THE UNIVERSITY OF MANITOBA

THE INTERPRETATION OF GEOTHERMAL GRADIENTS

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By

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Introduction

Temperatures within the depths of the earth have been for a long time a subject of much speculation. High temperatures within the earth have been definitely indicated by the existence of hot springs, volcanoes, lava flows, geysers and other natural phenomena which have been observed from earliest historical time. The writings of philosophers and scientists included observations of these phenomena and offered various explanations for their occurence. During the past fifteen years, because of its importance to the rapidly growing science of geophysics the thermal problem has been attacked with new zeal by both geologists and geophysicists. Geothermal gradients, which are determined by measurement of the increase of temperature with depth, and some of which have long been known, assumed new importance. The common usage has been to employ an average gradient in developing hypotheses to show temperature conditions in the earth.

Since new interest was shown in these gradients, greater attention has been given to their accurate determination. Many new measurements have been recorded and an increasing divergence from the commonly accepted average has been noted. This variation has been neglected by modern geophysicists, who in other ways have developed the geothermal problem in a very comprehensive manner. Some geologists have considered this divergence of the gradient to be of great significance and have expressed doubts as to the feasability of using an average value for purposes of extrapolation in depth. Recently J. S. DeLury (1) pointed out that the average gradient has been used to arrive at temperatures below the surface, and that the lowest gradient is the logical one to project for this purpose. He emphasized the variation in the gradient from region to region and its geological significance.

An attempt will be made to show that the variation of thermal gradients is vital to geothermal problems, and further to show that the interpretation of the gradients has an important bearing on many other problems of the earth such as, the relation of depth to fusion point, origin of magmas, strength of rocks, and origin of earth structure.

Geothermal Gradients

The geothermal gradient may be defined as being the increase in depth required for a definite rise in temperature. With an increase in depth the temperature of the rock rises steadily or, conversely, the temperature in the crust of the earth diminishes as it approaches the surface. This outward decrease in temperature corresponds to the heat flow which is lost into space. The gradients are obtained by measuring the ground and rock temperatures at different depths in bore-holes and in deep mines. For continuous determinations at shallow depths, thermo-elements or electric resistance theromometers are most convenient. In measuring the temperatures at greater depths, notably in bore-holes, the use of mercury theromometers in suitably constructed protective coverings is the preferred method. (2)

There are many factors which affect the steepness of the gradient in any one locality. The initial heat of the earth, which is commonly attributed to its former molten condition, supplies a steady outward flow of heat. Radioactive disintegration is an important source of heat and the gradient would be determined by the quantity and the duration of time in which the local supply has been generating heat. The gradient, which is believed to be determined by these two sources of heat is also affected locally by various other factors. The circulation of underground water at various depths may have a serious effect. Physical properties of the rock such as moisture content, conductivity, and specific heat also produce variations. Climatic conditions are responsible for near-surface changes in the gradient affecting the rock to a depth of from one to three hundred feet. Recently calculations have been made to show the effect of long-period surface temperature variations on the geothermal gradient. (3) It was found that the glacial epoch--Pleistocene Ice Age--was followed by a period with distinctly warmer ground temperatures, succeeded in turn by one cooler, which lasted until comparatively recent time. Elevations and subsidences, and dynamical and chemical action may also affect the gradient in some measure.

History of Geothermal Gradients

In ancient times, the natural events which took place in regions inhabited by man, were recorded but were accepted as more or less supernatural phenomena. Thus the occurence of earthquakes and volcanic eruptions, gave the Greeks a subject for speculation, and brought forth a number of treatises on their causes and relation to earth conditions. The work of Aristotle (384-322 B.C.) marked the culminating point reached by the Greeks, both in the domain of speculative philosophy and in that of empirical study. However the earlier philosophers did not show any particular interest either in the nature of the earth's interior or in the composition of rocks.

It was not until about the 15th century and after the close of the Middle Ages that a revival of learning spread through Europe. The first mention of temperature conditions with depth was made by a Jesuit, Athanasius Kircher (1602-1680) who in Book X of his famous work "Mundus Subterraneus" mentioned the question of temperature in mines. He pointed out that the miners of Neusohl, Hungary noticed that the temperature in the mines increased with depth. The same writer also states that the first observation of the continuous increase of temperature with depth was made by an official of the mines, Johann Schapelman: "In the mines the temperature steadily increases in proportion to the depth below the surface; where water lies, the heat is less; it is greatest in the parts of the mines where marcasite occurs." (4)

During the 18th century it was determined that external influences, such as air temperature, are reflected only to depths of about 30 feet, or at a maximum of 80 feet, according to the geographical position of the locality. At the so-called 'neutral-zone', or critical horizon of depth there is a constant temperature which practically corresponds with the average annual temperature of a particular region. Below this zone, the temperature increases in mines, and the increase can only be attributed to the earth's own heat. This increase of temperature was noted by Kircher and Boyle in the 17th century but it was not until 1740 that definite observations were made by Gensanne in the lead mines of Giromagny in the Vosges. Gensanne's measurements showed an increase of $1^{\circ}C$ for 34.5 meters of depth. Measurements were made in 1790 and 1791 in the Freiburg mines by Freiesleben and Alexander Von Humboldt. Lean made observations in the Cornwall mines, Fantonetti in Italian mines, and Alexander Von Humboldt in South American and Mexican mines. Cordier and Reich made measurements of rock temperatures in French mines and reported an average increase of $1^{\circ}C$ for 25 meters with variations to $1^{\circ}C$ in 42 meters.

Since 1828, temperature observations have been continuously made in the mines of S axony and Prussia, and these yielded an average of 1°C for 51 meters, but as the variations ranged from 14.6 to 108.2 meters per degree C., it was impossible to draw definite conclusions. In Great Britain, the British Association for the Advancement of Science, appointed a special committee for the investigation of ground rocks, and the relative conductivities shown by different types. Generally speaking the results yielded by borings showed an increase of 1°C in 30 to 34 meters.

The foregoing observations marked the earlier determinations of geothermal gradients from a purely geological standpoint. The beginning of modern hypotheses of earthtemperatures, using the determined gradients, began with W. Thomson in a mathematical paper published in 1861 (5). He attempted to determine the age of the earth from the known general increase of temperature with depth. He stated that the temperatures varied from 1°F for 110 feet to 1°F. in 15 feet but that it was commonly accepted as 1°F. for 50 feet as a mean. He assumed that the Earth was originally molten, that it cooled rapidly by convection until the solidification point was reached, and that cooling then proceeded by the much slower process of thermal diffusion. The problem becomes one of a cooling sphere with constant surface temperature, and the temperatures at any depth can then be calculated in terms of the original temperature and of the time since solidification. Thomson concluded that the earth had cooled from a molten condition to a solid having a rigidity greater than glass and probably greater than steel. The process of cooling involved the solidification of portions of the crust to a thickness which would cause sinking and this continued until the sunken portions of the crust built up a solid skeleton or frame in a honeycombed structure.

Following Thomson's calculations of the age of the earth as determined by the known temperature gradient, a number of geophysicists tackled the problem using similar methods. Holmes, Jeffreys and Adams investigated the geothermal problem and drew gradient curves showing their interpretation of temperatures at various depths. Before discussing their conclusions it is expedient to consider the prevalent view of the earth's initial thermal condition.

In the modified hypothesis of earth genesis - the tidal disruption theory of origin - favored by Jeans and the above mentioned geophysicists, it is held that the earth was originally entirely in a liquid state and that cooling was effected in a few thousand years by convection and radiation of heat into space. Then as the fluid cooled, the melting point was first reached at the core and proceeded thence outwards; meanwhile, convection currents kept the liquid in continual agitation until solidification occurred. The iron core and the outer shell would cool together until solidification began and convection would stopped at the outer margin of the core. From then on the core could cool only by the conduction of heat through the solid and therefore would be a small factor, owing to the slowness of conduction. In the silicate shell cooling would continue from the bottom of the layer outwards, convection currents probably still taking an active part, until the viscosity became too great for further circulation, the high temperatures diminishing rapidly until conduction became the important factor in the expulsion of heat. As the cooling continued crystallization took place, reducing the liquid layer to a thickness of the order of 100 kilometers. When in this last stage of solidification, incrustation of the surface would go on simultaneously with the freezing at the bottom of the liquid layer with the formation of a honeycombed liquid and solid structure.

Holmes' Views.

The general view in considering the temperatures at moderate depths within the earth, by direct projection of the so-called average gradient led to inconceivably high temperatures at distances of about 100 kilometers. Holmes (6) was the first investigator who attempted to remedy this by treating the problem quantitatively. By making use of the age of the earth, as determined by radioactive disintegration, along with the thermal diffusivity, density and radioactive heat, he calculated the temperatures at various depths within the crust. The equation he used was that given by Ingersoll and Zobel, in which the effect of radioactivity and the rate of cooling have been taken as factors responsible for the present temperatures within the earth. The curve obtained based on the average gradient of 1°C. per 32 meters indicated a temperature of about 1575°C. at a depth of 100 kilometers. This curve is thus favorable to conditions for vulcanism at relatively shallow depths. However in a later paper (7) he came to the conclusion that the temperatures as determined were probably too high. "Careful revision of the original work has been in the direction of indicating lower temperatures in depth, and as the original estimates are in my opinion inadequate to meet the réquirements of igneous processes, it follows that the difficulties to be faced are even more serious than they appeared to be at first." (7a)

Jeffreys' Views.

Jeffreys, using data and the method similar to that of Holmes, as well as the average gradient of 32°C. per kilometer, plotted a temperature-depth curve. He published two curves for the temperature gradients using slightly different factors, but his later curve showed higher temperatures with depth than the earlier one. Both graphs indicate lower conditions of temperature than those favored by Holmes.

"Three factors clearly affect the observed gradient; the conductivity of the sedimentary rocks where the gradient is measured; the radioactivity of the local rocks; and the vertical distribution of the radioactivity. All of these vary from place to place, and in the circumstances it is curious that the observed gradient varies so little. Thus Daly gives the increase of depth corresponding to a rise of temperature of 1°C. for 18 stations in Europe and 14 in North America; those for Europe range from 24.7 to 37.8 meters with an average of 31.7 meters and the American ones from 35.7 to 53.7 meters with an average of 41.8 meters. Apart from the systematic difference between Europe and America, which is hardly surprising, the range in each continent is only in the ration of about 2 to 3." (8)

From the results of the determination of temperature at depth Jeffreys calculated the heat output from the interior and consequently the thickness of the upper layer of rock, which he found to agree approximately with the first discontinuity as determined by seismology, namely 31 kilometers.

Adams' Views

Adams followed Holmes' method for determining the temperature at moderate depths within the crust, using data which differed from that of the latter. His curve gives lower temperatures for various depths than do those of Holmes. Further, because of the view that the surface gradient is usually underestimated he used a gradient of 1°C. in 35 meters. In considering the data he concluded that "The temperatures at various depths within the earth are unaffected by any reasonable variation of the initial temperatures in the upper 100 kilometers. The present temperatures depend almost entirely on the original temperatures at considerable depths." (9)

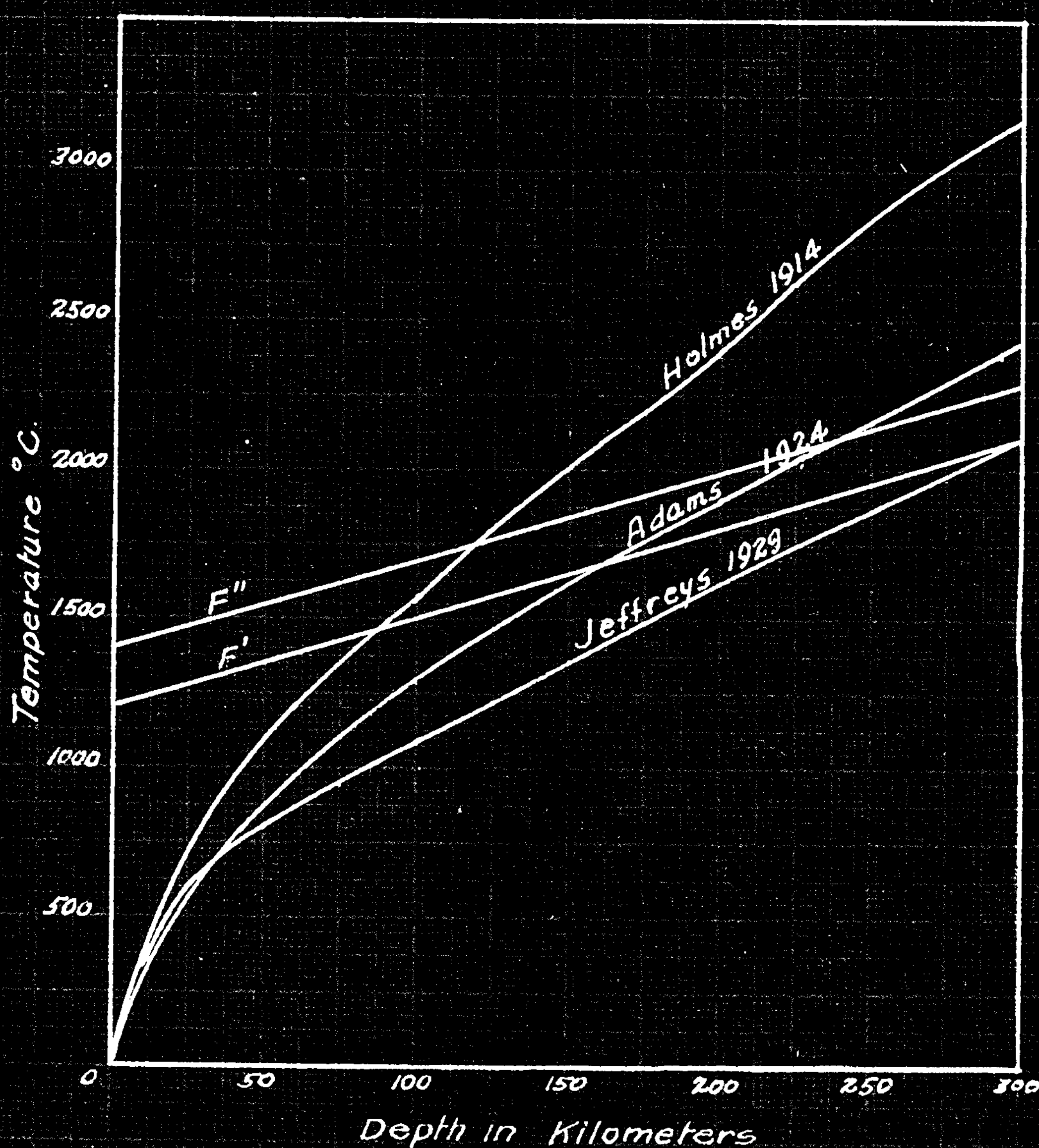

Figure 1. -- Temperature-Depth Curves.

F' and F" represent fusion curves with a gradient of [illegible]°C. per kilometer and a surface temperature of 1200°C. and 1400°C. respectively.

His curve shows that the temperatures at moderate depths are much lower than have been commonly assumed; at 100 kilometers the temperature is 1300°C., while by extrapolation of the superficial gradient it would be over 3000°C. The curve applies primarily to continental regions, and represents average thermal conditions at various depths.

Chamberlin's Views.

In discussing geothermal gradients, Chamberlin (10) states that a uniform average gradient such as 1°C in 32 meters cannot be accepted as a true conception of the heat evolved from the earth, even though the various factors such as inequalities of topography, circulation of water, conductivity chemical effects and compression effects are taken into consideration and allowed for. On projecting the gradients downwards to the earth's centre the temperature then would be abnormally high. His conclusion is, therefore, that the gradient becomes lower below the superficial zone. Barus' fusion curve projected to the center gives a temperature of 76,000°C. while Lunn's calculations from the compression give a central temperature of 20,000°C. Both of these values are much lower than that obtained by a rectilinear projection of the observed average temperature gradient. Also, according to the hypothesis of convective cooling, no sensible increase of temperature should occur below a depth of 200 or 300 miles.

Barrell's Views

Barrell discussed temperatures at depth in relation to the zone of magma formation and the asthenosphere. This latter is regarded as the region where the temperature curve becomes tangent to the fusion curve, but solidity is maintained by the recurrent emission of the material which becomes molten. A rectilinear downward projection of the temperature gradient observed at the surface would reach the fusion temperature of rocks at a depth of about 50 kilometers. Since this would contradict the suggestion of a deeper magma region there must be a marked curvature of temperature gradient. Such curvature would imply a greater outward flow by conduction of heat near the surface, due to the continued generation of heat by radioactivity; or also to rise of magmas from the asthenosphere. In the latter case, magmas which never reach the surface would bring heat by a convective process directly into the outer crust, and from there the heat diffused upward by conduction would increase the surface temperature gradient.

Stored quantities of heat brought up from the greater depths would be held in the crust for geologic ages, being dissipated in the course of time by conduction and tending to create a false impression of heat lingering from an initial molten state. Following this view the temperature gradient should naturally vary from place to place and at different intervals of time. Barrell's conclusion is therefore that igneous intrusion, and radioactive heat as well, are very important factors in accounting for the high temperature gradients. Barrell's views may be summarized by the following statement:

" If this view be true--that the invasive igneous rocks have been an important factor in determining the amount and distribution of heat in the crust--it is doubtful if any sound arguments can be derived from the study of the present gradients as to the initial temperature". (11)

Daly

Daly discusses geothermal gradients in relation to earth temperatures in order to arrive at what depth the outer crust changes to a glassy basalt substratum. In a comparison of gradients in Western Europe and Eastern United States, he finds that the average gradient for these two regions differ. The observed average gradient in North America is 1°C. in

42 meters as compared with the European Gradient of 1°C. for 32 meters. "The result is the suggestion that the surface rocks of North America are considerably cooler than the surface rocks of Europe." (12)

Further investigation showed that the rate of increase was more rapid at the bottom of the boreholes than near the top. This might be due to the influence of ground-water; also, the lowering of conductivity and therefore the diffusivity by increase of temperature in rock minerals. Daly further remarks that the rate of increase may fall away with depth, and as this rate of temperature increase, or gradient itself increases, down to maximum depths of more than two kilometers, it warrants the extrapolation of gradients down to 40 kilometers, at which depth rock matter cannot be holocrystalline.

Another fact brought out by Daly is that the mean rate of 3°C. per 100 meters represents a value derived from observations made at borings in sedimentary rocks, which for several reasons are likely to show especially high rates. The rate of increase in granite gneiss, which underlies most sediments and constitutes most of the continental crust is much lower. At Carnarvon, Cape Province, South Africa, the average rate is only 2°C. per 100 meters, and this result is obtained in gneissic rocks, "It is safer to estimate temperatures at depths of some tens of miles by assuming a rate of increase which is no higher than 2°C. per 100 meters." (13)

In Daly's latest discussion of the "Depths of the Earth" he assumes a new interpretation of geothermal gradients. (14) He recognizes the importance of radioactivity as a source of heat energy and states that probably half of the heat emitted from the earth is due to this source. Following the calculation of Holmes and Adams he calculates the temperatures to depths of his basaltic substratum and finds that the geothermal gradient as well as the temperature must be higher than those of the two former scientists. Daly therefore tends to allow higher temperatures at depth than were previously assumed. This allows for a process which he calls "Delayed tandem convection" whereby convection takes place in separate successive layers of the earth thereby cooling the hot interior.

Average Gradients versus Diverse Gradients.

From the foregoing studies it is shown that from the earliest records of the last century the value for the geothermal gradient was taken as one degree centigrade rise for every hundred feet of descent of 1°C. for 33 meters. The earliest determinations were made in the British Isles and Western Europe and there was very little variation from this average result. The first determinations in America were from the eastern portion of the continent in sediments very similar in age and composition to those of Western Europe and similar results were obtained. The "average" American gradient was 10 meters per °C. higher than that obtained in Europe but this was attributed to the general nature of the continent as a whole.

The average gradient of 1°C. per 32 meters was used by European geologists at an early date in the extrapolation of temperatures at depth. This was achieved by projecting the gradient downwards and determining from this the temperature at any depth to the centre of the earth. The results indicated that the earth was in a molten state at relatively shallow depths and an extremely high temperature at its center. Later speculations of geologists and geophysicists made use of this average gradient as a factor in the building of hypotheses on the thermal history of the earth from its early stages onwards.

As special geothermic surveys were not possible or warranted - being of no direct economic value - comparatively little information has been gathered upon this phase of the subject in any of the continents. The last few years has seen more attention paid to this study in North America, owing to its importance in the search for oil. Petroleum geologists and geophysicists have determined the gradients in regions where extensive drilling has been carried on. Thus certain localities have been explored rather completely but the gradients of the major portion of the continent have been determined only sporadically. Van Orstrand, of the United States Geological Survey, has done a great deal of valuable work in collecting gradients and in determining from these the isogeothermal surfaces. This work has only been possible in a few oil-producing States. Recently he made a survey of over 300 wells and carefully determined their gradients. His conclusions were that irregularities, over large areas, rather than uniformity, were the rule. (15)

Table 1.

Geothermal Gradients, (meters in depth for an increase of 1°C)

Holdenville, Oklahoma	8.4
Coalinga, California	9.2
Ozona, Texas	9.5
Comstock, Nevada	17.1
Longmont, California	22.8
Santa Maria, California	23.0
Longbeach, California	28.2
Average gradient	32.0
Kolar Mines, Mysore, India	33.2
Ligionia, Pennsylvania	35.0
Fairmont, W. Virginia	36.0
Homewood, Pennsylvania	36.7
Bay City, Michigan	36.8
Marietta, W. Virginia	37.9
Bridgeport, W. Virginia	38.4
Columbus, Ohio	40.0
Louisville, Kentucky	41.1
Calumet & Hecla, Michigan	60.7
St. John del Rey, Brazil	68.4
Mother Lode Mine, California	82.3
Frood Mine, Ontario	98.7
North Star Mine, California	104.1
Johannesburg, S. Africa	110.9
Dome Mine, Ontario	111.2
Hollinger, Mine, Ontario	120.4
McIntyre Mine, Ontario	126.8
Transvaal Mines, S. Africa	114.9-137.2

Table 1 shows various gradients determined mainly in North America, which have been taken from as extensive an area as possible. These gradients show that, aside from smaller variations in any one locality, there are more significant differences between one extensive region of a continent and another. Thus the Appalachian district, along the Eastern coast of North America, exhibits an average gradient slightly higher than that of the British Isles and Western Europe. However, the determinations of the Precambrian rocks in the Lake Michigan copper mines and the deeper mines of Ontario were much lower than this average. Also the gradients of the Western Coast in the Cordilleron region are much steeper than in Appalachian areas. This seems to indicate that there is more than a mere coincidence in the fact that the gradients should correspond with the geological history of each locality. The Precambrian Shield has not been thermally active since the beginning of Palaeozoic time. The high gradients seem to be characteristic of regions where comparatively recent rocks occurred, and mountain-building has taken place. That the low gradients are not only anomalous in the Precambrian Shield is verified by the similar values in the Precambrian rocks of South Africa and India.

Thus it may reasonably be said that low gradients are characteristic of the Shield areas or primary rocks of all the continents. The evidence from this table is that diversity of gradients rather than uniformity is typical for different localities of the continent.

The fact that low gradients exist is significant in dealing with the problem of earth temperatures. The hypotheses related to the thermal history of the earth, making use of an average gradient cannot readily explain the presence of exceptionally low gradients. In tracing the history of the earth from its origin, the generally accepted view is that there is still heat at depth resulting from the initial molten stage. This initial heat supplies part of that which is radiated from the earth's crust at all times. The low gradient places a limit on the amount of heat which can be radiated due to the initial temperature; it follows that the lowest gradient found anywhere would represent a maximum limit for the steady outward flow of that heat which is attributed to the earth's initial molten condition.

The Thermal History of the Shield

In North America, as in the other continents, the Precambrian period represents the oldest and most complex group of rocks in geological history. All the continents show traces or remnants of these old rocks which have been named Shield areas by Suess. The Canadian Shield represents the central core or nucleus of the North American Continent. This core has been welded into a rigid mass, not capable of further compression or folding, long before Cambrian time. The subsequent earth movements to which it had been subjected were only of the broad type, upwarping and downwarping, or changes of level without deformation.

In the Canadian Shield are represented the first and longest periods of thermal activity in geological history. Orogenic disturbances and igneous activity occurred continuously throughout the whole of Precambrian time. Mountains were raised and eroded in many successive periods. The whole region now represents a complex of granites and gneisses and also in places, considerable thicknesses of highly metamorphosed sediments. Sedimentary formatiions were present even in the earliest known group of rocks, indicating marine conditions and active processes of denudation at that early time. The Laurentian geosyncline was formed stretching 1400 miles from Labrador to lake Superior and at the end of the Archaeozoic era was folded into mountain ranges during the Laurentian Revolution. During the Proterozoic period the heat was not as intense and rocks were not subjected to such widespread metamorphism. The condition of these rocks implies in their more mature weathering and subsequent deposition the presence of the same agents as are now operative. During the Proterozoic era there were two major revolutions or periods of orogeny namely, the Algoman Revolution and the Killarney Revolution. Both periods were characterized by sedimentary formations interbedded with volcanics indicating more or less continuous igneous activity throughout.

The Shield thus represents the earliest rocks of the North American continent and the region where thermal adjustment should have been attained by the present time. During the subsequent periods of geological history the heat inherited from the prolonged thermal activity should have been dissipated. Since the area has been exposed for such a great length of time to epigene agents it is probable that the rocks richer in radioactivity have been eroded and deposited elsewhere. The loss of radioactive minerals together with the lower internal heat due to the long period of cooling should tend to reduce the temperature gradients to a minimum. Therefore, the low gradients obtained are to be expected and conform with the present conditions as interpreted from the thermal history.

Current Geothermal Conceptions

The usage of the average gradient, i,e. 1°C. for 32 meters of depth has been questioned by some geologists but their problems did not directly concern the nature of thermal conditions within the earth. Barrell remarked, however, on the probable effects of igneous intrusion which could bring stored heat from depths to the near surface and thus tend to raise the gradient. These effects of intrusion could not be considered in the calculations of Holmes and his co-workers as it is scarcely possible to indicate various thermal conditions on one curve. If separate curves are used for each typical locality, however, a more favorable approach to the solution of the problem may be attained.

Holmes and Jeffreys regarded Adams' curve as being the most logical, to depict the thermal condition of the earth. This curve however, cannot very well be taken as the logical one representing thermal conditions in the earth. Geological evidence shows that the continents are, at least in the upper crust, heterogeneous in composition and local variations cannot be explained away by the use of one representative gradient or curve. It seems more logical, if an average gradient is employed, to use a low gradient such as those of the Shield to denote initial thermal conditions and to this value add the increase brought about by the various shallow sources of heat. Holmes, Jeffreys and Adams take the period of time since consolidation began as 1600 million years. A sample of Uraninite from a pegmatite in one of the youngest Precambrian rocks of Manitoba gave the age as over 2000 million years. (16) Other determinations also point to similar results for the age of Uranium-bearing minerals. Doubtless the consolidation of the earth must have been effected long before the formation of these minerals, so that the age of the earth should be taken as at least 2500 million years and possibly as much as 3000 to 5000 million years. This factor alone should have an appreciable effect on the cooling curve from the time of consolidation of the earth and would tend to decrease the gradient in the curves of the above authors.

It is interesting to note that Holmes, in his quantitative treatment of heat due to radioactivity and that due to the initial cooling finds, on the basis of the average gradient of 1°C. per 32 meters that radioactivity is responsible for three quarters of the present heat lost by conduction and radiation. (17) From this computation he concluded that the heat issuing from the earth due to its initial thermal condition is .00008°C per cm. or approximately equal to some of the present gradients in the Canadian Shield. Now the gradient of this area is probably too high to give a fair approximation of the heat due to the initial state. Since the Shield is composed mainly of granitic rocks, which are believed to carry the highest concentration of radioactive matter, the heat due to this source should be a considerable factor in raising the gradient. The curve indicating initial heat due to the earth's cooling should, therefore, probably be lower than 8°C. per kilometer. If we assume, as Holmes does that the heat due to radioactivity is responsible for 3/4 of that evolved, then the gradient representing the original thermal output should be 2°C per kilometer. This estimate is in all probability too low, since, as will later be shown, the granites of the Shield are lower in radioactive mineral content than the average granites of later ages.

The Relation of Radioactivity to Geothermal Gradients

The geothermal gradient of the average region depends mainly on two major factors, viz., initial heat from the molten earth and upon radioactivity. The low gradients obtained in the Precambrian Shield indicate that the heat from these sources is small, not more than between 8°C and 12°C per kilometer. The gradients measured in the Precambrian region were taken in rocks of granitic composition and therefore should contain some radioactive minerals. The average distribution of radioactive minerals as determined by Holmes and Joly is considered as 3×10^{-12} gm. of radium per gram of granite and 2.0×10^{-5} gm. of thorium per gram or rock. also the average content for basalt rocks was found to be 1.19×10^{-12} gm. per gm of radium and $.77 \times 10^{-5}$ gm. per gm. of thorium. Lavas which have been extruded are found to be more radioactive than plutonic rocks. Also granites are more radioactive than basalts. There is thus a decrease of radioactivity with increasing basicity and also with increasing depth. The conclusions arrived at therefore are that the radioactive minerals are confined mainly to shallower depths.

In examining the radioactive content of granites of various ages it has been found that a large number of the older rocks of Precambrian age are less radioactive than the later granites. Sederholm (18) found, in studying the geology of the Baltic Shield, that of the four widely distributed groups of granites, the oldest gneissose granites, are chemically far poorer in the radioactive elements than the later granites. The age of the granites affects the content of radioactive elements to a very great degree, the order being increasing richness of radioactive matter with younger granites. Radioactive determinations in the Precambrian rocks of the Kolar Gold Fields near Mysore, India, have shown surprisingly low radium content (19). The gradient of these gold fields was also found to be correspondingly low. It is possible that since radioactive minerals are confined to shallower depths, the older granites which have been exposed to denudation during the greater part of geologic time, have suffered loss of the richest radium-bearing materials by erosion. The loss of this heat source would be an important factor in lowering the gradient, and offers a plausible explanation of the low values obtained in Precambrian rocks. Although the radium content of the Precambrian rocks is low, there must be some heat attributed to this cause so that the initial gradient would be even lower than the amount indicated by measurement. The gradient which would best depict the flow of heat from the interior may therefore be of the order of 5°C per kilometer of depth.

The amount of heat generated by radioactive elements in their decomposition has been calculated with a high degree of accuracy. The values as determined by physicists are 5.6×10^{-2} calorie per sec. for one gram of radium in equilibrium with all its related elements and 6.6×10^{-9} cal. per second for one gram of thorium. To determine the average amount of heat generated by the radioactive elements in each cubic centimetre of rock it is necessary to combine the average quantities of radium and thorium in the rocks with their respective heat generating capacities. An average radioactive content of three Archean granites was taken , the result being 1.56×10^{-12} gm. for radium and $.51 \times 10^{-5}$ gm. for thorium. In comparison with the foregoing result the radioactive content of average granites of a later age was also determined. The following table shows the relative quantities of heat thus produced.

Table II

Type of Rock	Archean Granite	Average Granite
Specific Gravity	2.66	2.66
Radium in g. per cc.	4.15×10^{-12}	5×10^{-12}
Thorium in g. per cc.	1.35×10^{-5}	3.25×10^{-5}
Heat produced from Ra. in cal. per sec. per cc.	23.24×10^{-14}	28×10^{-14}
Heat produced from Th. in cal. per sec. per cc.	8.91×10^{-14}	21.45×10^{-14}
A = total heat produced per cc. of rock in cal. per sec.	32.15×10^{-14}	49.45×10^{-14}

The total amount of heat Q lost by the earth is given by the equation $Q = 4\pi r^2 . K \frac{d\theta}{dx}$

where $4\pi r^2$ is the area of the earth's surface, k is the conductivity of the rock and $\frac{d\theta}{dX}$ is the geothermal gradient. The volume of rock required to maintain the earth in a state of thermal equilibrium is given by Q/A where A is the total heat production per cc. of rock due to radioactive disintegration. The depth of the layer in which radioactivity is concentrated is given by

$$D = Q / 4\pi r^2 . A$$

From these two equations it follows that $AD = \frac{Q}{4\pi r^2} = K \frac{d\theta}{dx}$

$$\text{or } D = K \frac{d\theta}{dx} / A$$

The conductivity of acid rocks is taken as .005 and using temperature gradients from 2°C to 10°C per kilometer the following table shows the corresponding thicknesses of the radioactive layer.

Table III

Type of Rock	Archean Granite.					Average Granite	
K	.005	.005	.005	.005	.005	.005	.005
$\frac{d\theta}{dx}$ in °C.	.00002°	.00004°	.00005°	.00008°	.0001°	.00032°	.00056°
D = thickness	3.1 km.	6.2 km.	7.8 km.	12.4 km.	15.5 km.	32.5 km.	56.6 km.

This table shows clearly that under these conditions the thickness of the layer required to supply the heat is directly proportional to the geothermal gradient. The layer of radioactive material is thicker in the regions having a high gradient and high radioactive content than in areas such as the Shield. Jeffreys' calculations showed the thickness of the upper layer to be between 10 and 12 kilometers in Great Britain and the adjoining parts of Europe, including the Alps. The foregoing results indicate the possible thickness of the radioactive layer as 12 to 15 kilometers in an area such as the Shield. Further the thickness of the layer varies from region to region with the gradient and the quantity of radioactive minerals.

Quantitative Determination of Initial Temperature Curve

In 1915 Holmes (20) made mathematical calculations to determine a temperature gradient curve using several factors including that of radioactivity and the initial temperature gradient. He followed an equation which was presented by Messrs. Ingersoll and Zobel of the University of Wisconsin (21). Jeffreys and Adams also used this equation in arriving at their interpretations of the temperature-depth curve. However, instead of using one equation Holmes resolved this equation into its two components giving one for the initial heat of the earth and the other for the heat due to radioactivity. The equation representing the heat due to the initial thermal condition is

$$\Theta'' = mx + S \cdot \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2h\sqrt{t}}} e^{-\beta^2} \cdot d\beta$$

where θ" = the temperature

m = the original temperature gradient of the liquid mass.

s = the initial temperature at or just below the surface.

x = the depth in meters.

h = the diffusivity of rock

t = the time since consolidation began.

The value of the integral attached to s has been determined and can be obtained for different values of $x/2h\sqrt{t}$ = .00212x from a table of probability functions (22).

The initial temperature at or near the surface is taken as 1200°C. This value is based on experimental evidence of the melting of granites and also actual observations of molten lava flows. The original temperature gradient in the liquid mass is taken as 3°C per kilometer which is the value favored by Jeffreys. The diffusivity of rock or value 'h' is determined experimentally and has a value of .084. The time or period since consolidation began is taken as 2500 million years or 3.15×10^9 secs. The value of $x/2h\sqrt{t}$ yields 00212x and using this factor the probability integral may be determined. The following table then gives the values or temperatures at different depths in the earth up to 1000 kilometers in depth. The resulting gradient as shown by the curve plotted is a little over $5^{\circ}C$ per kilometer which is the value determined from the Precambrian gradients previously. Therefore, the present initial temperature gradient may be taken as about $5\frac{1}{2}^{\circ}C$ per kilometer.

Table IV

x kms.	mx°C.	p prob. integ.	Sp(°C)	θ"(°C)
10	30	.0237	27	57
20	60	.0474	57	117
30	90	.0715	85	175
40	120	.095	114	234
50	150	.1192	142	292
60	180	.1425	170	350
70	210	.1658	198	408
80	240	.1889	225	465
90	270	.2125	254	524
100	300	.2357	282	582
150	450	.3471	416	866
200	600	.4512	541	1141
250	750	.5465	655	1405
300	900	.6316	757	1657
350	1050	.706	847	1897
400	1200	.7692	922	2122
450	1350	.8227	986	2336
500	1500	.8661	1039	2539
550	1650	.9008	1080	2730
600	1800	.928	1113	2913
1000	3000	.997	1196	4196

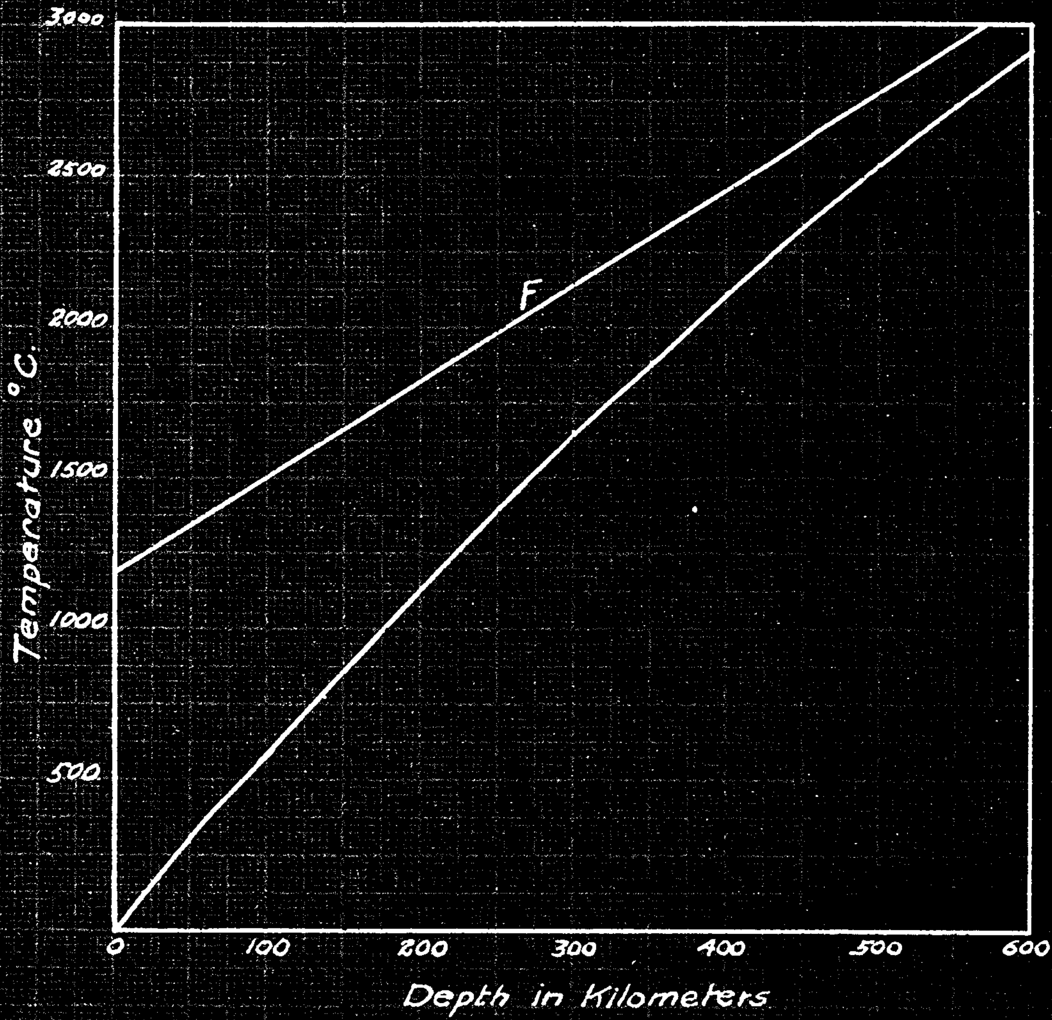

Figure 2.-- The Initial Temperature Curve.

This curve represents temperatures at depths where shallow sources of heat do not affect the geothermal gradient, that is in the regions where isogeotherms become smooth and concentric. F represents the fusion curve.

This gradient, thus determined will, therefore, represent the heat issuing from the depths of the earth due to the initial molten condition. Above the region of smooth isogeotherms the other thermal factors which are shallow effects, will combine with this gradient giving the various gradients which are obtained at the surface. At a depth of 100 kilometers the temperature is about 582°C which is far below the fusion point of rocks at this depth. This means that the strength of rocks at this depth is probably higher than at the surface and that the rocks are in a crystalline condition.

Temperature - Depth - Fusion curves in Relation to Magma Formation

There has been a great deal of speculation regarding the temperature at which magmas were formed at depth. Experiments in the laboratory show that granites melt at much lower temperatures than basalts, the difference being of the order of about 200°C (23). According to Larsen (24) the temperatures vary considerably, direct measurements on basaltic lavas at Kileau showing ranges of from 750°C to 1200°C. F rom the inversion temperature of quartz and the general characteristics of this mineral in rocks it is probable that magmas crystallize above 573°C. Larsen's conclusions are that basaltic magmas have temperatures below 870°C, few are as high as 1260°C and probably most are not above 800°C to 900°C. It is possible, however, that ground waters may have had a marked effect in lowering the melting point of these surface molten lavas.

It is quite obvious that pressures also have a marked effect on the melting or fusion point of magmas. Various investigators have shown that the fusion temperature increases with pressure and therefore with depth. Vogt's work, as well as that of Barus, Tammann and others showed that for every kilometer of rock the pressure increased by a definite amount (ranging from 2.5°C to 5°C). Jeffreys and the present theorists use an increase of 3°C per kilometer in calculations of the fusion point with depth. There are doubtless other factors besides the pressure effect in the fusion or melting point of rock. Mineralizers and water vapor would tend to lower the fusion point; Morey and others extimated that each percent of water added to a magma reduced the melting point about 50°C. While it is relatively simple to determine the increase of melting point with pressure, it would be difficult to estimate the amount of mineralizers present; this factor then will have to be excluded in considering the fusion curve. Using the pressure gradient of 3°C per kilometer, the fusion curve will be a rectilinear projection, starting with a surface temperature of molten magma.

Jeffreys claims that the melting point of rock under surface conditions is 1400°C but this result is rather high. The study of lava flows and laboratory experiments indicate that 1200°C should be the melting or fusion point of rock under surface conditions. In considering temperature-depth curves, if the pressure-depth curve is superimposed, it is obvious that where the two intersect, conditions favoring magma formation should exist. Thus the temperature and depth of magma formation vary according to the interpretation of thermal conditions of various hypotheses.

Figure 3 shows the curves of gradients in three typical areas of the North American Continent, namely, the Shield, the Appalachian district and the Cordilleran region. The fusion curve in this diagram indicates that magmas may form at less than 50 kilometers in areas of high gradients; depths of 100 kilometers in intermediate regions and with the low gradient at depths greater than 700 kilometers. Gradients lower than those of the Shield area would probably never cut the fusion curve at any depth at which it would be permissible to extrapolate the two curves. It is likely that at great depths the curves run parallel or almost parallel to one another and so the zone of magma formation does not occur in the deeper layers as a result of initial temperature alone.

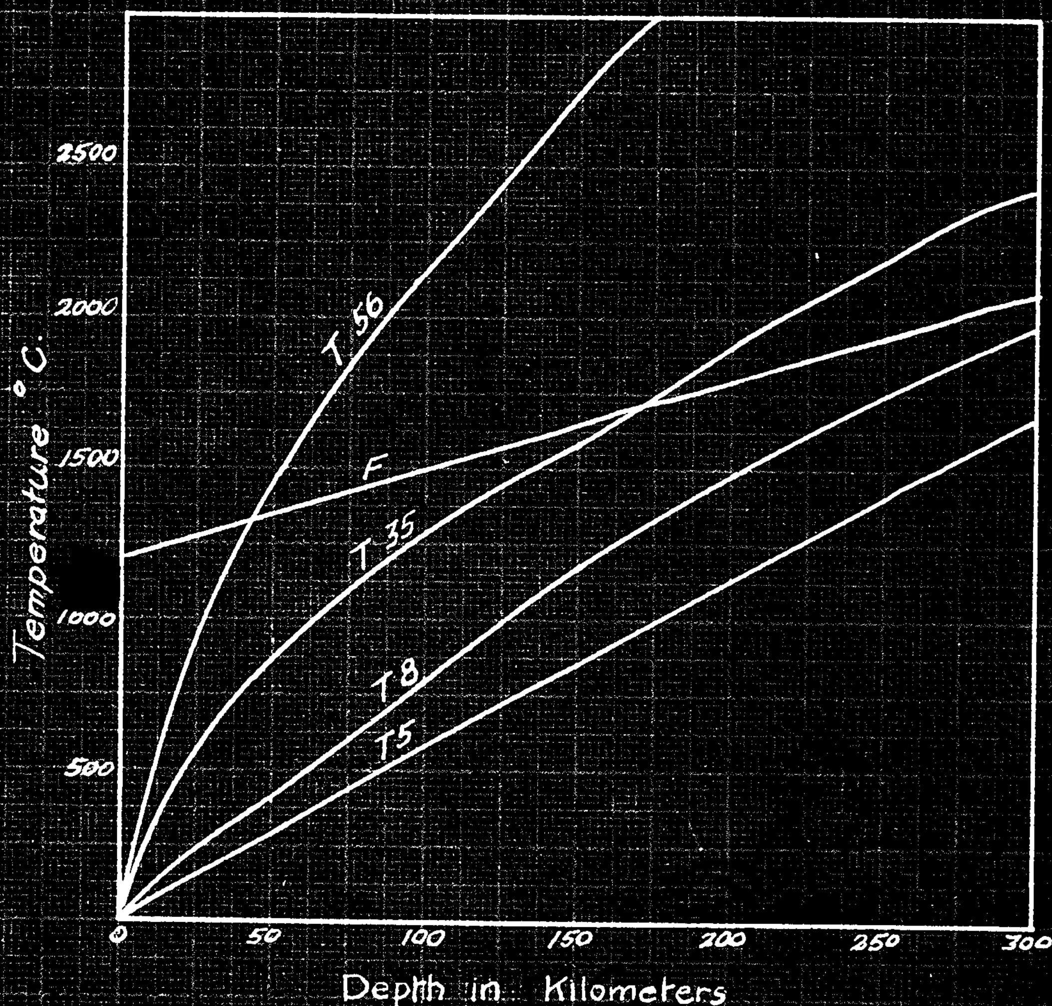

Figure 3.-- Diverse Gradient Curves.

T 56 represents gradients such as are found in the Cordilleron region. T 35, those of the Appalachian district, T 8 the Precambrian Shield, T 5 the initial temperature curve. F represents the fusion curve. Where it cuts the gradient curves magma may form.

Nature of the Temperature Curves at Depth

The theory of convective cooling of the earth from an initial molten condition is at present favored by most geophysicists in considering thermal problems. A necessary outcome of this theory is that temperature conditions in the deeper layers of the earth should be fairly uniform, that is, the gradient from the bottom of the outer shell of silicates to within about 300 kilometers from the surface should be very small. Now if the temperature within this layer is fairly uniform and the amount is believed to be between 1000°C and 1400°C it is obvious that gradient curves extrapolated to these depths should join the temperature curve denoting initial earth gradient. This means that various temperature curves depicting the rise of temperature in the outer few hundred kilometers of the earth should tend to curve downwards after passing a certain maximum and ultimately should join the curve representing initial heat of the earth. On this basis of convective equilibrium we must conclude that the temperature below 300 or 400 kilometers to the bottom of the outer shell at 1200 kilometers is fairly uniform and the gradient in this portion of the earth is relatively low. Adams uses a gradient of 4°C, Holmes 5°C and Jeffreys 3°C per kilometer as the probable initial gradient. The heat evolved from the upper part of the earth's crust is the sum total of that heat due to this initial condition, to radioactive heat, and to heat from compression or mechanical energy due to subsidence. That subsidence is a major factor in causing rise of temperature has been shown in a recent paper (25) by J. S. DeLury.

The outer shell or crust of the earth is the region in which the more important thermal phenomena probably take place; that is, lava flows, volcanic activity etc. are all near-surface in origin. It is believed that radioactive minerals are confined to the shallower portions of the crust, i.e. to a depth of about 50 kilometers. Igneous activity takes place at unknown depths in the crust but from geological evidence it is likely not more than 100 kilometers. The present exposed batholiths of the Shield which represent igneous activity were probably covered by 10 or 15 miles of sediment indicating a total depth of 20 miles or 25 kilometers below the surface. Similarly subsidence or changes of level tend to affect portions of the near surface; according to isostasists, the depth of compensation is 60 kilometers. Since all these factors which increase temperature are near surface phenomena, it is likely that there is a maximum temperature reached at shallow depths and below this temperature decreases, ultimately joining the steadily increasing curve representing initial temperature.

Holmes and Adams project their temperature-depth curves to depths of 300 kilometers as representative of thermal conditions at moderate depths; their respective values are 3000° and 2400°C at that depth. Jeffreys in the first edition of his volume "The Earth" presented a curve in which at 300 kilometers the temperature was represented as about 1000°C and increasing to a depth of 750 kilometers where it joined that representing the initial heat. Figure 4 shows the type of curve here suggested to denote conditions at various depths within the earth. Near the surface at shallow depths three curves are shown representing localities with different gradients varying from the lowest to the highest, thus depicting thermal conditions in shallow levels. The lowest curve, which the other three join at various depths, represents the heat flow from the interior of the earth due to the initial molten condition. The first three curves representing various gradients rise or increase according to the depths at which the shallow heating effects occur, but they reach a maximum point and then fall to ultimately join the curve representing the initial temperature.

The nature of the curve, once it has passed its maximum point, is highly conjectural and depends entirely

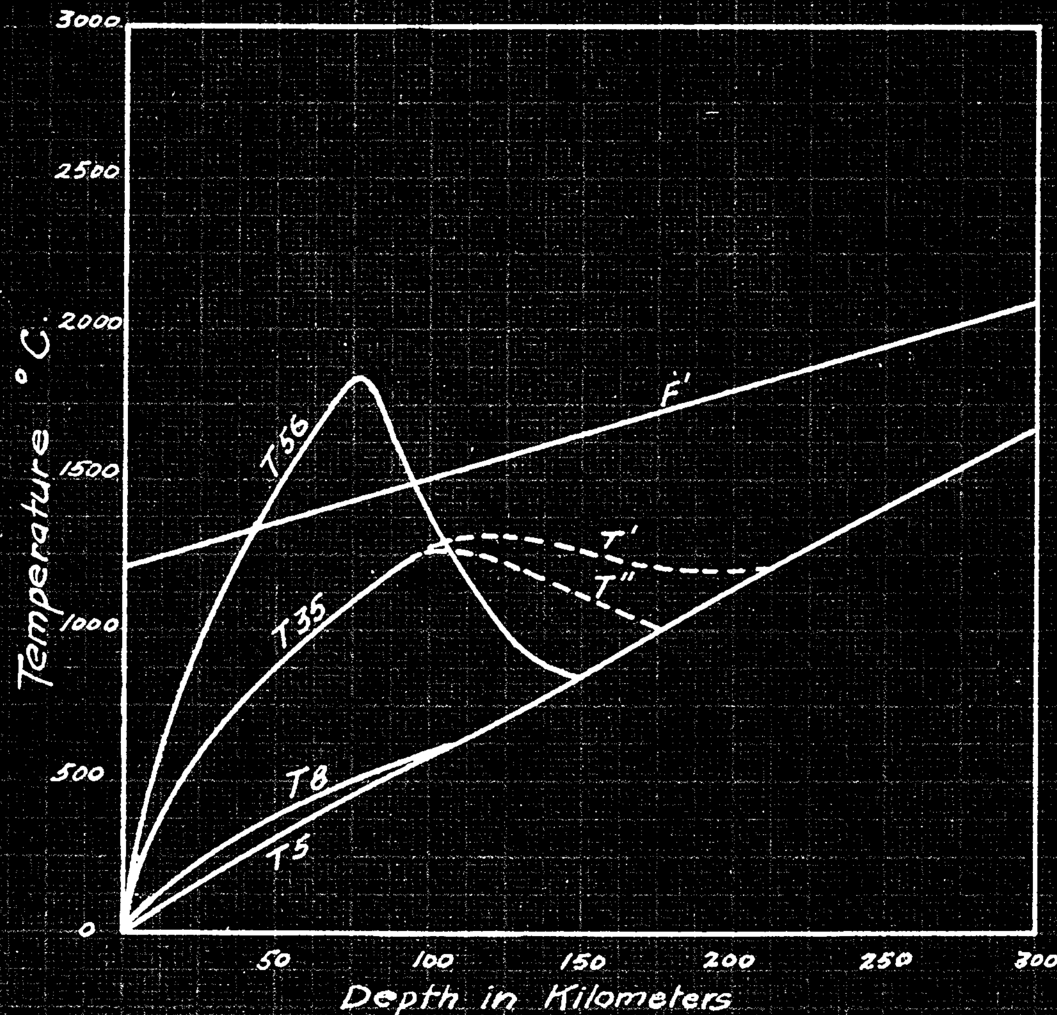

Figure 4.-- Nature of Gradient Curves at Depth.

The gradient curves for the various regions reach a maximum and then decrease to join the curve representing the initial temperatures at depth, i.e. where isogeotherms become smooth. Curves T' and T" show the effect of different heat sources on the rate of cooling in shallower levels.

on the sources of heat responsible for the high temperatures of that particular region and on the length of time permitted for thermal adjustments. If radioactive disintegration is the main factor, the time of heat generation will affect the temperature in the shallower portions of the crust and the slope of the curve will be fairly steep, bending downwards to join the initial heat curve at relatively shallow depths. If the cause of heat is a relatively thin sheet of migrating magma there will be a heating effect inwards as well as outwards and the curve will slope gently meeting the lower curve at greater depths. In this case the conductivity of the deeper rocks is less than that of the shallower rocks so that the curve will not slope as steeply past the maximum. The time factor would also affect this curve as the magmatic body would cool and the character of the curve would change with increasing age. Thus in the Cordilleran region where high gradients occur the reason for the high temperatures may be attributed to both radioactive heat and that from migrating magma. In the Appalachian region, there has not been igneous activity for a long period and the medium temperatures there are probably due mainly to radioactive heating and less likely, but perhaps partially, to residual heat from the effects of the igneous activity of the Palaeozoic era.

The Locus of Magma Formation as Interpreted from Temperature Gradients

Isogeotherms are hypothetical surfaces through the earth's crust joining points of equal temperature at various depths. Van Orstrand (26), considering the nature of geotherms in an hypothetical earth, i.e. an oblate spheroid free from oceans, valleys, and mountain chains finds that the isothermal surfaces would be oblate spheroids on which the flattening near the poles would be a little greater than that of the earth itself. Assuming that this earth had cooled from an initial temperature throughout its entire mass to a temperature at the surface of the equator of 100°F and 0°F at the poles, he finds that for values of temperature between these two amounts the geotherms would intersect the surface on parallels of latitude, while for temperatures in excess of this amount the surfaces would be complete oblate spheroids.

Actually there exist within the earth deviations from this ideal state, produced by oceanic depressions, mountain ranges, and geological structures and formations. The outer narrow shell of the earth from the surface to about 30 or 40 kilometers is known to be heterogenous in character, i.e. although granitic rocks prevail there are notable horizontal variations in composition.

From seismological data, discontinuities at this depth indicate a transition to another state of matter, probably a change to denser rock material. At greater depths within the crust the material probably becomes fairly homogeneous with compositional concentric zoning, and it may be assumed that at depths from 100 to 200 kilometers, surface deviations should have no marked effect on the isogeotherms. These surfaces would therefore be a series of concentric spheroids at regular intervals depending on the thermal gradient at that depth.

This distribution of isogeothermal surfaces within the earth together with the variation in gradient over large areas affords a method of approaching the approximate depth at which magmas may form below the surface. This may be best illustrated by taking a hypothetical section of the earth, one thousand kilometers long and two hundred and fifty kilometers in thickness, with high gradients at the center and low gradients at either end. The isogeothermal surfaces for 1000°C lie close to the surface in the central portion of this area and curve downwards to relatively greater depths at the outer margins. Figure 5 shows the nature of these surfaces using the values taken

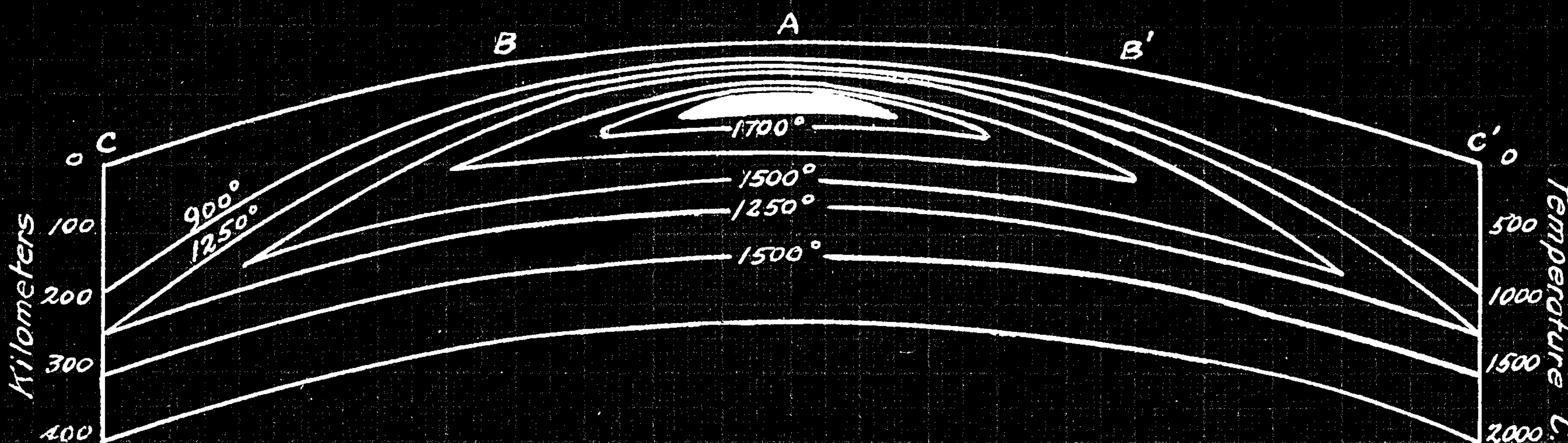

Figure 5.-- The Locus of Magma Formation from Geoisotherms.

Section of outer earth shells about 1000 kilometers long and 400 kilometers thick. The geoisotherms become smooth at about 250 kilometers, and above this level in regions of high gradients such as at A magma is formed at about 50 kilometers.

from figure 4. At 'A' temperatures of 1000°C. are attained at 30 kilometers in depth while at 'C' at a depth of 175 kilometers and isogeothermal surfaces should be smooth and concentric running parallel to the outer surface of the earth. The 1000°C. isogeotherm from regions close to 'A' will then join that of the region of low gradients, enclosing a portion of the earth crust in which higher temperatures occur. In this enclosed area the temperatures near the surface are higher than at depth so that the isogeotherms resemble convex surfaces, a few kilometers apart near the surface and tens of kilometers apart at depth. The ultimate result is that at relatively shallow depths - about 50 kilometers is indicated in the figure - a lens-like mass of rock is obtained, which has a temperature high enough to form magma under the existing pressure conditions. This result is obtained with a gradient of 56°C. per kilometer. Where the gradients are higher than this the zone of magma formation may be considerably less than 50 kilometers, and varies with the factors determining the gradient, which are mostly shallow in effect.

The Relation of Low Temperatures to Physical Properties of Rocks

Geophysical interpretation from all the available evidence permits a fairly complete picture of the nature of the earth as a whole. Studies of seismology, chemical composition of the abundant surface rocks, distribution of densities and the mean density of the earth, origin of the earth, and composition of meteorites all lead to the conclusion that the earth consists of a series of shells surrounding a metallic core. From the surface to a depth of 2900 kilometers there are a series of shells or layers of silicates ranging from extremely acid to densely basic. From 2900 kilometers to the centre at 6,370 kilometers there is the core of the earth, believed to be composed of nickel and iron. The general view is that to a depth of 40 kilometers the Sial or outer shell of the earth is composed of dominantly acid rocks. Underlying this shell is a layer of basalt, or basic rock, to a depth of 60 kilometers. Another discontinuity is indicated by earthquake waves at a depth of 1200 kilometers, suggesting a change in density at this level. The outer shell is the portion which is unstable and in which horizontal variations are responsible for the major changes that prevent a condition of thermal equilibrium.

Rigidity (form-elasticity) is a property of matter in the solid state and is the elastic resistance of a solid substance against deformation. It exists in degree and only up to certain limits of temperature and stress. The rigidity of the earth, as determined by gêophysicists, is accepted as twice that of steel. With the conception of low temperatures occuring below the region of shallow heat sources the rigidity should therefore steadily increase. It would be governed by the relation of temperatures at depth to the fusion curve. Figure 2., which shows that the temperatures are below the fusion point at a depth of 600 kilometers allow the suggestion that the rigidity increases steadily at least to this depth.

Strength is the ability to resist permanent set under long enduring pressure. It depends on the relation of temperature to the fusion curve and upon the cubic compression. Experimental evidence has shown that the strength of ordinary rocks increases enormously under confining pressures corresponding to those which exist up to a depth of at least 11 kilometers. (27) Temperature tends to reduce the strength of rocks and as the fusion point is approached this property is nullified. With low temperatures to depths of 600 kilometers the strength of rocks should increase steadily. This means that there should not be a universal zone of weakness at shallow depths such as is postulated by isostasists. This view has already been presented by J. S. DeLury (28).

Weakness would then be a local phenomena in different depths and would be characteristic of regions of high temperature and therefore steep thermal gradients.

Conclusions.

Geothermal gradients supply an excellent means of approaching the highly problematical question of temperature within the depths of the earth. A survey of reliable gradient data shows that gradients vary greatly in their steepness from place to place in the outer shell, in fact, diversity is the rule rather than the exception. The gradients vary from very low, such as 8°C per kilometer, to very high, 60°C per kilometer. In extrapolating these values, to obtain the temperatures at various depths, it is logical that the lowest gradient be used. The reason for this is that there are shallow sources of heat and if there is initial heat from the original molten condition of the earth, the lowest gradient will place a limit on the amount attributed to it. It is likely that even the lowest gradient is too high to represent the initial heat which is radiated from the earth, because no shallow rocks are entirely free from radioactive minerals.

Radioactivity is an important source of heat in determining the gradient of any region. Old granites such as those of the Canadian Shield contain less radioactive minerals than do those of younger age.

The radioactive elements are largely confined to the shallower rocks and decrease in amount with increasing basicity of the silicates. An approximation of the thickness of the radioactive layer may be obtained, from the conductivity, radioactive content and thermal gradient of any region. The low gradients found in the Canadian Shield may be due to the absence of the richer radioactive materials which probably have been eroded and deposited elsewhere by epigene agents.

An approximation of the temperature at depth was arrived at by quantitative treatment using the following factors; diffusivity, initial temperature at the surface, initial temperature gradient in the molten mass, age since consolidation. The result gave a temperature-depth curve indicating relatively low temperatures in the interior, and a low gradient of $5\frac{1}{2}^{\circ}$C per kilometer at shallow depths and decreasing to $4\frac{1}{2}^{\circ}$C perkilometer at 600 kilometers. Considering the factors used, the time since consolidation began has not a very great effect in lowering the temperatures. The age is so great that a steady state has probably been reached and cooling proceeds at a very slow rate. The initial gradient also has not a great effect in lowering the temperatures. The important factor is the initial temperature at, or near the surface of the molten mass. In the quantitative estimates this factor was taken as 1200°C. If the temperature were 1000°C, the resulting present temperature would be 200°C less than those shown in table 4. However, the determination serves its purpose as an approximation to the thermal conditions at various depths.

The initial temperature curve, which may be extrapolated to great depths represents the amount of heat radiated into space from depths at the present time. In the outer shell, the various sources of heat cause an increase in the gradient and may explain the variations which are obtained at the surface. Therefore in attempting to depict the thermal conditions in depths, it seems logical to use an interpretation such as is shown in figure 4. The gradient curves of various localities all increase to a maximum and then fall to join the curve representing temperatures in the deeper shells of the earth.

Geotherms in the outer shell are apportioned unsymmetrically and vary from region to region with the diverse gradients. At depths of from 150 to 300 kilometers they tend to become smooth and concentric. This is where the diverse gradients all decrease and combine to give one constant value at depth. The fact that gradients vary from high to low in an extensive region, offers an explanation of the nature of magmas and the depths at which they may form. Figure 5 shows a possible interpretation of the geoisotherms and the depth at which the magmas are formed. This depth varies with the gradient and may be from 25 to 100 kilometers. Magmas are therefore largely confined to the outer shell.

Temperature variations are confined to a large extent to the shallower portions of the earth, generally spoken of as the outer shell. The gradients vary extensively from region to region in the continents. At a depth of between 100 and 150 kilometers the gradients decrease to one low value, namely that representing the initial temperature conditions in the bulk of the earth. Magma formatim is also confined to the outer shell, in which levels alone the various factors and causes may combine to produce conditions favorable to liquefaction. It is possible that in unstable areas, such as the continental belt bordering the Pacific Ocean, thermal distortion affects the region to greater depth and the geotherms may be unsymmetrical to depths of three or four hundred kilometers.

It is believed that the writer's conclusions permit a more logical view of temperature conditions in the earth as a whole. The interpretation of geothermal gradients, and their variation from low to high, offers a means of establishing the temperature conditions within the earth from a fairly direct means of approach.

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