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GEOTHERMAL GRADIENTS AND THEIR APPLICATION TO PETROLEUM GEOLOGY

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ABSTRACT: The geothermal gradient is the rate of temperature increase with depth which is determined by dividing the difference in temperature between two vertical points by the vertical distance between them.

Various methods of obtaining subsurface temperatures include temperature measuring devices, estimates, and temperatures recorded during drill-stem tests, bottom-hole-pressure surveys, and production tests. The most frequently used temperature measuring device is the thermistor-resistance thermometer. Bottom-hole-pressure surveys and production tests furnish excellent temperature data.

Major factors that influence temperature measurements are drilling processes and thermal conductivity. Other less significant factors include borehole convection currents, borehole contents, subsurface water flow, climate variations, weathering, erosion, uplift, topography, structure, geologic age, casing effects, local sources of radioactivity, and intrusive masses.

The time necessary for re-establishment of thermal equilibrium disturbed by drilling processes depends primarily on the drilling method, drilling rate and time, hole diameter, mud circulation, and rock nature. In general, the slower the drilling rate, the longer the drilling time, the larger the hole diameter, the longer the mud circulation the longer will be the time necessary for re-establishment of thermal equilibrium.

Geothermal gradients are inversely related to thermal conductivity. The thermal conductivity is influenced by composition, porosity, grain size and shape, fluid content, temperature, and pressure. Decrease in porosity (increase in bulk density) increases the conductivity. Grain size and shape are directly related to porosity and any combination of sorting and shape that reduces porosity increases conductivity. Fluid saturation, as compared to air, increases conductivity. Increasing the temperature results in decreasing the conductivity, while increasing the pressure results in increasing the conductivity.

Convection currents, if they exist, have a very minor effect on the geothermal gradient. Temperature gradients may be appreciably altered, positively or negatively, by subsurface water flow. Climate variations affect the gradient; for example, glacial advance results in a gradient increase. Diurnal and annual temperature variations can usually be neglected at depths greater than 20 to 30 yards. Weathering, erosion, and uplift all tend to increase the temperature gradient. Disturbances caused in the temperature gradient by topography and structure may be either positive or negative. The geothermal gradient is increased in the vicinity of both radioactive sources and igneous intrusions.

Petroleum applications of temperature and temperature gradients include correlation, electric log interpretation, reservoir engineering, relation to secondary migration and hydrodynamics, origin and maturation of hydrocarbons, and evaluation of borehole conditions.

Editors Note: Rocky Mountain Association of Geologists members are active in the nationwide American Association of Petroleum Geologists geothermal project, and the editors believe that a review paper on this subject is timely.

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INTRODUCTION

The purpose of this discussion is to acquaint the reader with progress that has been made in the study of geothermal gradients and their present applications to petroleum geology. This writer's intention is to rely heavily upon previous literature; the literature cited is to be consulted for further consideration.

Before discussing geothermal gradients, it is necessary to outline the basic sources for subsurface temperature. The various sources of the earth's heat are attributed to the earth's central core, igneous magmas, disintegration of radioactive elements, and possibly gravitational potential energy (resulting from the redistribution of masses inside the earth; for example, subcrustal thermal convection currents). Local sources include heat formed during diastrophism and heat evolved during exothermal chemical reactions (Verhoogan, 1956, p. 18; Levorsen, 1967, p. 423).

GEOTHERMAL GRADIENT

Geothermal gradient may be defined as the difference in temperature between two vertical points divided by the vertical distance between them — the rate of temperature increase with depth. In practice, the geothermal gradient is usually determined by dividing the difference between the formation temperature and the average ambient surface temperature by the depth of the formation (Levorsen, 1967, p. 415):

$$\text{Geothermal grad} = \frac{\text{fm temp - avg amb surf temp}}{\text{depth in ft.}}$$

This formula assumes that the geothermal gradient is essentially linear and that the average ambient surface temperature falls on the line. In some cases this surface temperature is not representative and should be corrected (see Factors Influencing Temperature).

Instead of using the geothermal gradient, the reciprocal gradient is sometimes used, that is, feet per degree.

METHODS OF OBTAINING TEMPERATURES

Various instruments have been developed for the measurement of temperatures in boreholes — some for measuring discrete temperatures and others for measuring continuous temperatures. If the assumption is made that the borehole has been given sufficient time to attain equilibrium, continuous temperature logging is generally preferred over discrete temperature measurements. Continuous logging equipment offers the advantages of (1) obtaining continuous temperatures as a function of depth (geothermal gradient), (2) accuracy, and (3) efficiency. In abbreviated terms the temperature measuring instruments include (1) mercury-in-glass maximum thermometers, (2) platinum-resistance thermometers, (3) thermocouples, (4) thermistor-resistance thermometers, and (5) oscillator-thermistor thermometers.

Mercury-in-glass maximum thermometers have been found to be accurate from about 0.01 to 0.1° C depending upon the care taken in the measurement. Because of the complicated procedure and the time consumed in taking discrete measurements, this method has generally been replaced by electrical methods (Van Orstrand, 1930, p. 9-18; Misener and Beck, 1960, p. 14-15). However, maximum thermometers can be relied upon in case of emergencies which sometimes occur whenever electrical equipment is used (Beck, 1965, p. 43-44).

Platinum-resistance thermometers, one of the first electrical temperature measuring devices, range in accuracy from about 0.01 to 0.1° C. The advantages of accuracy and reliability are greatly offset by the bulkiness of the apparatus (Misener and Beck, 1960, p. 16-17). These thermometers can be used to measure both discrete and continuous temperatures.

Thermocouples, also an early electrical method of temperature recording, can be accurate to 0.01° C when measuring discrete temperatures, but owing to the sensitivity and the lack of stability of thermocouples this accuracy is seldom achieved. However, thermocouples are useful for continuous recording of temperature gradients (Beck, 1965, p. 40).

Thermistor-resistance thermometers, the most commonly used temperature recording device, are accurate to within 0.01 to 0.05° C for measuring both discrete and continuous temperatures. These instruments are good because of their simplicity in design and operation (see Figs. 1 and 2). The only major drawback of these instruments is that thermistors are sometimes unstable. For excellent discussions of thermistor temperature recording devices see Misener and Beck (1960, p. 17-31), Beck (1965, p. 40-44), Simmons (1965, p. 1349-1352), and Roy and others (1968, p. 5208-5210).

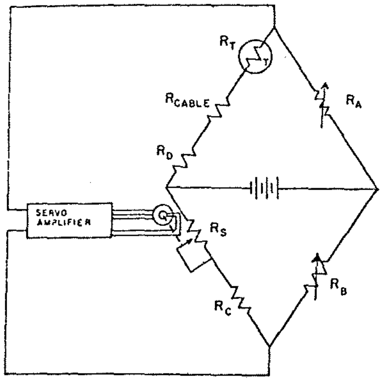

Fig. 1. Schematic diagram of recording circuit (Simmons, 1965, p. 1349).

Oscillator-thermistor thermometers, potentially the most useful, are accurate to 0.05° C. The essential part of this device is a thermal sensitive oscillator, such as a quartz crystal, with frequencies calibrated to temperatures (see Fig. 3). These thermometers are very stable with the only drawback being complexity (Doig and others, 1961, p. 4263-4264; Simmons, 1968, p. 4).

Loofbourow (1966, p. 85-86) has suggested that it may be possible to make useful estimates of subsurface temperatures by adding to the average ambient surface temperature a temperature increment equal to the product of a "selected" geothermal gradient and the depth. The "selected" geothermal gradient is based on correlating the nature and condition of the subsurface rock to be drilled with known geothermal gradients of similar types of rock. If possible, this estimate should be corrected for any known variations in the area (see Factors Influencing Temperature).

Other sources of temperature data are temperatures measured during drill-stem tests (DST), bottom-hole-pressure surveys (BHP), and production tests. Another source of temperature data is the maximum bottom-hole temperature measured while logging (recorded on log headings). DST, BHP, and production test temperatures are fairly reliable, whereas maximum bottom-hole temperatures measured while logging are not. Many of these latter temperatures are not measured by a thermometer but instead are computed from assumed geothermal gradients. In gas producing areas, excellent reservoir temperature data may be acquired from the Federal Power Commission.

FACTORS INFLUENCING TEMPERATURE

In recent years with the increased interest in subsurface temperatures and geothermal gradients, it has become evident that there are

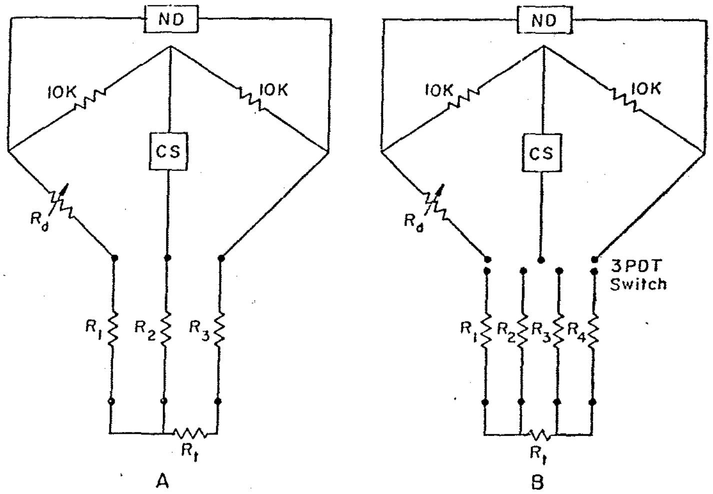

Fig. 2. Schematic diagrams of recording circuits. A: Siemens circuit, B: Mueller circuit (Roy and others, 1968, p. 5208).

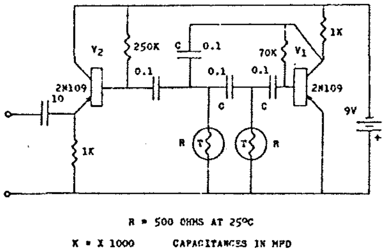

Fig. 3. Schematic diagram of the temperature-sensitive oscillator (Doig and others, 1961, p. 4263).

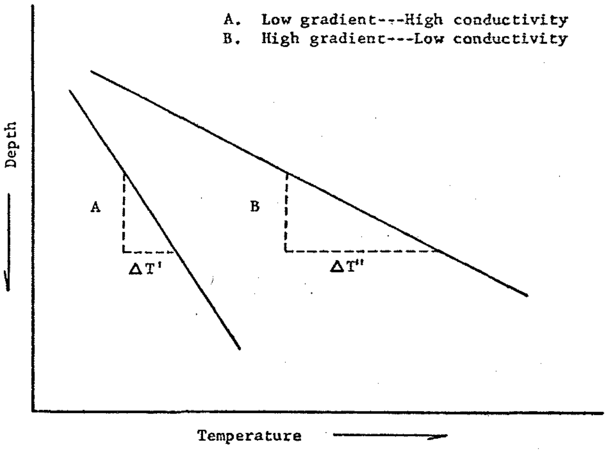

Fig. 4. Relationship between geothermal gradient and thermal conductivity.

numerous factors influencing their measurement in boreholes. The primary factors are temperature variations associated with drilling processes and thermal conductivity. Other factors of less significance include borehole convection currents, borehole contents, subsurface water, climate variations, geologic age, topography, et cetera. These secondary factors can generally be ignored at depths greater than several hundred feet.

Temperatures of rocks surrounding a borehole are altered by drilling processes. The time necessary for re-establishment of thermal equilibrium depends primarily on the drilling method, drilling rate and time, hole diameter, mud circulation, and rock nature (Birch, 1954b, p. 657; Bullard, 1960, p. 3).

Two of the principal drilling methods include diamond drilling and rotary drilling. In general, diamond drilling differs from rotary drilling in having a smaller hole diameter, faster drilling rate, and a much smaller mud (water) circulation. Jaeger (1961, p. 565-569; 1965, p. 18) concludes that because of the relatively small amount of water circulation used during diamond drilling, the effect on the geothermal gradient is negligible except near the top and bottom of the hole, and that the geothermal gradient may be accurately measured two days after drilling ceases. Beck (1965, p. 44) indicates that diamond drilled rock temperatures can be measured to less than 0.05° C after a 12- to 24-hour standing time. Rotary drilling, fundamental to the petroleum industry, and its influence on geothermal gradients will comprise the remainder of this discussion.

The effect of drilling rate on the thermal equilibrium of a borehole appears to be a simple relationship — the faster the drilling rate, the smaller the temperature disturbance (Birch, 1954b, p. 658). Drilling time, hole diameter, mud circulation, and rock nature have been quantitatively related by Bullard (1947, p. 127-130). He concluded that the temperature disturbance will return to within 1 percent of equilibrium in 10 to 20 times the time interval between the time the drill reaches a specific point and the final cessation of mud circulation. Therefore, the longer the drilling time, the larger the hole diameter, and the longer the mud circulation the longer will be the time necessary for re-establishment of thermal equilibrium. Jaeger in 1956 (p. 316-321) obtained similar results by another method. Jaeger (1965, p. 17) states that Lachenbruch and Brewer (1959) have shown by a practical case that 3 times Bullard's time interval falls within 0.05° C of equilibrium. Based on this concept the major advantage of measuring bottom-hole temperatures as contrasted with points elsewhere in the borehole is the small amount of time necessary for re-establishment of thermal equilibrium.

Drilling mud circulated in a borehole results in cooling at the bottom of the hole and warming at the top of the hole. Edwardson and others (1962) give an excellent discussion of methods for calculation of formation temperature disturbances caused by mud circulation. Graphical representations of mathematical solutions enable an examiner, who has sufficient knowledge of the variables, to determine either accurately or approximately formation temperatures and temperature gradients. Cooper and Jones (1959) suggest a similar approach.

Thermal conductivity variations between rocks is a major variable associated with

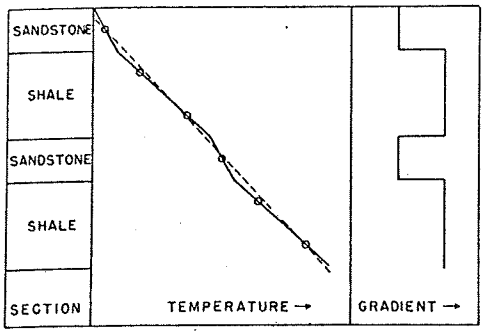

Fig. 5. Averaged nature of geothermal gradients (Birch, 1954b, p. 651).

geothermal gradients. Inasmuch as geothermal gradients are inversely related to the thermal conductivity (the lower the geothermal gradient, the higher the thermal conductivity; or the steeper the graph of the geothermal gradient, the higher the thermal conductivity — see Fig. 4), variations in rock type may greatly influence the temperature gradient.

Buyod (1946, pt. 1) and Birch (1954b, p. 651-653) conclude that the geothermal gradient is actually a series of averaged gradients from the bottom of the hole to the surface (see Fig. 5). Each gradient in the series has a slope dependent upon thickness and thermal conductivities (both vertical and horizontal). The thermal conductivity variables, only partly understood, include composition, porosity, grain size and shape, fluid content, temperature, and pressure.

Birch (1954b, p. 653) states that quartz and some of the ultrabasic and metamorphic minerals are the best thermal conductors; dolomite is better than calcite; and, feldspars, clays and bituminous minerals are poor thermal conductors. Loofbourow (1966, Table II, p. 87) lists the thermal conductivities of some common minerals, rocks, and soils along with a bibliographical reference for other sources of thermal conductivities (see Table 1). Decrease in porosity (increase in bulk density) increases the conductivity (Guyod, 1946, pt. 1; Jam, 1968, p. 32). Grain size and shape are directly related to porosity and any combination of sorting and shape that reduces porosity increases conductivity. Because air is a very poor thermal conductor, fluid saturation increases conductivity (Birch, 1942, p. 258). The nature of the saturating fluid is important; for example, hydrocarbons are somewhat poorer conductors than water (Guyod, 1946, pt. 1). Studies by Birch and Clark (1940) and Birch (1942) on limestones showed a decrease in conductivity of about 2 percent for a 10° C increase in temperature. Bridgman (1924, p. 88-90) concluded that thermal conductivity increases almost linearly with pressure; he found the average conductivity increase for the earth's crust to be 0.5 percent or less per kilobar of hydrostatic pressure. Diment and and Robertson (1963, p. 5036) found that by increasing the pressure from 25 to 100 atmospheres on their samples, there was an apparent increase in conductivity ranging from 1.4 to 2.1 percent. In conclusion, it should be mentioned that Jaeger (1965, p. 15-16) has an excellent mathematical approach to the effect of local variations in thermal conductivity on the geothermal gradient.

Millical/cm² sec°C or cal x 1000/cm²· sec transmitted at gradient of 1°C/cm
(to convert to BTU/ft²·hr·°F·ft, multiply by 0.242)
at room temperature except as noted

Rock, Mineral Types		High	Mean or Single Value	Low	Bibl. Ref.
QUARTZ, crystal, parallel axis	50°C		22.0		16
QUARTZ, crystal, perpendicular axis	50°C		13.0		16
QUARTZITE, chloritoid, Gerhardmon, So. Afr.			15.6		7
QUARTZITE, non-feldspathic, Gerhardmon, So. Afr.			14.2		7
QUARTZITE, feldspathic, Gerhardmon, So. Afr.			10.7		7
ANHYDRITE (12 obs. from 4 places)		13.7		11.7	14
SALT	30°C	13.9		11.7	18
SALT	60°C		11.0		38
DOLOMITE, W. Va.	(52 obs.)	13.8	11.5	9.3	32
DOLOMITE, Permian Basin, Tex.			10.6		18
SLATY SANDSTONE, DOLOMITE, Valleyfd, Quebec			12.0		33
SCHIST, GNEISS, Moffat Adams, Colo.	(38 obs.)	11.0	8.5	7.7	3
DUNITE, PYROXENITE		10.5		9.2	16
GRANITE GNEISS, Griffin LaGrange, Ga.			9.72		16
LAVA, Jacobs, So. Africa		8.0		6.9	36
GRANITE, Moffat Adams, Colo.	(56 obs.)	8.5	7.8	6.7	3
GRANODIORITE, Grass Valley, Calif.	(14 obs.)	8.3		7.0	8
PORPHYRITE (Andesite) Grass Valley	(21 obs.)	8.1	7.14	6.1	8
QUARTZ DIORITE, Moffat Adams, Colo.	(17 obs.)		7.5		3
LAVA, Doornkoutrivier, Reef Nigel, So. Afr.			7.4		7
QUARTZ MICA SCHIST, Washington, D.C.			7.13		13
GRANITE, Carnarvon, So. Africa			6.8		7
SHALY SANDSTONE, Permian Basin, Tex.			6.7		18
LIMESTONE, W. Va.	(41 obs.)	7.8	6.7	5.5	32
GREENSTONE, Mt. Weather, Va.			6.0		30
SANDY SHALE, Permian Basin, Tex.			5.2		18
BASALT			5.2		17
SANDSTONE & SHALE, Ste. Hyacinthe, Quebec			5.06		33
SANDY SILTSTONE, Permian Redbeds			4.9		18
LIMESTONE	0°C		4.8		19
SHALE, above salt, Permian Basin, Tex.			4.7		18
SLATE			4.7		19
GYPSUM			3.1		10, 17
SANDSTONE & SHALE, Lanoraie, Quebec			3.03		33
LIMESTONE (Chalky)			2.0		17
SANDY SOIL, soaked,	24 in. cover	5.4		4.5	28
CLAY SOIL, moist to wet,	24 in. cover	3.7		2.5	28
SANDY SOIL, moist	24 in. cover	2.5		2.1	28
CLAY SOIL, moist	24 in. cover	2.1		1.7	28
SANDY SOIL, dry	24 in. cover	1.7		1.0	28
CLAY SOIL, dry	24 in. cover	1.2		0.8	28
WATER	100° to 0°C	1.6		1.35	17

Table 1. Thermal conductivity of some minerals, rocks and soils (Loofbourow, 1966, p. 87).

Because boreholes contain some form of fluid and because in all boreholes there exists

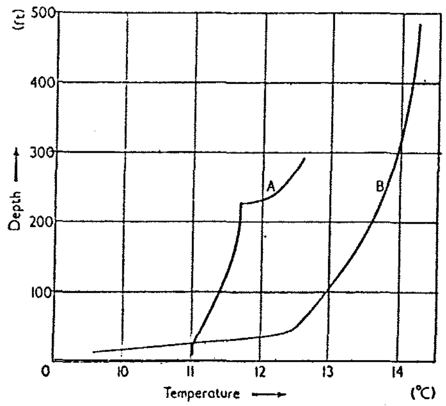

Fig. 6. Temperature depth curves for two holes with water flowing along them (Misener and Beck, 1960, p. 30).

a temperature gradient, convection currents should exist and influence temperature measurements. Kirge (1939, p. 452) and Bullard (1960, p. 3) have shown that in thermally stable boreholes convection currents, if they exist, have a very minor effect on the geothermal gradient.

Boreholes are either dry or contain some drilling fluid. For the convenience of measuring borehole temperatures, it is preferred to use boreholes that are filled with water or drilling mud because of the relative differences in thermal conductivity between liquids and air. A temperature measuring device requires much less time to reach thermal equilibrium if the borehole contains liquid rather than air (Misener and Beck, 1960, p. 13; Jaeger, 1965, p. 18).

The geothermal gradient may be appreciably altered by subsurface water movement (convection currents). The effects of rapidly moving water are easily detected by abrupt changes in slope of the geothermal gradient (see Fig. 6). However, the effects of slow moving water is usually difficult to recognize. In this case, Misener and Beck (1960, p. 34) suggest that isothermal planes should be contoured and any consistent dip of the isothermal planes which cannot be correlated with lithology or geologic history will indicate regional water flow (see Fig. 7). Bullard and Niblett (1951, p. 235-237) isolated such a slow water flow in Nottinghamshire, England. Donaldson (1965) and Jaeger (1965, p. 14-15) suggest mathematical treatments for correcting variations in temperature gradients resulting from convective water flows.

Climate variations affect the temperature gradient near the surface. Diurnal and annual temperature variations can usually be neglected at depths greater than 20 to 30 meters (Beck, 1965, p. 25; Jaeger, 1965, p. 8). In contrast, past glaciation may affect the geothermal gradient to a significant depth. Glacial advance results in an increase in the geothermal gradient (Fig. 8, A to E), while glacial retreat results in a decrease in the geothermal gra-

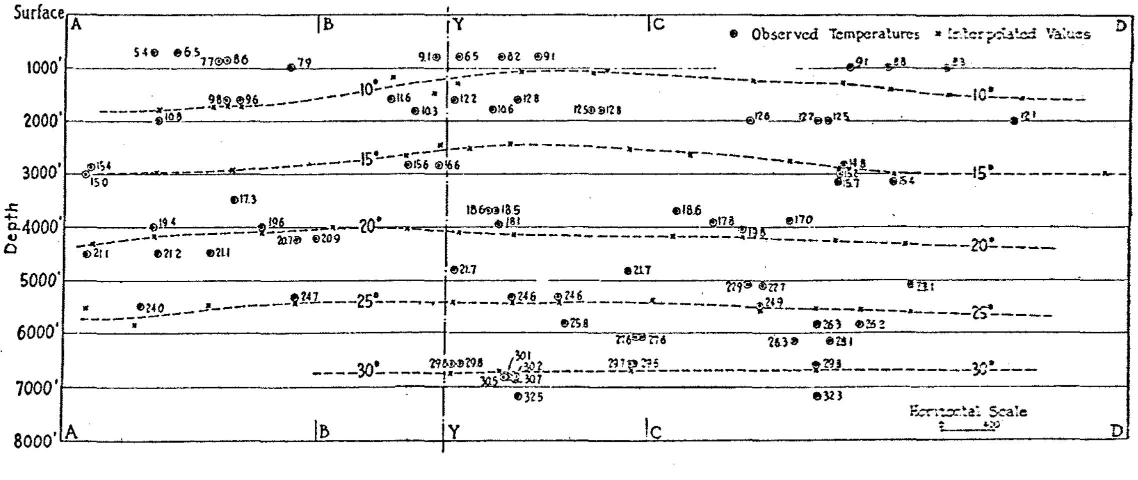

Fig. 7. Variations of isothermal levels (5° C) at Kirkland Lake area, Ontario (Misener and others, 1951, p. 731).

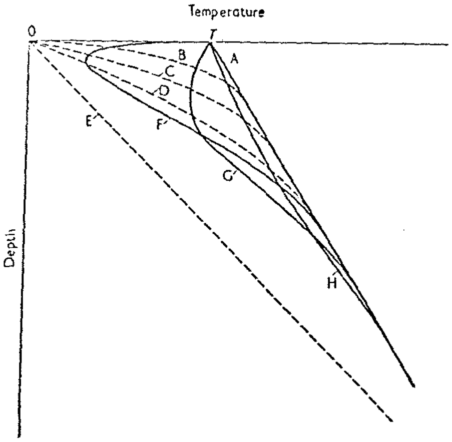

Fig. 8. Schematic representation of the effect of glaciation on the surface temperature gradient (Misener and Beck, 1960, p. 56).

dient (Fig. 8, E to H) — (Bullard, 1960, p. 5; Misener and Beck, 1960, p. 56-57). Jaeger (1965, p. 12-13) approaches the problem from a mathematical viewpoint, and has concluded that the effect of glaciation on the geothermal gradient could be in the order of 15° C/km. However, Birch (1948) has calculated that the reduction in geothermal gradient should not be greater than 3° C/km.

Weathering, erosion, and uplift all tend to increase the temperature gradient and the effect may persist to considerable depth (Jaeger, 1965, p. 8-15; Misener and Beck, 1960, p. 57). Figure 9 illustrates the effect of uplift and erosion on the geothermal gradient. However, Benfield (1949, p. 66-70) has calculated that the effect of uplift on the gradient is negligible and that erosion, unless rapid, will have little effect on the gradient. Beck (1965, p. 24) has concluded that the geologic history of most areas is insufficiently known to make any corrections for uplift and erosion.

Topography and structure have various effects on the geothermal gradient. The disturbance created in the geothermal gradient by topography may be positive or negative (Misener and Beck, 1960, p. 57-58), but because of the uncertainty concerning the geologic history surrounding the borehole, caution should be used in applying corrections (Bullard, 1960, p. 5). Fortunately, correction is only important in mountainous areas, with the main influence contributed from within a 1- or 2-mile radius

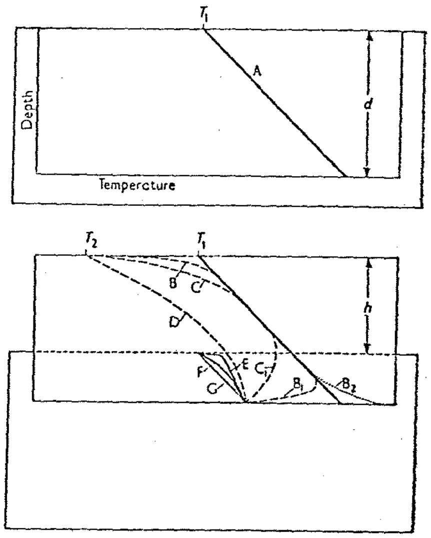

Fig. 9. Schematic representation of the effect of uplift and erosion on the surface temperature gradient (Misener and Beck, 1960, p. 58).

of the borehole (Beck, 1965, p. 24). Jaeger (1965, p. 10-12) presents an excellent mathematical discussion of topographic corrections for simple situations. Guyod (1946) and Van Orstrand (1951, p. 142-143) have shown the temperature relationships for many geological structures (see Applications of Temperature to Petroleum Geology). Simmons (1966, p. 2) concludes that the primary cause of temperature distribution and variation associated with structure is the refraction of heat flow resulting from lateral contrasts in thermal conductivity.

Loofbourow (1966, p. 82-84) discusses the relationship of geologic age to geothermal gradients and concludes that ancient stable rock masses (Precambrian to Cretaceous) generally have lower temperatures and temperature gradients than do younger rock masses (Cretaceous to Recent).

The effects of metal casing will not influence the geothermal gradient unless the temperature measurements are taken at a distance less than 50 times the borehole radius (about 15 meters) from the top of the casing (Misener and Beck, 1960, p. 34; Beck, 1965, p. 44).

The geothermal gradient may be slightly disturbed if there is a local source of radioactivity. Such disturbances appear to be associated with thick beds of interspersed igneous and sedimentary rocks (Mullins and Hinsley, 1957-58, p. 382). As a result of local radioactivity, the geothermal gradient should increase in the vicinity of the radioactive source.

Lovering (1955, p. 256) and Jaeger (1965, p. 13), using a mathematical approach, discuss the effects of various types of intrusive masses on the geothermal gradient. The effect is to increase the gradient in the vicinity of the intrusion.

APPLICATIONS OF TEMPERATURE TO PETROLEUM GEOLOGY

Temperatures and geothermal gradients have numerous applications to petroleum geology in exploration, petroleum engineering, secondary migration, hydrodynamics, origin of petroleum, borehole conditions, et cetera. Outside the realm of petroleum geology, they may be useful in the search for thermal energy (geothermal wells), for mineral exploration (radioactive minerals, metallic ore bodies, and coal), possibly for evaluation of deep thermal anomalies (metamorphism and/or recrystallization), et cetera.

In petroleum exploration, temperature gradients may be used for correlating strata because each lithology has a "different" thermal conductivity and therefore a different geothermal gradient (Birch, 1954b, p. 651-653; Levorsen, 1967, p. 422). Inasmuch as thermal conductivity is, in part, influenced by the nature of fluids contained within the rock (refer to Factors Influencing Temperature), it follows that it may be possible to differentiate hydrocarbon-bearing rock from water-bearing rock. However, because the reservoir volume occupied by hydrocarbons is small compared to the total volume, the resulting effect on reservoir conductivity is small (Guyod, 1946, pt. 3).

Any logging device that measures electrical resistance or conductivity is influenced by temperature. These electrical properties (inversely related) are directly related to the salinity of the fluids contained within the rock, the salinity of the drilling mud, and the temperature. For a given salinity the resistivity decreases or the conductivity increases as the temperature increases (Parkhomenko, 1967, p. 145; Tixier, 1958, p. 269-271).

Various studies have indicated that temperature is related to earth structure — a basic geophysical hypothesis (Schoeppel and Gilarranz, 1966, p. 667). Van Orstrand (1951, p. 142-143), after observing numerous anticlinal structures, has concluded that generally there are slightly higher gradients at the crests than on the flanks of anticlinal structures. Two of the better explanations for this are (1) that the rocks with higher temperatures are brought closer to the surface (Levorsen, 1967, p. 421) or (2) that there is refraction of heat flow resulting from lateral contrasts in thermal conductivity (Simmons, 1966, p. 2). Guyod (1946) has discussed, with illustrations, temperature distributions for common geologic structures.

Lasky (1956 and 1967) suggests that surface alteration products may be related to hydrocarbon occurrences, both structural and stratigraphic. He purports to show that such alterations represent the cumulative effects of geothermal variations at the surface throughout geologic time.

Knowledge of temperature gradients is necessary in petroleum engineering to determine or estimate reservoir temperatures, to calculate reserves and gas storage capacities, to determine reservoir depletion methods, to determine phase relations of reservoir fluids, et cetera. Some of the effects of increasing reservoir temperature are to increase the volume of gas, oil, and rock, to increase fluid pressure when fluids are confined, to decrease the solubility of gas in oil, and to increase the solubility of salts in water (Levorsen, 1967, p. 424-427).

Because reservoir pressures increase as the temperature increases (expansion of confined fluids and rock), secondary migration may eventually occur. By observing the geothermal gradient patterns over a region, it may be possible to determine the direction of secondary migration and the location of the new reservoir.

As was previously mentioned, subsurface regional water flow (hydrodynamic flow) may be detected by observing any consistent dip of the isothermal planes which cannot be correlated with lithology or geologic history (Misener and Beck, 1960, p. 34; Bullard and Niblett, 1951, p. 235-237). Therefore, by observing regional geothermal gradients it may be possible to determine the effects of hydrodynamic flow upon reservoir fluids, for example, tilting of the oil-water contact or secondary migration.

Temperature appears to affect both the origin and maturation of hydrocarbons. Heat plus pressure (with or without the aid of catalysts) has been suggested as a means of converting organic matter into hydrocarbons. However, it is possible that geologic time may reduce the importance of temperature. As depth of burial increases, the temperature and pressure increase and, in general, the composition of hydrocarbons changes (matures) from higher to lower boiling-point fractions (Levorsen, 1967, p. 517-530). It is apparent that a temperature may be reached with depth below which hydrocarbons may be destroyed. For this reason, a knowledge of the geothermal gradient is important when considering the testing of deep reservoirs.

Some of the very practical applications of continuous temperature logging include the location of tubing or casing leaks, zones of lost circulation, zones of downhole water loss in injection wells, zones receiving fluids from injection wells, zones of cross-flow or unwanted flow outside of casing where multiple zones are involved, cement tops, producing zones, and gas-oil-water contacts. They may also be used to evaluate the results of fracture jobs. Many of the above uses of continuous temperature logs are briefly discussed by Goins and Dawson (1953), Pierce and others (1966), and Riley (1967).

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