on samples taken from 5 grams

of the 60 mesh rock, ground in an agate mortar to a fineness of (estimated) 325 mesh. Omitting the extreme reading (2.29) the mean of these eight is 1.06 and the average deviation, 22.6%--about the same as for the whole group. It is certain that layer variation and contamination do not play such a large part. Therefore, one must conclude that for samples of this size, the activity distribution is random--in other words, the activity is concentrated in grains of such size that the variation in the number of grains from sample to sample is the controlling factor.

B- DISTRIBUTION OF RADIOACTIVITY IN A SPHERE OF RADIUS TEN FEET.

In Table II it was shown that by using a thick sample of about 200 mg effective weight, the average deviation from sample to sample is approximately 4%; therefore, the thick source method was used to answer two questions: (1) what is the variation in radioactivity within ten feet of a given point, and (2) is this the same variation which one would find in taking samples throughout the batholith?

In answer to the first, a group of representative samples were taken from about six points in the tunnel. The positions of these points can be read from Fig. 7 with the aid of the following:

#1 Series was gathered near 12024 + 50

#2 Series was gathered near 12022 + 47

#3 Series was gathered near 11980 + 62

TABLE IV

TOTAL α ACTIVITY OF EIGHT SAMPLES OF GRANO-DIORITE FROM AROUND A POINT (THIN SOURCE)

#1 Series = 12024+50; 1 rev = 80 min

Rock	wt.mg	BACKGROUND Total	Revs	SAMPLE Total	Revs	NET K/mg/rev	Average	Dev.	%DEV.
1 a	28.51	113	14	188	8	.71 ± .05	1.02	.31	30
	27.68	56	8	250	7	1.33 ± .06			
1 b	28.48	160	20	280	6	1.83 ± .07	1.87	.04	2
	26.34	52	6	275	6	1.91 ± .08			
1 c	27.10	61	7	208	4	2.18 ± .10	2.07	.11	5
	22.74	42	5	299	7	1.96 ± .08			
1 d_1	26.52	26	3	201	5.89	1.29 ± .07			
	27.88	64	7	110	4	.92 ± .07			
	26.08	39	5	190	8	.78 ± .05			
1 d_2	27.57	50	5	116	3.31	1.30 ± .09	1.16	.27	23
	26.64	34	4	193	7	.95 ± .06			
	28.10			218	5	1.70 ± .08			
1 e	24.69	45	4	355	8	1.93 ± .07	1.64	.29	18
	28.00	36	5	143	4	1.35 ± .08			
1 f	34.13	295	33	251	7	.72 ± .04			
	26.91	30	5	154	5	1.10 ± .07			
	26.61	-	-	189	8	.76 ± .05			
	20.30	85	10	312	7	2.29 ± .09			
	32.29	58	8	303	9	1.09 ± .05			
	26.95	41	6	162	6	.91 ± .06	1.22	.34	28
	26.56	82	10	194	6	1.20 ± .06	(omitting 6.17)		
	27.78	35	4	341	8	1.67 ± .06			
	25.70	64	6	281	8	1.38 ± .06			
	26.65	44	4	498	4	6.17 ± .17			
	27.62	41	4	174	6	.85 ± .06			
	28.80	55	7	190	5	1.40 ± .07			
1 g	26.2	52	4.83	266	11	.80 ± .04	1.15	.35	30
	27.71	47	6	78	2	1.50 ± .12			
1 h	27.0	29	3.64	147	4	1.42 ± .09			
	30.51	67	7	268	8	1.13 ± .05	1.21	.10	8
	28.28	42	5	219	7	1.09 ± .06			

Background = 8.6

Average Dev. = 18%

#4 Series was gathered near 11973 + 75

#6 Series was gathered near 11983 + 30

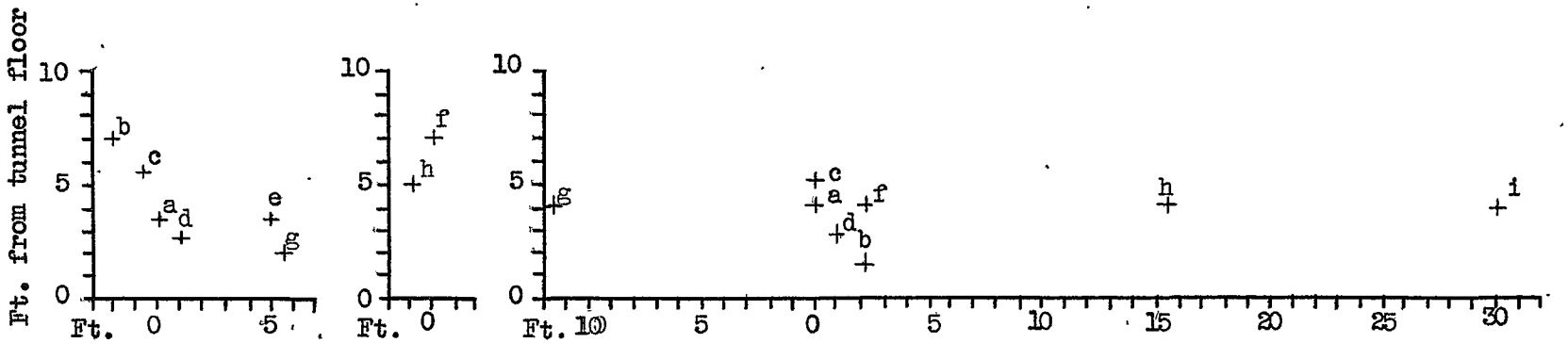
#7 Series was gathered near 11996 + 60

The positions of the various samples of a series with respect to each other are given in Figures 10a to 10f.

Careful measurements and check runs, with at least one background reading before each measurement, were made with results as shown in Tables V to X inclusive. The check runs were made from two weeks to six months after the initial runs which shows that change in the sensitivity of the counter in such a period is slight.

Each table is divided into two parts, the lower part containing those specimens which were different from the country rock usually because they were in or near an inclusion; while in the upper part are grouped the fresh, uniform samples of tonalite. (Series 1 is in the grano-diorite.)

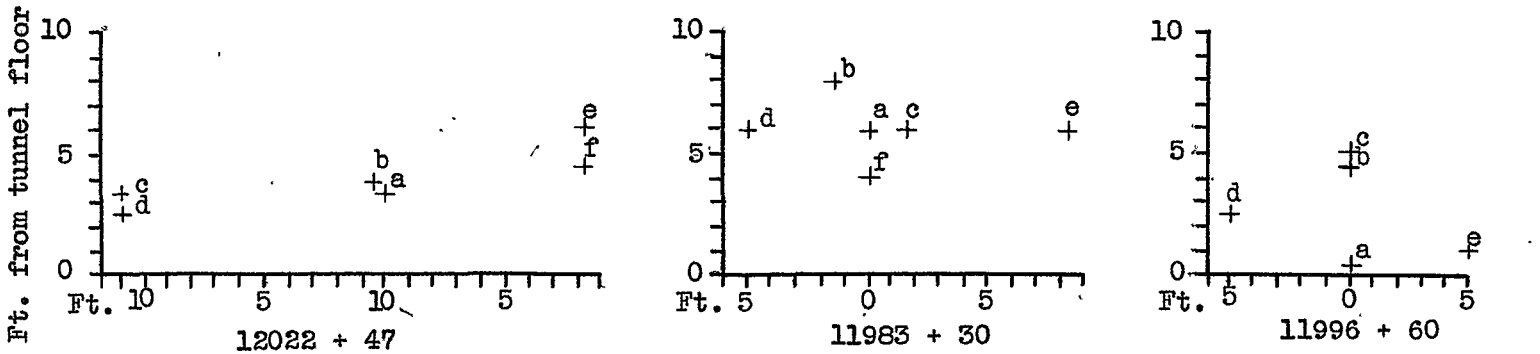
The rock designation is given in column one of Table V. The next two columns give the observed number of counts of background and the corresponding times, while columns four and five give similar data when the sample was in the chamber. The calculated percentage counting errors of each run are given in column six; and in column seven, the corresponding percentage deviation. In the final column is given the average net effect of the source and the corresponding counting error. The mean of column eight for the six good samples



12024 + 50
S.Side of tunnel
Fig. 10_a Series #1

N.Side of tunnel
opposite $#1_a$
Fig. $10_{a'}$ Series #1

11980 + 62
N.Side of tunnel
Fig. 10_c Series #3



12022 + 47
S.Side of tunnel
Fig. 10_b Series #2

11983 + 30
Fig. 10_e Series #6

11996 + 60
Fig. 10_f Series #7

Data on Series #4 not available

LOCATION OF SPECIMENS IN VAL VERDE TUNNEL

TABLE V

VARIATION OF TOTAL α ACTIVITY AROUND A POINT

#1 Series = 12024 + 50; Grano-Diorite; 1 rev = 80 min

Rock#	BACKGROUND Total	BACKGROUND Revs	SAMPLE Total	SAMPLE Revs	Counting Error %	Average Dev. %	Net K/rev
1 a	59	4	538	5			
	53	4	519	5	3.1	2.3	100.5 ± 2.0
	61	4	326	3			
1 b	66	3	536	5			
	97,73	5,5	548	5	2.8	4.3	99.3 ± 1.8
	91	4	600	6			
1 c	68	4	576	5			
	85	5	449	4	2.9	2.9	106.5 ± 2.0
			429	4			
1 d			454	5			
	116	7	390	4	3.7	3.2	86.7 ± 2.0
	55	5	190	2			
1 e	87	5	504	5	3.1	1.5	93.1 ± 2.3
	112	6	394	4			
1 f	97	6	458	5			
	108	5	463	5	3.8	.8	84.7 ± 1.8
	63,67	4,4	279	3			
							Mean = 95.1
							Av.Dev.= 5.3

ROCKS EXCLUDED BECAUSE OF NON-UNIFORMITY

1 g	110	8	355	5	3.9	3.4	59.8 ± 2.0
	90	5	233	3.46			
1 h	90	5	191	3	4.2	6.0	50.0 ± 1.9
	76	5	292	5			
					Av. = 3.4%	Av. = 3.1%	

TABLE VI

VARIATION OF TOTAL α ACTIVITY AROUND A POINT

#2 Series = 12022 + 47; Tonalite; 1 rev = 80 min

Rock#	BACKGROUND Total	Revs	SAMPLE Total	Revs	Net K/rev
2 a	78	3	289	4	
	76,54	4,4			67.2 ± 1.7
	62	4	402	5	
	83	5	203	4	
2 b	94,110	5,6	307	5	48.5 ± 1.7
	87,83	5,5	283	5	
2 e	89,68	6,4	388	5	
	31,42	2,4			67.3 ± 2.0
	91,92	6,5	300	4	
2 f	63	5	347	5	56.2 ± 1.9
	34,72	2,4	250	4	

Mean = 59.8 Average Dev.= 7.5

ROCKS EXCLUDED BECAUSE OF NON-UNIFORMITY

2 c lt.	71,67	5,3	513	4	
	54	3	501	4	117.4 ± 2.1
	119	8	564	5	
2 d lt.	81	5	395	4	
	34,118	2,6	380	4	90.7 ± 2.1
	128	9	301	3	
2 c dk.	58	4	262	6	29.6 ± 1.3
	80	5	233	6	
2 d dk.	67	4	194	6	19.3 ± 1.2
	57	4	119	4	

TABLE VII

VARIATION OF TOTAL α ACTIVITY AROUND A POINT

#3 Series = 11980 + 62; Tonalite; 1 rev = 80 min

Rock#	BACKGROUND Total	Revs	SAMPLE Total	Revs	Net K/rev
3 a	105	6	243	4	52.4 ± 1.7
	42	3	384	6	
3 b	121	7	303	5	50.3 ± 1.8
	162	11	243	4	
3 d	70	5	444	7	51.6 ± 1.6
	43	3	301	5	
3 e	94	6	383	5	65.5 ± 1.6
	79,82	6,6	591	8	
3 f	105	7	260	3	79.6 ± 2.3
	118,72	7,5	446	5	

Mean = 59.9 Average Dev. = 10.1

ROCKS EXCLUDED BECAUSE OF NON-UNIFORMITY

3 c	71	5	638	6	99.2 ± 2.2
	49	4	432	4	
3 h	65	5	165	5	19.4 ± 1.0
	64,49	6,4	274	9	
3 I	74,53, 82	3,3,5	212	5	32.1 ± 1.4
	107	6	268	6	

TABLE VIII

VARIATION OF TOTAL α ACTIVITY AROUND A POINT
#4 Series = 11973 + 75; Tonalite; 1 rev = 80 min

Rock #	BACKGROUND Total	Revs	SAMPLE Total	Revs	Net K/rev
4 a	76	4	527	7	65.7 ± 2.2
4 b	99	5	243	4	50.6 ± 2.2
4 c	95	5	328	4	73.3 ± 3.1
4 e			281	3	86.6 ± 3.9

Mean = 69.1 Average Dev. = 10.9

ROCK EXCLUDED BECAUSE OF NON-UNIFORMITY

4 d	64,49	4,3	675	6	107.4 ± 3.0

TABLE IX

VARIATION OF TOTAL α ACTIVITY AROUND A POINT
#6 Series = 11983+30; Tonalite; 1 rev = 80 min

Rock#	BACKGROUND Total	BACKGROUND Revs	SAMPLE Total	SAMPLE Revs	Net K/rev
6 a	44	3	321	6	42.6 ± 2.0
6 b	95	6	219	4	44.0 ± 2.5
6 c	72	5	160	3	42.4 ± 2.9
6 d	101	7	307	5	51.0 ± 2.4
6 e	72	6	210	3	60.0 ± 3.3
6 f	53	3	412	6	58.9 ± 3.5

Mean = 49.9 Average Dev. = 6.9

ROCKS EXCLUDED BECAUSE OF NON-UNIFORMITY

6 g Lt.	31	2	554	6	84.7 ± 2.7
6 g dk.	65	4	185	6	18.8 ± 1.5

TABLE X

VARIATION OF TOTAL α ACTIVITY AROUND A POINT
#7 Series = 11996 + 60; Tonalite; 1 rev = 80 min

Rock#	BACKGROUND Total	Revs	SAMPLE Total	Revs	Net K/rev
7 a	104,62	5,3	467	5	
	81	5			84.7 ± 2.1
	58	3	456	5	
7 b	83,52	5,3	436	5	76.8 ± 1.8
	77	6	585	7	
7 c	159	10	342	4	
	110	6	393	5	72.6 ± 1.7
	100,53	5,4	321	4	
7 d			529	5	101.8 ± 2.4
	65,45	6,3	439	4	

Mean = 84.0 Average Dev. = 9.3

ROCK EXCLUDED BECAUSE OF NON-UNIFORMITY

7 e	83	5	189	4	
	102,95	6,5	129	3	34.1 ± 1.7

is 95.1 K/rev and the mean deviation is 5.3 K/rev. It is interesting to note that the mean probable error calculated on the square root law is 3.4%, while that calculated from the deviation is 3.1%--a check that is within the human error of counting the records (estimated at 1%).

The mean of the four good samples in Table VI is 59.8 K/rev with an average deviation from the mean of 7.5 K/rev. Also is seen in the lower part of this table an interesting phenomenon: the hand specimens from which 2 c and 2 d were taken contained considerable inclusions, so samples were taken from the tonalite parts (designated 2 c light and 2 d light) and from the inclusions an inch or so away (2 c dark and 2 d dark). The variation in radioactivity over this short distance is amazing--the light sample having almost double the activity of the country rock while the inclusions followed the general rule of being very low in activity. Since this occurred in only four out of seven cases tested, no great significance is attached to it.

To summarize: The means and average deviations for the six tables are as follows:

Series#	Number of Samples	Mean	Mean Dev.
1	6	95.1	5.3
2	4	59.8	7.5
3	5	59.9	10.1
4	4	69.1	10.9
6	6	49.9	6.9
7	4	84.0	9.3

These results show that for carefully chosen samples there is a definite clustering about a particular value, and therefore such samples are closely representative of an adjacent volume of rock.

C- DISTRIBUTION OF RADIOACTIVITY IN SAMPLES TAKEN 2,000 FEET APART.

One of the moot questions in measurements of the radioactivity of rocks is: How near to the average radioactivity of a rock mass will one come by measuring the radioactivity of a few specimens chipped from some convenient outcrop? The data presented in Table XI are relevant and illuminating.

Ten unweathered, macroscopically uniform samples (column one) were chosen at intervals of approximately 2,000 feet apart in the main body of the tonalite (Fig. 7), and to these are added the means of the five series of tonalite samples already studied, making a total of 15 points in the tonalite at which the radioactivity is known. Columns two to five inclusive give the observed data as

TABLE XI

VARIATION OF α ACTIVITY IN TONALITE ALONG TUNNEL

1 rev = 80 min

Rock#	BACKGROUND Total	BACKGROUND Revs	SAMPLE Total	SAMPLE Revs	Net K/rev	THIN SOURCE K/mg/rev
11730	90	5	177	4	34.5 ± 1.5	.63
	48	3	236	5		
11750	84	5	189	3		
	108	6	430	7	53.1 ± 1.4	.90
	77	5	396	6		
11771	49	3	173	6	17.3 ± 1.2	.22
	105	5	121	4		
11790	72	4	155	5	18.8 ± 1.2	.44
	116	7	153	5		
11811	47	4	126	2	51.5 ± 2.7	1.00
	25	2	121	2		
11830	54	3	165	5	23.0 ± 1.3	.19
	91	6	149	4		
11894	81	4	173	4	27.0 ± 1.5	.29
	84	5	136	4		
11910	28	2	225	4	45.1 ± 2.1	.73
	93	4	119	2		
11930	58	4	431	5	82.6 ± 2.2	.62
	36	2	381	4		
11953	88	3	414	5	71.5 ± 2.1	.89
	48	3	310	4		

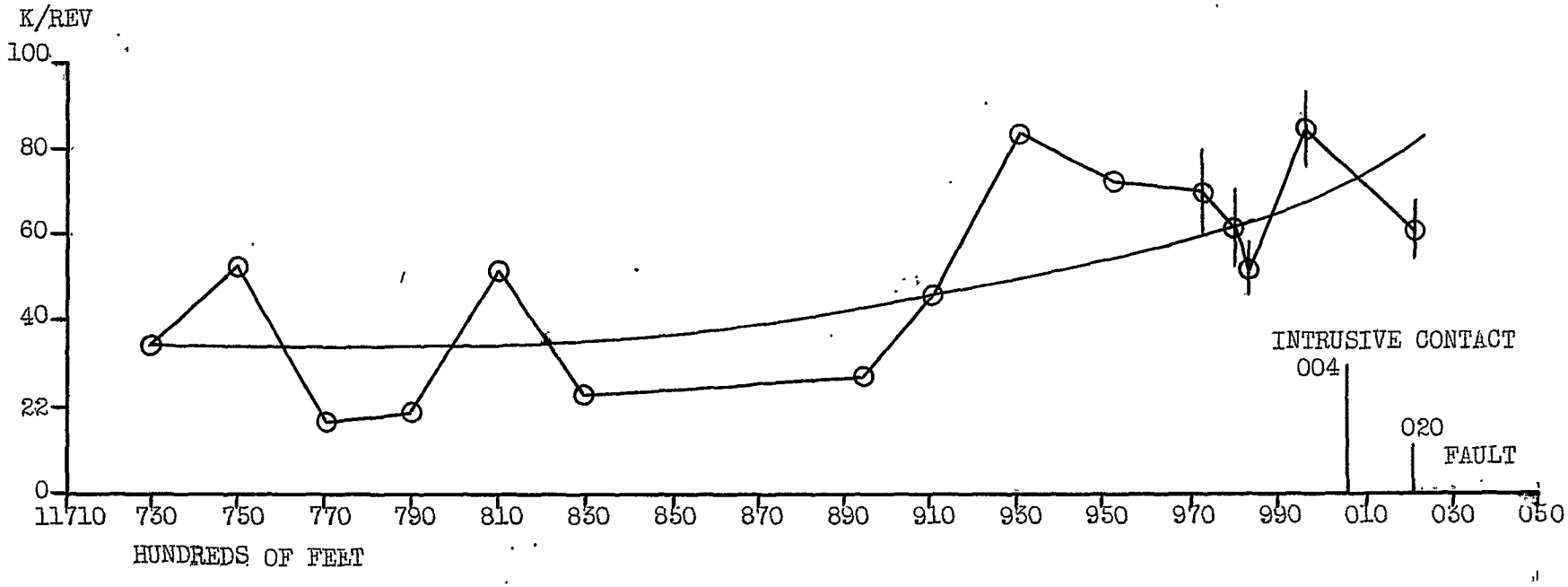
	Mean	Dev.
11973 + 75 average of four samples - - - - -	69.1	10.9
11980 + 62 average of five samples - - - - -	59.9	10.1
11983 + 30 average of six samples - - - - -	49.9	6.9
11996 + 60 average of four samples - - - - -	84.0	9.3
12022 + 47 average of four samples - - - - -	59.8	7.5

Mean = 49.8 Average Dev. = 17.8 or 36%

indicated, and the calculated effect of the sample is given in column six. For comparison, the total activities in alpha particles/mg/rev as determined with the Raitt thin source apparatus, are listed in column seven. It should be emphasized that the check runs were made from one week to six months apart in order to make sure the sensitivity of the apparatus had not changed. From column seven we see that the value of the total alpha-particle activity varies from 17.3 counts per revolution for the sample located at 11771 to 84.0 for #11996 + 60, and that the values definitely are higher as one goes from top to bottom. The mean of all sixteen points is 49.8 with an average deviation of 17.8 or 36%, as compared to an average deviation of 13% for the six series of samples discussed in the last section. The variation along the tunnel may be better seen in Fig. 11 where the activity in counts per revolution is plotted against the distances, and the average deviations from the mean are indicated in the case of the series about points.

From these data we can say in answer to the question propounded at the beginning of the paragraph that the value arrived at by measurement of a few samples taken from the outside of a batholith will give only a very rough estimate of the mean value of the whole. The sample will probably be within 40% of the mean.

What are the causes underlying this variation? Can we correlate any other quantities with the measured distribution of



VARIATION IN TOTAL ∝ ACTIVITY ALONG VAL VERDE TUNNEL

Fig. 11

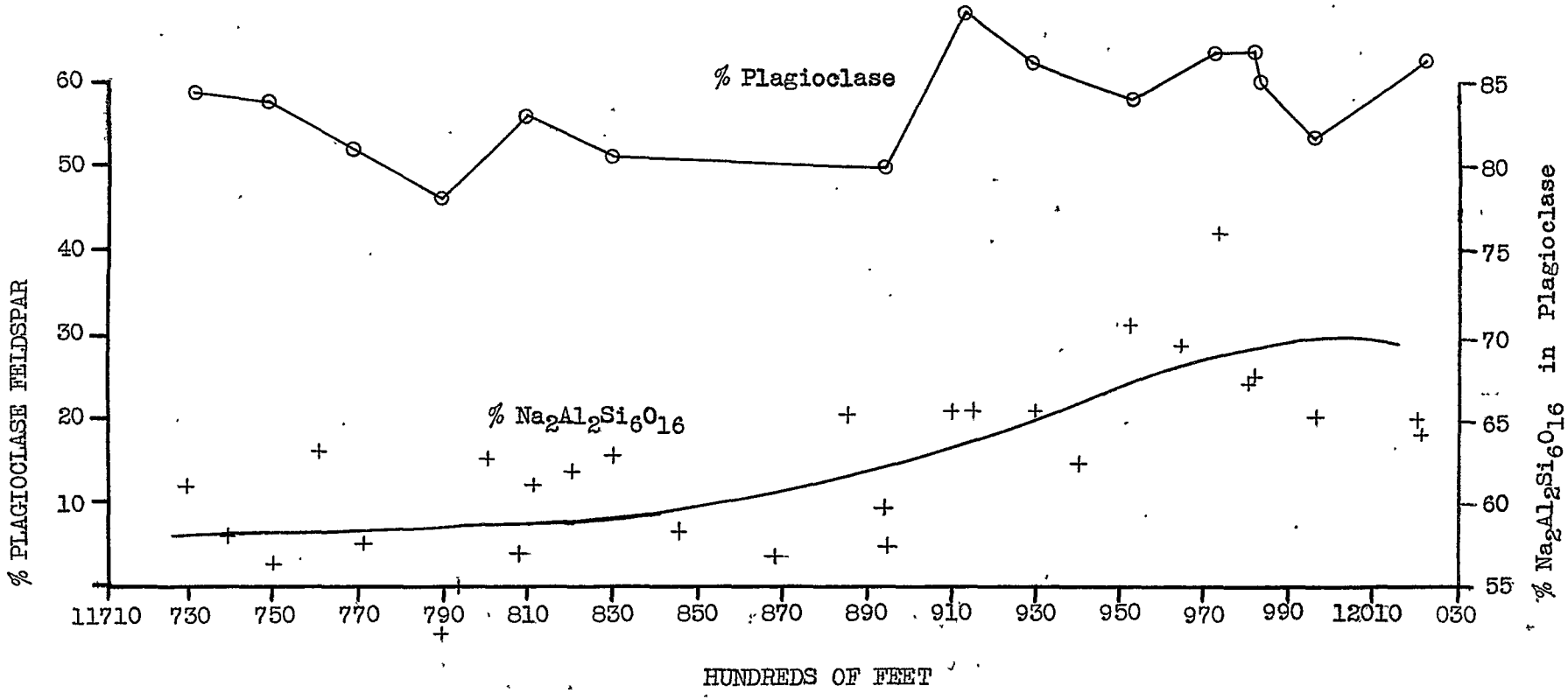


Fig. 12. VARIATION OF PLAGIOCLASE FELDSPAR ALONG VAL VERDE TUNNEL

radioactivity? We know from heat considerations that the radioactivity decreases towards the center of the earth, and also that due to gravity and the existing temperatures and pressures at the time of crystalization of the molten magma, certain minerals are associated together at various depths. The intrusive contact of the tonalite with the schist is a zone of differentiation at the edge of the magma, and we might infer that there would be found a concentration of radioactive minerals. This is what the measurements give.

Further correlations might be found by an examination of the composition analyses. Fig. 12 gives the plagioclase feldspar content of the samples and it appears on comparison with Fig. 11 that there is at least a secondary correlation. Very probably the mineral, or minerals, bearing the active ingredients are closely associated with the feldspar. To determine just which is the active mineral remains a problem for future investigation.

It has been known for a long time that the radioactivity of rocks increases with the acidity. Wilson, in his analysis of the heavy accessory minerals, found the rock to be more acidic towards the west; and Osborn has found that the plagioclase feldspar itself is more acidic in the same direction. In fact, his curve (the lower one of the two in Fig. 12) for the change in composition of the feldspar looks remarkably like our curve for the increase in radioactivity. This makes the correlation with the plagioclase curve much closer as it explains why the plagioclase curve does not rise at the west end

as does the radioactivity. The points are much too scattering, and the values not precise enough to draw valid conclusions regarding the actual curve as represented by the broken line in Fig. 11. But since ample samples have been taken and are available at 100 foot intervals for the eastern five miles of the tonalite, it is probable that more information will soon be forthcoming on this point.

V

DISTRIBUTION OF RADIOACTIVITY IN NON-COUNTRY ROCK AND THE GENESIS OF THE INCLUSIONS

Up to the present we have confined our discussion to measurements of the radioactivity of the tonalite which makes up the bulk of the exposed rock in the tunnel. We shall now consider the other types of rocks found in the vicinity in the hope that we may be able to shed light upon the most difficult problem the geologist has to face; namely, the disentanglement and reconstruction of the several magmas which make up the rock.

The most plausible picture in the present case for the appearance of the six main types of rocks found is that some 10^9 years ago the schist and granite which form the upper layer at present (Fig. 7) were deep under the surface (this is shown by the relatively large crystal sizes). At that time these rocks were intruded by a magma which, when solidified, formed gabbro, such as is found in outcrops to the north, south, and west of the tunnel. Some 9×10^8 years later the schist was again intruded by a magma which, when

cooled, formed the inclusion spotted tonalite and grano-diorite. Still later, as the batholith approached the surface, the dikes appeared. Now, after a hundred million years of faulting, erosion, etc., this formation is found in a tunnel some 200 feet below the surface of the earth.

Osborn has given the following brief descriptions of these rock types:

Inclusions The inclusions are variable in appearance and composition but always darker colored and finer grained than the tonalite. The average grain size is 0.025 to 0.05 mm. They are composed of 30 to 50% medium basic plagioclase, 10 to 40% quartz, 15 to 30% hornblende, and 15 to 20% biotite. One specimen contains 6% orthoclase, but in all other specimens orthoclase is absent.

Gabbro The gabbro is a dark colored, medium grained intrusive rock composed of 50 to 60% bytownite, and 40 to 50% hornblende and augite. A small percentage of olivine is present in some of the specimens.

Granite The granite is a light colored, medium grained intrusive rock composed of 40 to 50% orthoclase and microcline, about 35% quartz, 10 to 20% oligoclase, and 5% or less biotite.

Basic Dikes Intrusive into the tonalite are a few dark colored, fine grained dikes with the composition of a diorite. One of these has an average grain size of 0.1 mm and is composed of 57% andesine, 3% quartz, 28% hornblende, and 12% biotite.

Schist The schist is a well indurated quartzose sedimentary rock. Schistosity is rarely well developed. It is composed of 50 to 80% quartz, 5 to 10% oligoclase, and 15 to 30% biotite and hornblende and 0 to 14% orthoclase.

The locations, in relation to the tunnel, of the samples whose radioactivities were measured are as follows: (See Fig. 7)

SAMPLE DESIGNATION		DISTANCE FROM VAL VERDE TUNNEL
F36	Inclusion	on surface directly above 11900
912	"	in tunnel at 11912
022-2C	"	in tunnel at 12022 + 47
022-2D	"	in tunnel at 12022 + 47
980-3H	"	in tunnel at 11980 + 62
980-3I	"	in tunnel at 11980 + 62
983-6G	"	in tunnel at 11983 + 30
742	"	in tunnel at 11742
F8	"	on surface 3/4 mile northwest of 12020; 400 yards west of schist contact.
F18	"	from tonalite; 3 miles west of 020 on surface, where contact of schist and tonalite appear; 20 ft. from F19
VV011	Schist	in tunnel at 12011
012	"	in tunnel at 12012
F37	"	on surface 3/4 mile southwest of 12020
F22	"	on surface 3 miles west of 12020
F19	"	on surface 3 miles west of 12020; 20 ft. from F19 on schist side of contact.
F11	Gabbro	on surface 2 miles north of 12020
F31	"	on surface from Gavilan Peak 2 1/2 miles southwest of 12020
F29	"	on surface 3 miles west of 12020
034	Granite	in tunnel at 12034
F23	"	on surface 2 1/2 miles west of 12020
F21	Tonalite	on surface near F18
905I	Dike	in tunnel at 11905
916	"	in tunnel at 11916
B476	Tonalite (?)	from Bernasconi tunnel 5 miles east of eastern end of Val Verde tunnel
---	Pegmatite	in tunnel (taken from dump)
B456	Inclusion	near B476

We note that out of the eleven inclusions measured, seven came from the Val Verde tunnel, three from the surface at points which were directly above, 3/4 mile northwest, and 3 miles west of the tunnel respectively; while one was taken from the Bernasconi tunnel to the eastward. Of the five schists, two came from the

tunnel, two from an outcrop 3 miles to the west, and one from a body of schist 3/4 miles southwest of the tunnel. No gabbros were found in the tunnel but three samples were taken from outcrops to the north, west, and southwest. One granite was taken from the extreme west end of the tunnel and the other from the surface 2 1/2 miles farther west. The one specimen of tonalite came from the same outcrop as the inclusion F18. Two samples of dike were taken from the tunnel, none being found on the surface. The question mark is placed after B476 in the above table because the composition was not quite that of tonalite. The inclusion from the Bernasconi tunnel also differed somewhat in composition from those of the Val Verde tunnel.

The radioactivity of these rocks was found to be as follows:

TABLE XII

INCLUSIONS

Rock#	BACKGROUND Total	Revs	SAMPLE Total	Revs	Net K/rev
742	103	7	93	4	11.7 ± 1.0
	72	3	146	6	
912	95	6	279	9	19.0 ± 1.3
980-3H	65	5	170	5	
	64	6	271	9	19.4 ± 1.0
	49	4			
980-3I	82	5	203	5	32.1 ± 1.4
	107	6	253	6	
983-6G	65	4	185	6	18.8 ± 1.5
022-2C	58	4	256	6	29.6 ± 1.3
	80	5	222	6	
022-2D	67	4	184	6	19.3 ± 1.2
	57	4	123	4	
F36	58	4	223	6	25.2 ± 1.7

Mean = 21.9 Average Dev.= 5.3 = 24%

TABLE XIII

BIOTITE -- SCHIST

Rock#	BACKGROUND Total	BACKGROUND Revs	SAMPLE Total	SAMPLE Revs	Net K/rev
VV011	141	11	161	3	41.9 ± 2.0
	66	5	156	3	
012	62	4	216	5	31.5 ± 2.0
	75	5			
F19	107	5	324	5	54.7 ± 2.5
F22	85	6	181	5	24.4 ± 1.8
F37	75	7	483	6	71.7 ± 2.6

Mean = 44.8 Average Dev. = 14.7 = 33%

TABLE XIV

GABBROS

Rock#	BACKGROUND Total	BACKGROUND Revs	SAMPLE Total	SAMPLE Revs	Net K/rev
F11			41	4	0
F29	61	5	50	5	0
F31	102	5	87	6	0

Mean = 0

TABLE XV

GRANITES

Rock#	BACKGROUND Total	BACKGROUND Revs	SAMPLE Total	SAMPLE Revs	Net K/rev
034	56	5	435	3	144.6 ± 4.9
F23	68	6	557	5	105.3 ± 3.3

Mean = 125.0 Average Dev. = 19.6 = 16%

TABLE XVI

DIKES

Rock#	BACKGROUND Total	BACKGROUND Revs	SAMPLE Total	SAMPLE Revs	Net K/rev
905I	95	7	124	5.5	10.2 ± 1.4
916	96	7	115	5	10.8 ± 1.5

Mean = 10.5 Average Dev. = .3 = 3%

TABLE XVIII

VARIATION OF RADIOACTIVITY WITH ACIDITY OF ROCK

Rock type	Rock#	Biotite%	Hornblend%	Quartz%	Plagioclase%	Orthoclase%	(Q+Pl+Or)	Radio-activity of sample K/rev	Mean radio-activity of all samples measured K/rev
Gabbro	F29	0	52	0	48	0	48	0	0
Dike		12	28	3	57	0	60	10	10
Inclusion	742	18	33	19	30	0	49	11.7	21.9
Tonalite	022 + 47	9	11	15	62	3	80	59.8	49.8
Grano-diorite	024 + 50	9	5	28	42	16	86	95.1	95.1
Granite	034	Bi + Hbl = 1		33	24	42	97	144.6	125.0

quartz (SiO_2), plagioclase, and orthoclase ($K_2Al_2Si_6O_{16}$) is not directly proportional to the radioactivity points to the fact, which is emphasized by the existence of pleochroic haloes in rocks, that the activity is due to rare strongly active associated minerals distributed as grains throughout the mass. (This was apparent in the case of small thin source measurements.) The fact that the plagioclase itself varies in acidity, i.e. from ($Na_2Al_2Si_6O_{16}$) to ($Ca_2Al_4Si_4O_{16}$) in an isomorphic series, also is a factor as was indicated by the rise in radioactivity in the tunnel tonalite with the change in composition of the plagioclase.

We see that the radioactivity varies strongly with the orthoclase content of the rock. This is especially emphasized in the case of F8, an inclusion, (Table XVII) which had 6% orthoclase and radioactivity 80.9 as compared to the other inclusions which had no orthoclase, and an average value of 21.9 for the radioactivity. However, the correlation is again a secondary one because there is little correlation between the orthoclase content and the variation in the tunnel except in the fact that on the average it is higher at the western end as is the radioactivity. This points to the need of carefully made mineral separations to determine just which mineral contains the active ingredients.

The fact that the two samples from the Bernasconi tunnel are low in activity may mean that the radioactivity continues to decline as one goes farther east, thus indicating that the eastern rock was

difficult to see how radioactivity could be lost in the case of the tonalite absorbing the schist, because the average value of the radioactivity of the tonalite is 49.8, while the mean for the schist is 44.8. Thus the schist would have had to lose activity to a rock of higher activity than itself. But this is improbable since from the compositions given in Table XVIII the tendency would be to lose quartz and gain plagioclase, thus increasing the activity of the schist. It is much more probable that the relatively heavy gabbro was diluted by the lighter tonalite raising the activity from 0 to 21.9. This also fits well with the known positions of the outcrops.

There is only one inclusion which we definitely believe was a schist--F18 was taken from tonalite on the surface some 10-15 feet away from the schist-tonalite contact, and is quite similar to the schist in composition. F19 was taken from the schist about 20 feet away from F18. Their activities are: F18--45.8; F19--54.7. This certainly supports the "stoping" theory of inclusions.

The second theory of the formation of inclusions is that a segregation took place prior to solidification. This does not seem to have occurred here. The only evidence we have which might be construed as supporting this theory is that the rock immediately adjacent to the inclusion in four out of seven cases was much higher than the surrounding rock (Tables V to X). This is not

convincing, but should not be overlooked since the two theories are not mutually exclusive.

VI

RADIUM AND THORIUM CONTENT OF VAL VERDE TONALITE

Since the solution of the major problems of this research do not depend on a knowledge of the absolute content of radium and thorium in the rock, extreme accuracy was not striven for in the calibration of the apparatus. However, the calibration measurements were carefully made, and the uncertainty in them is less than that in the value given for the standard sources. Calibration of the radium apparatus has been discussed (page 26) and the calibration constant obtained. Using this result, the radium contents of six tonalite samples from the tunnel were determined.

Determination of the thorium content depends on a knowledge of the total alpha particle emission rate from a given weight rock. Since the values given by our apparatus are a function of the sensitivity of the counter and the stopping power of the rock, neither of which is known with accuracy, a calibration constant was obtained by measuring the activity of two "cosmic ray rocks" whose total emission rate had been measured by Raitt using a thin source. These rocks were granites and were chosen--first, because their stopping powers are approximately the same as the tonalite; and secondly, because of the good agreement between Evans' and Raitt's

radium determination which indicated that the samples were uniform. The measurements are given in the following table.

TABLE XIX

COUNTER CALIBRATION MEASUREMENTS

Rock#	Ra in g/g x 10^{12} Evans	Ra in g/g x 10^{12} Raitt	Total alpha emission K/hr/mg Raitt	Alpha emission thick source K/rev	Ratio of activities x 10^{2}
C_7	1.52	1.25	5.77	316.4 ± 8.5	1.83
C_8	.19	.25	.48	22.9 ± 1.5	2.09

Mean = 1.96×10^{-2}

The agreement is quite satisfactory considering the errors of the thin source. The radium and thorium contents obtained using this value are given in the next table.

In the first column of Table XX are given the rock designations (See Fig. 7). Column two gives the radium content in grams per gram of rock x 10^{12} as measured by the direct fusion furnace, electrometer method. In columns three and four are given the uranium content in grams per gram of rock x 10^{6}, and the alpha activity of the uranium plus actinium series, respectively. To get the uranium content the Ra/U ratio[20] 3.40×10^{-7} was used while the uranium-actinium series activity was calculated using the determination of Kovarik and Adams[21] that the alpha particle emission

(20) Lind and Roberts, Jour. Am. Chem. Soc. 42: 1170, (1920).
(21) Kovarik and Adams, Phys. Rev. 40: 718, (1932).

TABLE XX

RADIUM AND THORIUM CONTENT OF VAL VERDE TONALITE

Rock#	Ra in g/g x 10^{12}	U in g/g x 10^{6}	U series activity K/mg/hr	Total activity K/rev	Total activity K/mg/hr	Th series activity K/mg/hr	Th/U activity ratio	Th/U Concentration ratio	Th in g/g x 10^{5}
730	.34 ± .01	1.00	.36	34.5 ± 1.5	.68	.32	1.18	3.12	.31
750	.52 ± .02	1.53	.55	53.1 ± 1.4	1.04	.49	1.18	3.12	.48
811	.45 ± .01	1.32	.48	51.5 ± 2.7	1.01	.53	1.47	3.88	.51
830	.23 ± .04	.68	.24	23.0 ± 1.3	.45	.21	1.16	3.06	.21
930	.61 ± .02	1.80	.65	82.6 ± 2.2	1.62	.97	1.98	5.23	.94
953	.64 ± .02	1.88	.68	71.5 ± 2.1	1.41	.73	1.42	3.75	.71

Av. = 3.69

rate of uranium I is 12.4 x 10^3 alpha particles per second per gram, and the actinium-uranium activity ratio[4] 0.04.

Using these figures the numbers in column four are obtained by multiplying those in column two by 1.06. The alpha particle activities of the samples as measured by the "flat chamber thick source" method are given in column five, and column six gives these same values in counts per mg per hr. These are obtained by multiplying by the calibration constant .0196.

The activity of the thorium series in counts/mg/hr (column seven) is now obtained by subtracting columns six and four. The eighth and ninth columns give the ratios of the elements uranium and thorium both in terms of alpha activity and in terms of concentration. The activity ratio is obtained by dividing the series activities of columns seven and four and multiplying by 4/3; while the concentration ratios are obtained by multiplying the ratios of column eight by 2.64, the ratio with which the same quantities of thorium and uranium emit alpha particles as determined respectively by Fesefeldt[22] and Kovarik and Adams[21]. Finally the thorium in grams per gram of rock is arrived at (column ten) by the multiplication of columns three and nine.

The values arrived at for the thorium contents are in fair agreement with those given by Kirsch[1] for this type of rock,

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(22) Fesefeldt, Zeit, f. Phys. 86: 605, (1933).

which indicates that the calibrations are not far from right. The constancy of the thorium uranium ratio would be very significant if it were supported by more data, because it indicates that there may be in any one batholith an association between the uranium and thorium minerals such as exists for no theoretical reason between the uranium and actinium series.