Radioactivity and Geothermotics.

by

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Radioactivity and Geothermotics.

Chapter I History of the Subject.

The discovery of the phenomena of radioactivity suggested new fields of geophysical research. Lord Kelvin and Lord Rayleigh (R.J.Strutt) were among the first to apply radioactivity to a study of the earth's thermal history. Strutt, in 1906 (1) made what were probably the first determinations of the radium content of rocks and arrived at the conclusions that radium can easily be detected in all rocks and that acid rocks contain far more radium than basic rocks. The same writer beleived he had determined the distribution of radium sufficiently well to warrant a fair estimate of the total quantity present in each mile of depth of the earth's crust. His results suggested that the radioactive layer can not be much more than 45 miles thick; otherwise the outflow of heat would be greater than is observed. This conclusion, Strutt believed, agreed with the seismologic data of the time. He also examined meteorites and found that stony meteorites contain about as much radium as the basic terrestrial rocks they resemble while iron meteorites contain little or none.

G.Louderback (2) emphasised the importance of placing restrictions on the horizontal and vertical distribution of radioelements in the crust, in order to account for the lack of a higher geothermal gradient than is observed. He suggested that if radioactivity be considered as sufficient cause for the present gradient it must also be concluded that no quantities of heat have been developed by contractional movements in recent geologic time.

Arthur Holmes took up the question in 1915 (3) and since that time a considerable number of the leading geophysicists and geologists of Gt. Britain and America have given much thought to this entracing field of research.

Holmes and Joly in framing their hypotheses of geothermal history assumed that heat is generated in all of the earth's materials by radioactive elements and that any heat generated in excess of that which can escape by radiation from the surface must necessarily go towards raising the internal temperature of the earth. The important question is here raised--Is the earth getting hotter? The answer to this query is not yet forthcoming.

Radiothermal hypotheses may be divided into two broad groups. In one group there is an assumption that radioactive substances are distributed in some uniform manner throughout the rocks of the earth. Hypotheses of the other group postulate an irregularity of distribution.

Hypotheses Based on the Uniformity of Distribution of Radioactive Elements.

Possibly the foremost advocate of uniformity of distribution is Holmes. In 1928-29 this writer modified his original statement that radioactive elements are largely confined to the outer crust. He is now of the opinion that they are concentrated largely in the outer shells but are also distributed throughout the substratum to a depth of 2900 km. in amounts sufficient to maintain a condition approaching fusion and to require that the substratum is devoid of strength, a condition consistent with the idea of convection currents.

Holmes views may best be tabultaed as follows:

(1) Radioactivity is not limited to the crust. There is ample evidence of a faintly radioactive substratum withe production of heat in excess of that which is conducted to the surface.

(2) The substratum should still be in a fluid or glassy state.

(3) In order to discharge the loss of heat it is necessary to conceive a mechanism, involving circulation of the substratum material by convection and continental drift operated by such currents. X

(4) The average radioactive content is sufficiently well determined to permit an estimate " of the total generation of heat in average rock types."

(5) No radioactive energy is expended in effecting physical or chemical changes, as had been suggested by J. W. Evans. No heat is lost when the active materials are buried deeply.

(6) On the basis of petrological and seismological evidence, the outer shell of the earth, 60 km., must contain sufficient radioactive materials to make good the total loss of heat by radiation from the surface.

Joly assumed that the interior and the outer shell of the earth are heated independently by radioactivity. He also assumed that the heat of the crust escapes by conduction to the surface, while the crust itself forms a thermal blanket for the interior. "If more heat is generated in the crust than can be conducted to the surface, then the excess flows downward to heat the interior." Like Holmes, Joly assumes that the average radioactive content has been adequately determined, and therefore uses the average to calculate the temperature at the base of the substratum, which is considered to be at a depth of 30 km. The fact that so many variable factors are involved in determining temperatures at such depths makes any such determinations, at best, very uncertain. Joly's hypothesis includes the conception of thermal cycles, which embodies an alternate melting and freezing of the substratum. This condition demands a rather precise balancing of gradients and radioactive contents which is not likely to exist. Any theory of earth phenomena, which demands a delicate balance of factors, is not built on a safe foundation.

Hypotheses Based on Unevenness of Distribution of Radioactive Elements.

Those investigators who postulate an irregular distribution of radioactive materials are perhaps most formidably represented by T. C. Chamberlin, Joseph Barrell, L. H. Adams, and Bailey Willis.

T. C. Chamberlin (4) was among the first advocates of non-uniformity. He pointed out that radioactive elements enter readily into solution and are carried wherever the hydrosphere reaches. Their unique porperty of passing readily into gaseous emanations also aids in their diffusion. Radioactive matter, he concluded, is found in practically all rocks of the earth's surface, all of the waters and in practically all of the atmosphere. He suggested that if the liquefaction of rocks is dependent on the heat derived from radioactivity, the distribution of radioactive elements in the rocks should vary inversely as their temperatures of mutual solution. Chamberlin questions Strutt's conclusions that acidic rocks contain more radium and thorium than basic rocks. He raises the question --- must we abandon the nebular hypothesis of earth origin if we believe that so much heat is derived from radioactive sources that we must place severe limitations on their distribution? Chamberlin concludes that radioactive substances must be confined to a relatively thin outer layer of the earth's crust.

In 1916 Barrell used radioactive heating as an agent of magma formation in his "asthenosphere". Whether the idea of the asthenosphere is inacceptable or not, the importance of radiothermal energy as a source of heat for magma formation must be recognised.

L. H. Adams (5) brought forth the idea that radioactivity might be the cause of magma formation in regions where the radioactive content is somewhat higher than the average. This idea is analogous to Barrell's and was proposed in 1930.

Recently Willis has made an attempt to tie these several theories together. He favours the view of irregular distribution. In his opinion it is questionable if available rock analyses offer anything sufficiently conclusive. "However completely we may sample the surface rocks we should remain ignorant of the richness or poverty of the deepseated zones." (6)

Willis considers that radioactive minerals, being heavy, would tend to sink and by self-heating cause convections. The more persistently mobile character of radioactive magmas would cause them to coalesce into streams which are ascending and descending, thus tending to destroy uniformity of distribution. Thus, according to Willis, "We conclude that the distribution of radioactive elements could not have been uniform and it follows that hypotheses built on the unreal assumption of uniformity, must, themselves lack reality." (7).

Reasons for the Investigation.

Even a casual glance at the data at hand serves to reveal several broad generalisations. Radioactive materials are present in the accessible rocks of the crust in exceedingly minute quantities. The range between the relatively rich and relatively poor rocks is very wide. Rock analyses thus far available are too scant and too indefinite to permit any certain or specific conclusions regarding the associations of radioelements with the various rock types. In later pages the writer will present certain data and make some deductions therefrom concerning the distribution of radium and thorium which, it is felt, are well supported by the asembled facts.

From a survey of rock analyses by Piggot, Watson, Joly, Poole, Strutt, Fletcher and others, and from a consideration of geothermal gradients the writer recognises some rather significant relationships which seem to exist between these two phenomena. In view of the diversity of opinion regarding the manner of distribution of radioactive elements, it is felt that the evidence should be reviewed and an attempt made to arrive at more definite conclusions. Accordingly the results of this attempt are developed in subsequent pages.

Chapter II. Quantities of Radioactive Elements in Rocks.

As has been mentioned, several of the earlier investigators assumed a considerable degree of regularity of distribution of radioactive materials in the rocks of the earth. Several significant facts are opposed to this assumption and seem to point to great uneveness of distribution.

The fact that atmospheric waters leach out radioactive substances from rocks is an important factor in distribution. It will be shown later that ocean-bottom sediments carry considerably larger amounts of radium than any other type of rock. This fact seems, not illogically, to support the contention that water is an important agent of distribution. It is also an observed fact that fresh igneous rocks contain more radioactive matter than weathered rocks.

Certain rather elaborate conclusions have been drawn concerning the association of radium and thorium with definite rock types, to the effect that acid rocks contain more radioactive matter than basic, which in turn carry more than ultrabasics while sediments contain the least. However, while these conclusions seem to be borne out in a general way they are only borne out very generally. Final conclusions can not be drawn until many more analyses have been made.

Table I gives the average radium content for various regions, for basaltic and granitic rocks. A study of these averages emphasises the uncertainty of drawing any definite conclusions as to the uniformity of association of radioactive matter with the various types of rock. The very low values obtained for

Table I.

(Radium contents given in grs. x 10^{-12} per grm. of rock.)

Region	Basalts	Granites	Analyst
Brito-Arctic	0.50	--	Strutt
Hebridean	0.77	1.48	Joly
Scotland	--	1.71	Joly
Cornwall	--	3.55	Strutt
Lenister	--	1.68	Fletcher
European	1.30	--	Joly
Aar Massif	--	6.00	Joly
Finland	--	4.39	Joly
Deccan	0.77	--	Joly
Mysore India	--	1.02	Smeeth and Watson
Karroo S.Africa	1.44	--	Joly
Mozambique	0.90	2.33	Holmes
S.Africa	--	2.27	Holmes
West U.S.A.	1.69	--	Joly
East U.S.A.	1.09	--	Joly
East U.S. Lab. etc.	--	1.22	Piggot
Hawaiian Is.	0.96	--	Piggot
Antarctica	0.89	0.55	Fletcher
Antarctic Is. of N.Z.	0.54	1.76	Farr and Florance
Pacific Is.	1.09	--	Joly
Indian Oc. Is.	0.86	--	Joly
Atlantic Is.	1.31	--	Joly
Hungary	1.70	2.50	De Finaly

granites from Antarctica, Mysore India and the high values for basaltic rocks from Hungary, western U.S.A., and the Karroo district of S.Africa indicate clearly the difficulties encountered in trying to establish any definite relationships between acidity and radioactive content. The table shows that on the whole granites tend to be more radioactive than do basalts. Quoting Smeeth and Watson (8), " The amount of radium in the segregated portions of a magma sometimes increases and sometimes decreases with basicity. " Farr and Florance (9) after making an examination of rocks from the Antarctic Islands of New Zealand, discovered that the rocks contained more radium than was necessary to maintain " the constancy of the heat of the earth." They therefore emphasised the necessity of making examinations of rocks from other districts before any conclusions were drawn.

It has been shown that only wide generalisations can be made concerning the association of radium and thorium with definite rock types. The results of analyses which are available to the present writer show the inadvisibility of drawing specific conclusions.

Smeeth and Watson (10) studied the rocks of the Kolar Gold fields of Mysore and obtained remarkably low values for acidic rocks which, according to expectations, should be much higher. The results obtained by these writers are given in table II. An interesting point will be noted with the Charnockites which show an increase in radium content with an increase in basicity, a direct contradiction of the conclusions of Holmes, Strutt and others.

Table II.

Ra. Content of Rocks of Mysore India. (after Smeeth and Watson)

Description of Rock	Ra. in grs per gr of Rock.
Amphibolite Coregum Mine	0.82×10^{-12}
Hb. schist Bababudan Hills Kadur	0.25 "
Hb. granulite Kolar schists	0.19 "
Granite Mass Patna Kolar	1.50 "
Pegmatite Balaghat Mine	1.44 "
Acid charnockite Charmrajnagar	0.04 "
Int. charnockite Charmrajnagar	0.10 "
Basic charnockite Heggaddevankotte	0.12 "
Hypersthenite Nanjangud	0.06 "
Grey granite Closepet	0.63 "
Red granite Closepet	2.14 "
Grey porph-granite Closepet	0.27 "
Quartz-feldspar porph. Yelwal	1.37 "
Normal dolerite dyke Kolar	0.45 "
Santaveri trap Bababudan Hills	0.20 "
Chlorite schist Sacrebail Shimoga	0.27 "
Hb. diabase Bababudan Hills	0.16 "
Bellara trap Tumkur	0.05 "
Grey trap Chitaldrug	0.07 "
Titaniferous Iron ore Urbani Shimoga	0.05 "
Grey microgranite Kolar	0.85 "
Mica granite Mysore Mine	1.34 "
Massive porphyrite Champion Reef Mine	0.07 "
Auriferous quartz Mysore Mine	1.28 "

Table III.

Abnormally High Radium Contents from St.Gothard Tunnel.

Rock Type	Radium
Gneissic Granite	8.3×10^{-12}
Coarse Gneissic Granite	9.9 "
Coarse Gneissic Granite	14.1 "
Quartz Cipolin (zircon bearing)	14.3 "
Gneissic Granite	9.6 "
Mica Gneiss	9.2 "
Quartz Gneiss	8.9 "
Hornblende Gneiss	8.4 "

Table IV.

Low Radium Contents from St.Gothard Tunnel.

Rock Type	Radium
Grey Cipolin	0.7×10^{-12}
Usern Mica Gneiss	1.7 "
Brown Mica Schist	0.4 "
Coarse Black Mica Gneiss	0.8 "
Brown Glistening Schist	0.6 "
Greenish Grey Schist	0.9 "

In direct contrast to the low radioactive contents at Mysore, analyses of the rocks of St.Gothard Tunnel (11) revealed some interestingly high results which are given in Table 111. Table 1V. shows some low values for the same locality.

The evidence presented seems to justify at least a temporary conclusion that the distribution of radioactive materials in the rocks of the earth depends on something more than their content of silica.

As to the vertical distribution of radium and thorium, there are reasons for the view that these elements decrease in concentration with depth. Analyses of certain granites of Finland, Table V., showed that the radioactive content increases with a decrease in age. The probable reason for this is that radioactive materials are originally concentrated in shallow levels and the younger rocks have not lost so much active material through erosion.

Table V.

Order of Decreasing Age	Radium ($x\ 10^{-12}$)	Thorium ($x\ 10^{-5}$)	Potash($x\ 10^{-2}$)
A	2.36	0.87	2.51
B & C	4.60	2.67	3.61
D	6.21	5.85	5.06

Radioactive material is self-eliminating. By self-heating it tends to form magma which works its way out to the surface and is removed by erosion. In the Finnish granites, Table V. above, the granite A reached the surface first and was base-leveled. B and C were intruded at a later period and have not been so greatly eroded while D which is the youngest, has not been eroded as much as B or C and is consequently more radioactive.

Radioactive Elements in Natural Waters.

It seems, not unlikely, that in sedimentary rocks, moving ground waters would play an important role in altering the distribution of radioactive substances. The singular property of passing into gaseous emanations enhances the possibilities of radioelements being leached out of rocks, as these gases are very soluble. The property of returning to the solid state would likely cause precipitation in some rocks and a dilution in others. Hootman, Nelms, and Buehrer have made studies of the radioactive content of hot springs and natural waters. Buehrer (13) noted that the radioactive content of the water of Castle Hot Springs, Arizona, was equivalent to 1.57×10^{-9} grams of radium per litre. Gas bubbling through the water was found to contain 7.0×10^{-9} grams of radium per litre.

Salient Features of the Distribution of Radioactive Materials.

In the opinion of the writer the salient features of the distribution of radioactive elements in the rocks of the earth may be outlined as follows:

(1) Ocean-bottom sediments contain more radioactive matter than any other rocks.

(2) Acid igneous rocks appear to contain, on the average, more radioactive materials than other igneous types, while basic and ultrabasic types carry relatively small quantities.

(3) Sediments contain an amount of radioactive matter comparable to basic igneous rocks and usually more than ultrabasics, which contain least of all.

(4) Springs and natural waters carry very considerable quantities of active elements in the form of dissolved emanations.

(5) The unusual property of passing into gaseous emanations, which are very soluble, has an important bearing on the distribution of radium and thorium.

(6) Among the intrusions, younger intrusions seem to carry more radium and thorium than older intrusions, which have suffered much more erosion.

Chapter III. The Bearing of Geothermal Gradients on the Problem of the Distribution of Radioactive Elements.

In the opinion of the writer, the answer to the whole question of distribution lies with the geothermal gradients. With such a wide diversity of gradients we could not have uniform distribution of radioactive elements.

At depths below 30 km. where the gradients are beginning to converge a more even distribution of radioactive materials would occur. Seismic evidence from earthquake shocks shows a concentric zoning of the earth at depth. It is felt, therefore, that the radioactive materials are zoned accordingly, at these depths.

The low temperature gradients of Northern Ontario, Mysore, Transvaal and elsewhere supply evidence for the view that radioactive elements are unevenly distributed throughout a relatively shallow depth in the crust. If we assume that radioactive is the major source of heat in the earth we could not have radioactive substances uniformly distributed unless we had an uniformity of geothermal gradient, which obviously does not occur.

However, to use these low gradients as a starting point in any argument we must be sure there are no unforseen, disturbing local factors which determine their lowness. In sediments many factors affect the flow of heat; constitution of the strata, conductivity, amount of circulating ground water, porosity, attitude of the strata etc. all tend to determine the temperature gradient. In the Northern Ontario districts the gradients have been taken in the Pre-Cambrian crystalline rocks in which, very few, if any, disturbing factors are encountered. Adiabatic expansion and climatic changes are possibly the only factors which might affect the geothermal gradients in the shield area. The mean annual temperature of the Pre-Cambrian area is likely somewhat lower now than when the ice-sheet receded. With a mean annual temperature of about 34°F as exists at the present time the ice would not have melted very readily so that at the time the ice was receding the temperature must have been somewhat higher than it is now. Thus change in mean annual temperature would have had some part in changing the gradient. As to the effect of adiabatic expansion it seems fairly obvious that the removal of the ice took place over a sufficiently long period of time as to reduce its effect to a minimum.

With a low gradient of 8°C per kilometre as found at the Hollinger mine, at least 3°C per kilometre are accounted for by radioactive heat of shallow depth, therefore with only 5°C to be accounted for by internal heat obviously there can be little radioactive matter buried deeply. With the low gradient indicating there can belittle radioactive matter in the outer shells, it follows there will be even less at greater depths.

A study of the total heat produced by radioactive elements if each gram of the earth contained as much as the surface rocks, using average contents, indicates that the earth's crust could not yet have solidified which, very obviously, is not the case. Therefore a very definite limitation must be placed on the thickness of the "radioactive layer", i.e. that portion of the crust which contains the majority of the radioactive elements. Strutt (14) set the limit at 45 miles or less. This, he beleived, agreed with seismological data which showed a discontinuity at that depth. Jeffreys limits radioactivity to a much more restricted layer, placing the limit at 11 kilometres, while Joly (15) makes a similar estimate, 10 to 15 kilometres.

The present writer has the view, based on the following calculation, that Strutt's figure of 45 miles (about 72 km.) is much too high, while those of Joly and Jeffreys are rather low.

Assuming an average gradient of 30°C per km., adopting the average radium and thorium contents for the world from the determinations of Poole and Joly, a calculation of the thickness of the layer was made with the use of the following data.

H--heat production per cc.

D--depth of radioactive layer.

k--thermal conductivity of rock (.005)

g--geothermal gradient in ° C per cm.

Ave.radium content 5.00×10^{-12} grs. per cc.
Ave.thorium content 3.25×10^{-5} grs. per cc.
Heat production of radium per grm. 5.6×10^{-2} cals. per sec.
Heat production of thorium per grm. 6.6×10^{-9} cals. per sec.
Total heat production for radium 28.00×10^{-14} cals. per sec.
Total heat production for thorium $\underline{21.45 \times 10^{-14}}$ cals. per sec.
Total heat production per grm. rock 49.45×10^{-14} cals. per sec.
Average gradient-- .0003°C per cm.

$$D = \frac{kg}{H}$$

$$D = \frac{(.005)(.0003)}{49.45 \times 10^{-14}} = 30 \text{ kilometres}$$

From the results of the above calculation we can say with some degree of certainty that the figure of 30 kilometres represents a fair average for the thickness of the radioactive layer. However, it should be borne in mind that 30 kilometres represents only the average thickness. Under special conditions which will be discussed later a much smaller or a much larger value would be truly representative, where conditions are far from average.

An examination of iron meteorites, which most nearly correspond to the composition existing at the centre of the earth, of any materials available, shows that they contain little, if any, radium. This gives us some clue to the probable conditions at the earth's core. As is well known, neither heat nor pressure inhibits the disintegration of radioactive elements, therefore it is evident that if any considerable quantity of active materials existed at the centre of the earth they would exercise a profound effect on geothermal history. There is no evidence in geological history of such a "profound effect", so far as is known at the present time. The possibility, then, of an appreciable quantity of these elements existing in the nickel-iron core of the earth is very remote.

Deviations in Geothermal Gradient.

Deviations from the average gradient are produced by geologic structures, inclined strata, schistosity, ocean-bottoms, mountain ranges, anticlines and synclines, erosion and deposition, igneous activity, circulating ground water, and in the opinion of the writer, radioactivity. The unequal distribution of radioactive substances in the crust must have a very pronounced effect upon the temperature gradient.

Some rather surprising variations in gradient over relatively small areas have been noted. It is the present writer's opin-

Table VI.

Variations in Geothermal Gradient over Small Areas.

(after Van Orstrand(16)).

Locality	Ft. per °F.	°F per Ft.
Johnstown Westmoreland Co. Pa.	108.8	.0099
Long Bridge Westmoreland Co. Pa.	71.0	.014
Glen Pool Creek Co. Okla.	40.4	.024
Drumright Creek Co. Okla.	78.8	.012
Thermoplis Hot Springs Co. Wyom.	22.3	.045
Thermoplis Hot Springs Co. Wyom.	68.6	.014
Klamath Falls Klamath Co. Ore.	25.7	.039
Merrill Klamath Co. Ore.	40.5	.024
Ardmore Carter Co Okla.	135.5	.0074
Ardmore-Hewett Carter Co. Okla.	106.6	.0094

Table VII.

Rock Conductivities (British Association).

Sandstone	0.0055
Micaceous Flagstone	0.0053
Slate	0.0048
Marble and Limestone	0.0051
Trap Rock and Mica Schist	0.0038
Basalt	0.0067
Syenite	0.0060
Granite	0.0059

Table VIII.

Distance from N. Entrance in Metres	Rock Type	Radium	Thorium
0	Gneissic Granite	5.2×10^{-12}	1.8×10^{-5}
540	Gneissic Granite	9.0 "	4.3 "
957	Gneissic Granite	4.5 "	1.3 "
1032	Quartzose Granite	3.6 "	2.3 "
1348	Aplite	2.9 "	1.3 "
1800	Coarse Granite	8.1 "	3.3 "
2116	Usern Gneiss	3.2 "	1.4 "
2930	Usern Gneiss	2.1 "	1.3 "
4290	Usern Mica Gneiss	1.7 "	0.5 "
4832	Hornblendite	3.0 "	0.2 "
5734	Qtz.Mica Gneiss	2.6 "	0.5 "
6171	Brown Schist	0.8 "	1.8 "
7480-7530	Brown Mica Gneiss	2.1 "	1.3 "

ion that radioactivity might hold the answer to some of these deviations. Some rather wide variations in temperature gradient over small areas in the United States are shown in Table Vl.

Obviously, over such small areas climate could have no part in altering the gradient at one point and not at another. The depths to which annual variations in atmospheric temperature effect the temperature of the rock could not be very great, in any case.

Differences in the thermal conductivity of rock could hardly explain some of the sharper variations as rock conductivities do not vary sufficiently. Table VII. gives the thermal conductivities of various rock types as adopted by the British Association for the Advancement of Science.

The writer offers the suggestion that differences in radioactive content might be a plausible explanation for some of these variations. Observations made in the St. Gothard Tunnel in Switzerland showed the temperature gradient to vary from 20.9 metres per degree C at the north end ofthe tunnel to a mean of 46.6 metres per degree C in the central section. The quantity of radioactive materials in the north end of the tunnel was found to be in excess of those in the central section of the tunnel. Radioactive determinations made by Joly for the rocks ofthe tunnel illustrate this fact clearly; they are given in Table VIII.

Undoubtedly, in the case outlined above, radioactive content has a very important part in determining the rise in gradient noted in the north end of the tunnel. In view of this evidence it seems logical to suppose that some of the variations noted in Table VI. might be caused in this manner.

Conclusions.

(1) By a consideration of radioactive contents and geothermal data it can be readily seen that a limit must be placed on the thickness of the "radioactive rich layer".

(2) Holding that previous investigators have not arrived at sufficiently accurate determinations of the "radioactive rich layer", the writer arrived at the mean figure of 30 km. for the layer.

(3) From an examination of iron meteorites it was found that they contained practically no radium or thorium. As these meteorites very closely approximate the composition at the earth's core, it is inferred that this may be considered one reason for believing that the nickel-iron core of the earth is non-radioactive.

(4) Some surprising deviations in temperature gradient over relatively small areas have been noted and it is the belief of the writer that many of these deviations can be explained by variations in the radioactive content. Direct observations made in the St. Gothard Tunnel support this conclusion.

Chapter IV. Radioactivity and the Problem of the Pre-Cambrian Shield.

The lowness of the gradients from the shield present an interesting problem which can well be considered at this point. A comparison of gradients from the Pre-Cambrian Shield with some from other places are found in Table IX.

Table IX.

Locality.	Degrees C per Km. of Depth.
Idria, Austria	96
Ave. in common use	30
Ave, for Eastern U.S.A.	24
Ave. of 6 shafts, Kirkland Lake	11.5
Lowest from Kirkland Lake	10
Frood Mine, Sudbury	10
Dome Mine	9
Hollinger Mine	8
McIntyre Mine	7.5
Transvaal	8.5-7.0

(table after J. S. DeLury.) (17)

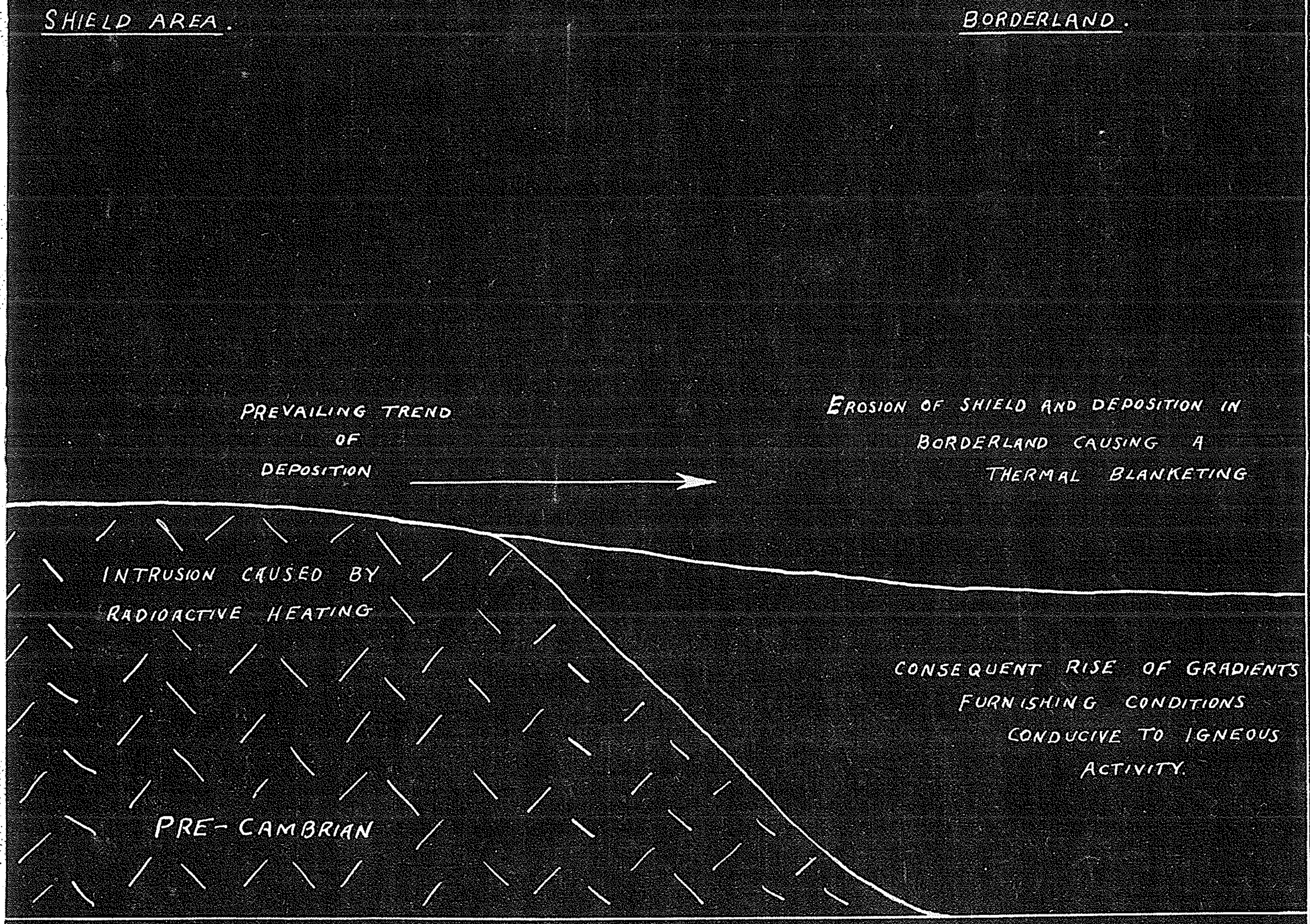
It is the opinion of the present writer that existing thermal conditions in the Shield can be accounted for only by appealing to the migration of radioactive materials through erosion. It has been estimated that approximately 10 miles (about 16 kilometres) of rock have been eroded from the Shield since the close of the Pre-Cambrian time. It is believed that this 16 kilometres, which has been lost, contained the bulk of the radioactive materials which were formerly present in that region and which permitted igneous activity during Pre-Cambrian time.

Using the calculation outlined on p. 17 and the average gradient (for the Shield) of 10°C per km. and world averages for radioactive content, it can be calculated that 10 km. represents the present thickness of the radioactive layer for the Shield area. By simply adding the 16 km. lost by erosion, there is arrived at an original thickness of 26 km. which is consistent with the writer's estimate of 30 km., which was derived on p. 17.

The lost material is supposed to have been deposited in the borderlands of the continent, particularly in the Appalachian region to the east, causing there a thermal blanketing with a consequent rise of gradients. As a result of this thermal blanketing the gradients for the Appalachians rose and attained their maximum, probably during the Permian or shortly thereafter. Since that time the area has been cooling, as much of the thermal blanket has been removed by erosion, consequently the gradients are not now as high and igneous activity has long since ceased. The gradients, however, are still somewhat higher than those for the Shield area and are given in Table X.

The supposed mechanism of the production of the thermal blanketing of the Appalachian area is shown in Figure I.

Rise of temperature gradients caused in the manner outlined above would furnish conditions conducive to the formation of magmas. The fact that igneous activity has taken place along the eastern seaboard of North America in late Palaeozoic time is now well established. According to Schuchert and Dunbar (18) "Extensive granites in the modern piedmont belt and probably



MECHANISM FOR REMOVAL OF RADIOACTIVE MATERIAL FROM THE SHIELD.

FIGURE I.

part of the granites of New England were intruded at this time (close of the Palaeozoic.) ---- Removal of the younger rocks from the intruded masses has made it difficult to date the granites with assurance, but the fact that their minerals do not show strain or shearing proves that the intrusion did not precede Permian thrusting." The obvious inference is that the igneous activity in the region mentioned is either Permian or younger. This is in keeping with the writer's statement that the temperature gradients for the region were at their maximum about Permian time. There was ample time during the Palaeozoic for the deposition of radioactive matter, removed from the Shield, which has largely, since Pre-Cambrian time, stood above the level of the seas.

Table X.

Location.	Degrees F per foot.
Gaines Junction Pa.	.01619
Ligonier Pa.	.01645
Ligonier Pa.	.01617
Ligonier Pa.	.01567
Bridgeport W. Va.	.01401
Fairmont W. Va.	.01521
Lake Shore Mine Kirkland Ont.	.0061
Kirkland Lake Mine	.0074
Sylvanite Mine	.0068
Hollinger Mine	.0044
McIntyre Mine	.0044
Dome Mine	.0050
Frood Mine, Sudbury Ont.	.0062

While, of course, the igneous activity in the Appalachian region does not prove that the theoretical thermal blanketing existed, the plausibility is greatly strengthened by this remarkable coincidence.

The Cordilleran region to the west was not affected by this thermal as early as was the Appalachian region. The great igneous activity marked by the Coast Range batholith began in ~~late~~ early Mesozoic, while the principal activity of the Appalachian area is Permian in age. The Corilleran region is still relatively hot, as can be seen by a comparison of gradients with those of the Pre-Cambrian Shield, from which the thermal blanket is supposed to have been derived. Table XI. shows gradients for the Cordilleran region.

Table XI.

Location.	Degrees C per Kilometre.
Comstock Nevada	58.40
Santa Maria Calif.	43.47
Longmont Colorado	43.85
Coalinga Calif.	36.00
Virginia City Nevada	62.00
Klamath Falls Ore.	71.20
Vale Ore.	93.00
Burns Ore.	106.71
Northern Ontario	7.5 to 11.5

Conclusions.

(1) Existing thermal conditions in the Pre-Cambrian Shield can only be explained by appealing to the loss of radioactive matter through erosion. Approximately 16 km. have been lost from the area since the close of Pre-Cambrian time.

(2) The lost materials were deposited in the borderlands of the continent causing a thermal blanketing. The result of this thermal blanketing was a rise in temperature gradient with resulting conditions conducive to igneous activity.

(3) The Appalachian region was first affected by this blanketing and showed activity during the Permian and shortly after. The Cordilleran region was blanketed later, with igneous activity beginning about Jurassic time. Gradients from the Pacific coast show that the Cordilleran area is still hot.

Chapter V. Geophysical Significance of Ocean-Bottom Sediments.

Evidence collected by C. S. Piggot, Pettersson, and Joly shows the radioactive content of ocean-bottom sediments to be from 2 to 10 times as great as the richest granites. The estimations of Piggot (19) are given in Table XII., together with determinations by Joly and Pettersson.

Table XII.

Radium Content of Ocean-Bottom Sediments.

Type of Sediment	Latitude	Longitude	Depth in Metres	Ra. Content
A. (after Piggot)				
Globigerina Ooze	2°30'S	95°43'W	3352	7.84×10^{-12}
Globigerina Ooze	3°15'S	99°48'W	3423	5.96 "
Red Clay	40°24'S	97°33'W	4007	3.20 "
Red Clay	31°38'N	124°48'W	4251	10.40 "
Red Clay	12°40'N	137°32'W	4918	21.40 "
B. (after Joly)				
Blue Mud	38°34'N	72°10'W	2268	3.1×10^{-12}
Globigerian Ooze	51°37'N	12°10'W	1040	6.6 "
Calcareous Mud	21°04'S	133°01'W	4069	22.2 "
Red Clay	10°38'N	105°47'W	3575	13.0 "
Red Clay	24°28'N	149°30'W	4298	52.6 "
Radiolarian Ooze	2°48'S	152°56'W	4755	22.8 "
Radiolarian Ooze	7°25'S	152°15'W	5030	50.3 "
C. (after Pettersson)				
Red Clay	36°48'S	42°45'W	3575	21.9×10^{-12}
Red Clay	37°38'N	39°36'W	5303	49.5 "
Radiolarian Ooze	3°48'S	152°56'W	4755	18.3 "

Globigerina Ooze	38°06'S	88°02'W	3337	4.9 x 10^{-12}
Radiolarian Ooze	11°24'N	143°16'E	8184	8.0 "
Red Clay	35°18'N	144°08'E	6629	5.4 "
Red Clay	139°28'S	149°30'E	4298	39.1 "

From the figures of Table XII. the following means are obtained:

Radiolarian Ooze	24.85 x 10^{-12} grs. Ra. per grm. of sediment
Red Clay	26.27 x 10^{-12} grs. Ra. per grm. of sediment
Globigerina Ooze	6.32 x 10^{-12} grs. Ra. per grm. of sediment

Allowing for the possibility that some of these determinations are too high and some too low, the radium content of ocean-bottom sediments is still several times greater than the richest rocks found elsewhere on the earth. At the present time the exact geophysical significance of these rich sediments is a matter of speculation, but some few inferences seem warranted by the known facts.

The importance of these sediments as geological agents is greatly dependent on their thickness. If they are thin their bearing on geothermal history will be slight. However, the probability of their being thin is slight; ocean basins are considered by most geologists to be of more or less permanent nature and deposition therein to have taken place over a vast period of time, these sediments may also be buried under lava, therefore the logical supposition is that ocean-bottom sediments are relatively thick.

Thich sediments of such high radium content would have a profound affect on the geothermal gradient, either as a blanket insulating the flow of heat from the interior or as providing a source of intense energy for that portion of the crust in which they are likely to be incorporated.

In view of the conditions outlined above, temperature gradients under the ocean floor are likely to be much higher than hitherto estimated. The lack of supporting evidence, in the form of determined gradients, leaves this statement in the realms of speculation, but the evidence available indicates that the gradients under the ocean may not be much lower than those for continental areas.

Chapter VI. Summary.

The writer has presented certain data and has endeavoured to present a comprehensible sketch of their bearing on the earth's thermal history. In conclusion, then, a brief survey of the writer's conclusions are here offered.

The quantity of radioactive elements present in the rocks of the earth is exceedingly minute. The range between the relatively poor and relatively rich rocks is very great. Exact reasons for this are, as yet, obscure; lack of evidence prevents any explanations. The distribution of radioactive matter in the accesible rocks is very irregular. Radioactive content appears to increase with acidity but the associations of these elements with definite rock types is, on the basis of present evidence, too indefinite to warrant the specific conclusions drawn by many geologists.

Natural waters carry very appreciable quantities of radium and thorium, mostly as dissolved emanations. Moving ground waters, therefore, are a very important factor in the determination of the distribution of the radioelements.

Available data on geothermal gradients and radium and thorium contents indicate that the major portion of radioactive materials is concentrated in a layer averaging 30 kilometres in depth, but varying within wide limits. This layer is thinest under the Pre-Cambrian areas. Pre-Cambrian areas are positive areas; they have been subject to erosion through long intervals. Evidence from the Pre-Cambrian indicates that younger rocks contain more radioactive substances than older rocks principally because they have suffered much less erosion.

The concentration of radium and thorium has a very important bearing on the temperature gradient. Some wide deviations in gradient over a relatively small area are directly attributable to no other cause than wide variations in radioactive content.

The lowness of the temperature gradients in the Canadian Shield area presents a very interesting problem. In the opinion of the writer they are due to the fact that the Pre-Cambrian has lost by erosion the majority of the radioactive materials which it originally contained. Approximately 10 miles is estimated to have been lost from the Shield by erosion. This material is supposed to have been deposited in the borderlands of the continent, principally in the Appalachian region, there causing a thermal blanketing with a consequent rise of the temperature gradients. This furnished suitable conditions for igneous activity such as has occurred in late Palaeozoic and early Mesozoic time, in that region. Thermal blanketing of the Cordilleran era, in the same manner, has been much more recent; the gradients are still high.

The high radioactive content of ocean-bottom sediments tends to keep the geothermal gradients under the ocean floor higher than was formerly supposed. If, and they most porbably are thick, they would form a thermal blanket insulating the flow of heat from the crust; further they would tend to supply a source of intense radiothermal energy to the crust.

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