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Wien, Juni 1938.

The increase of the Temperature downwards in the Crust of Rocks

Von **Th. Dahlblom**, Falun, Sweden — (Mit 1 Abbildung)

The said increase is considered to have been stated statistically by measurements in deep bore holes. According to the British Assoc. Committee it is 1^0 C for 32.4 m. Such average values, obtained from very differing statements, are considered to be valid to great depths. H. Jeffreys sais: „a good average value is 32^0 per kilometre.“ If the increase were so rapid, then the crust of rocks could scarcely have greater thickness than 40 kms, as the rockforming minerals melt or at least are soft at 1200^0, but according to Heiskanen its thickness is in Kaukasus 75 kms, and in Tibet it is said to be 120 km.

Ever since experiments made in Washington (L. H. Adams and J. W. Green, Geoph. Lab. No. 747) on demagnetizing temperatures at high pressures, showed that these temperatures were lowered and not raised by pressure, the cause of the earth's magnetism has seemed impossible to explain*). It must to 94%

*) Dealing with the "Theory of the Earth's Magnetism", D. L. Hazard writes: "Coincident with the accumulation of obserational data regarding the earth's magnetism by means of magnetic surveys and the operation of magnetic observatories there has been a continous attack on the fundamental problems of the phenomenon: what is it, what caused it to change? Many of the leading physicists and mathematicians of the past century have joined in the attack. One theory after another has been advanced only to be withdrawn when it was found inconsistent with some of the observed fact. Some theories fitted well enough qualitatively, but were entirely inadequate when quantity was taken into account, while others which seemed plausible at one stage of our knowledge had to be discarded when the extent of our knowledge increased." "Advances in other fields of science have been seized upon in the hope that they might

be caused of magnetic substances (Bauer) on considerable depth below the surface. The cause cannot be iron, for if it exists into a central core the specific gravity of the earth and the moment of inertia about the polar axis (stated by the precession) show a depth to it as about 1200 kms, where the temperature might be at least 2000^0 above its demagnetizing temperature (about 754^0 for meteoric iron). It cannot be magnetite, the demagnetizing of which (about 569^0) would with the increase as 30^0—32^0 per km. be reached at less than 20 km. depth, and rocks from almost such depths have been brought to the surface at the great foldings of the crust, and found to be mostly acid with a content of magnetite generally below 0.1 %.

The earth's magnetism is a fact, and the temperatures at depths ten to twenty times greater than those reachable for men are suppositions, based on violent extrapolation. The dealing with the question of the increase downwards of the temperature has never been scholarly. Instead of proceeding statistically we need to proceed from the cause of the downwards increase of the temperature, namely the transfer of heat in the opposite direction.

The law for transfer of heat is almost the same as for transfer of electricity. A potential difference is required for the current and a temperature difference for the transfer of heat. *The amount of heat is thermal conductivity times thermal gradient.* The gradient is here the increase per lenght-unit dt/dX, and as the conductivity is expressed in the C G S. system, we must in calculations express the gradient in the increase downwards per cm.

It used to be thought that the heat was conducted from the interior of the earth, but since the year 1906 it has been known that part of it, generally considered the half of it, is generated in the rocks by radioactive changes. This heat generation is limited to a surface layer, the thickness of which seems to be less than 3 km., but has been considered to be "tens of kilometres" (H. Jeffreys).

J. Joly*) calculates with the increase as 1^0 for 3200 cm., and the conductivity as 0.004, which gives the amount of heat at the surface as $12.5 \cdot 10^{-7}$ cal./cm^2. sec.**) It seems to vary between 10^{-7} and $1.4 \cdot 10^{-7}$ in not late volcanic regions.

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furnish a clue to the mystery of the eart'hs magnetism. Cathode rays, the electronic theory of matter, the constitution of the sun, and probable condition of the interior of the earth are all being studied as to their possible bearing on the magnetic field of the earth."

*) The decrease, generally neglected by the geophysicists, has been considered by J. Joly (Radioactivity and Geology). He calculates with the decrease downwards by $4 \cdot 10^{-12}$ grams Ra per gram of rocks as $4 \cdot 10^{-12} \cdot 0.056 \cdot 2.7 = 6 \cdot 10^{-13}$ cal./cm^3. sec. but by numerical error he has got the heat reduced from the above said to $0.686 \cdot 10^{-6}$ in $2.2 \cdot 10^{-6}$ cm. or at 22 km. depth instead at 9.4 km.

**) In regions, where the surface temperature is considerably higher now than during the glacial period, the amount of heat has been found to be less. As the specific heat of the rock-forming minerals is about 0.19 or per cm^3. 0.5 cal, we find that the above said amount of heat would be required during about 5 days to raise the temperature 1^0 in a layer of thickness 1 cm. In regions as at the copper mines in Michigan the amount of heat is only $0.5 \cdot 10^{-6}$ ($= 0.0033 \cdot 1/6900$), showing that equilibrium not has been established after the glacial period.

It has been stated that the conductivity of rocks increases very slowly with the rock pressure and decreases with raised temperature, though probably — as for metals — the decrease might go down to zero at 250^0—300^0 and be reversed, to increase again at higher temperature.

When heat is generated in the rocks, it is evident that *the amount of heat must decrease downwards and thence also the gradients,* but it cannot be reduced to zero, because then the temperature of the interior of the earth would be the same as that at the bottom of the heat generating layer.

If the supposition were correct that the half of the heat at surface comes from the interior of the earth, then the amount of heat below the heat generating layer would be about $6 \cdot 10^{-7}$ cal./cm^2. sec., and if there the conductivity were 0.008 instead of 0.004, the gradient must there be $7.5^0 \cdot 10^{-5} = 7.5^0$ per km., incredibly low to those who have calculated with the increase as 30^0-32^0 even to great depths.

As close correspondence between stated and calculated increase of the temperature might indicate some correctness concerning the part of the heat at the surface which comes from the interior of the earth, we will below cite calculations of the increase downwards of the temperature.

The increase of the temperature, caused by the heat from the interior of the earth, is g_i^0. When corrections are made for the decrease of the conductivity (C) with raised temperature, the increase to the depth X is

$$t_i = X \cdot g_i \cdot C_{18}/C_m$$

where C_m, the mean temperature between the surface and the depth X is, $C_m = C$ $(I - a\,(t_m - 18^0))$ and a = the temperatur coefficient.

The temperature, caused by the heat generation into the rocks is

$$t_r = \frac{H}{C_m} X\left(D - \frac{X}{2}\right) \text{ and the gradient } g_r = \frac{H}{C_m}(D - X)$$

where H = the heat generation in cal. cm^3. sec. and D = the depth to which the heat generation is going on. (The deduction of this equation shown in Appendix A to „Radioactivity and Geology“ by J. Joly.)

Stated and calculated increase of the temperature. Statements in “Green Valley“, California. The statements below — table 1 — are reported to have been published in J. Washington Accad. of Science V. 22, No. 10, year 1932.

Table 1.

Increase downwards of the temperature				Gradient times 10^5	Increase	
between feet	feet per 1^0 F	between metres	metres per 1^0 C		to metres	^{0}C
300 and 1260	168.6	91 and 390	92.5	10.81	390	4.23
1260 2400	175.8	390 730	96.45	10.36	730	7.76
2400 3200	186.1	730 980	102.1	9.79	980	10.21
3200 3700	189.6	980 1130	104.2	9.60	1130	11.65

The gradients are supposed to have the values above at the centres of the different depths, thus at 240, 560, 855 and 1055 m. The gradient at the surface is found to be $11.24^0 \cdot 10^{-5}$. The conductivity is indicated by C.

The decrease of the gradients, caused by the diminution of the heat from $11.24 \cdot 10^{-5} \cdot C$ at the surface to $9.60 \cdot 10^{-5} \cdot C$ at 1055 m. $= 1.055 \cdot 10^5$ cm.

$1.64 \cdot 10^{-5} \cdot C$ cal./cm². sec. gives the heat generation per cm³. as $1.55 \cdot 10^{-10} \cdot C$. When the other values of the gradients are used, the average of (H) the heat generation is obtained as $1.653 \cdot 10^{-10} \cdot C$ cal./cm³. sec.

Were the half of the heat $5.62 \cdot 10^{-5} \cdot C$ generated into the rocks, then it would correspond to the heat generation in $\dfrac{5.62 \cdot 10^{-5} \cdot C}{1.653 \cdot 10^{-10} \cdot C} = 3.4 \cdot 10^5$ cm. 3400 m. = the thickness D of the heat generating layer.

In the same manner we find the value of D, when the gradients are supposed to decrease to g_i resp. 6^0, 7^0 and 8^0 per km. the corresponding values of D as resp. 3170, 2565 and 1900 m.

Calculating the increase $t_i = g_i \cdot X$ and $t_r = \dfrac{1.653 \cdot 10^{-10} \cdot C}{C} X \left(D - \dfrac{X}{2}\right)$ we obtain almost exactly the stated increase (table 1) with the different values of g_i and of D, as seen in table 2 concerning $D = 1956$ and 3170 m.

Table 2

	$D = 1965$ m.					$D = 3170$ m.			
Depth m.	t_i $8 \cdot g_i$	t_r	$t_i + t_r$	diff.	stated increase	t_i $6 \cdot g_i$	t_r	$t_i + t_r$	diff.
390	3.12°	1.06°	4.18°	0.05°	**4.23°**	2.34°	1.79°	4.13°	0.10°
730	5.84	1.92	7.76	0.00	**7.76**	4.37	3.38	7.75	0.01
980	7.85	2.38	10.23	0.02	**10.21**	5.88	4.34	10.22	0.01
1130	9.14	2.61	10.65	0.00	**10.65**	6.78	4.87	11.65	0.00

The question, which is the probable value of D, will later on be taken in consideration. As the conductivity scarcely can be greater than 0.008, the amount of heat at the surface cannot be greater than $9 \cdot 10^{-7}$ cal./cm². sec. and the heat generation about $1.3 \cdot 10^{-12}$ cal./cm³. sec., lower than found from other statements.

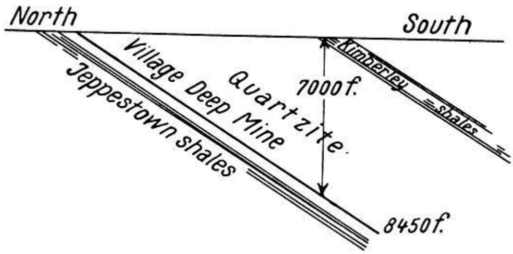
Statements relating to Village Deep Mine, Transvaal. Statements in this mine are more than in other ones adapted to calculations, because there are not hidden sources of errors, as much variable conductivity of adjacent rocks and of drifts above the surface of the rocks, or the walls cooled by the ventilation air.

In order to find out to which depth (how many years) the workings could proceed on account of the increasing temperature a research was made to find the increase of the rock-temperature.

Concerning the deeper part of the mine (below 1600 m.) it was then stated that increased ventilation did not — during the greater part of the year — cool the air in the mine, because the ventilation air, when sinking down, is almost adiabatically compressed, by which its temperature is raised a little more rapidly than the increase downwards of the rock-tempetaure. Thus in the deepest part the air heats rather than cools the walls of the mine.

The mine is dipping about 33° below a plane, where the rocks reaches almost to the surface; thus the thickness of the surface drift insignificant.

Fig. 1.
The rocks above the mine (Rand-quartzite) is almost pure quartzite, and its conductivity, determined by Kriege and Pirow, as 0.0092. Above the very deepest part of the mine quartzite and shales are mixed, Kimberley shales



The temperatures have been measured at different levels in 8 feet drillholes in the footwall. The statements cited in table 3 have been published in J. Chem. Met. and Mining Soc. Johannesburg.

Table 3

Vertical feet	depths metres	Temperatures °F	Temperatures °C
0	0	60	15.6
5772	1759	91.1	32.83
5920	1804	91.8	33.22
6068	1849	92.6	33.67
6214	1894	93.3	34.06
6374	1942	94.1	34.49
6543	1994	94.9	34.94
6704	2042	95.6	35.33
6869	2093	96.1	35.61
7000	2134	96.7	35.94

When visiting this mine (Sept. 1935) Mr. Whitaker, who had measured the temperatures above, informed the author of one measurement at 1230 m. as 28.33° C and other, cited in table 4, also in 8 feet drillholes into the footwall.

Table 4

Vertical feet	depths metres	Temperatures °F	Temperatures °C
7194	2192	97,7	36.50
7360	2243	98.2	36.77
7520	2293	99.0	37.22
7680	2341	99.8	37.66
7840	2390	100.6	38.11
8006	2440	101.5	38.61

The probable gradient near the surface is per cm. $12^0 \cdot 10^{-5}$. It seemes low, but were the conductivity 0.0034, as at the copper mines in Michigan, the same amount of heat would make it (92/34) greater or to 1^0 C in 30.5 m.

The temperature has from 1994 to 2134 m. for 142 m. increased 1^0, which gives the gradient $7.05^0 \cdot 10^{-5}$, and between 2042 and 2134 in 92 m. increased 0.61^0, giving the gradient as $6.63^0 \cdot 10^{-5}$. Deeper down the gradients are increasing which might depend on lower conductivity of the rock, Kimberley shales, from about 7000 feet depht of the mine is overlaying the Rand quartzite and probably dipping as the mine, thus its thickness increasing with the depth of the mine.

In order to be able to estimate the increase here of the temperature at great depths we will now *calculate* the temperatures at the depths at which they have been stated, and proceed from the supposition that by downwards diminished amount of heat the increase of the temperature per cm. has been reduced from $12^0 \cdot 10^{-5}$ near the surface to $7^0 \cdot 10^{-5}$ at 2050 ms.depth. Further that the conductivity of the rock is $0.0092 \,[1 - 0.002\,(t^0 - 18^0)]$, thus with the temperature 35.1^0 at 2050 m. it is 0.00887.

The amount of heat has been reduced

$$\begin{array}{lll} \text{from} & 12^0 \cdot 10^{-5} \cdot 0.0092 = & 11.0 \cdot 10^{-7} \text{ cal./cm}^2\text{. sec. near the surface} \\ \text{to} & 7^0 \cdot 10^{-5} \cdot 0.00887 = & 6.2 \cdot 10^{-7} \text{ at 2050 m. depth} \\ & & 4.8 \cdot 10^{-7} \text{ cal./cm}^2\text{. sec.} \end{array}$$

in 205000 cm., which gives H = the heat generation per cm^3. as $2.34 \cdot 10^{-12}$ cal./sec.

To what depth can the diminution of the gradient proceed? If the heat from the interior of the earth were the half of that one at the surface or $5.5 \cdot 10^{-7}$, thus causing there the gradient 6^0 per km. we find the other half sufficient for the said heat generation down to a depth $D = \dfrac{5.5 \cdot 10^{-7}}{2.34 \cdot 10^{-12}} = 2350$ ms. In the same manner we obtain for $g_i = 5.5^0$ per km. $D = 2540$ m., $g_i = 7^0$ per km. $D = 1960$ m.

The results, when calculating with the surface temperature as 15.6^0 and the increase with $g_i = 5.5^0 \cdot 10^{-5}$ and $D = 2540$ m. are shown in table 5 thus $t_i = 5.5 \cdot 10^{-5} \cdot X \cdot C_{18}/C_m$, and $t_r = \dfrac{2.34 \cdot 10^{-12}}{C_m} X \left[2.54 \cdot 10^5 - \dfrac{X}{2}\right]$.

Down to 2100 ms. depth the differences between stated and calculated temperatures are insignificant. At greater depths they are increasing, as could be expected. Calculations in the same manner but with g_i as 5^0, 6^0 and 7^0 per km. and D resp. 2752, 2350 and 1960 ms. gives differences of the same magnitude. Those with 7^0 are cited in brackets in the table.

The heat generation $2.34 \cdot 10^{-12}$ cal./cm^3. sec. is equal to the heat generation with an average content of Ra of $15.7 \cdot 10^{-12}$ grams per gram of rock, which seems unprobably, whyle calculations have been made for less heat generation, but have given the calculated temperatures considerably greater than the stated.

The changes of the radioactive atoms are generally considered to be spontaneously, the atoms are said to burst (zerfallen), but if so the changes would go on at every depth (F. Soddy, The Interpretation of the Atom, p. 319) but with stated average contents of Ra the amount of heat at the surface would be reduced to zero at 20—25 km. depth, thence the changes must have a cause able to act to a certain depth, different for atoms of different brittleness.

Table 5

Depth metres	t_i^0	t_r^0	Calculated temperature $15 \cdot 6 + t_i + t_r$	Measured temperature	Difference ($g_i = 5.5^0$) $D = 2540$ m.	Difference $g_i = 7^0$ $D = 1960$ m.
1230	6.82	6.10	28.52	28.33	0.19°	(0.21°)
1759	9.79	7.37	32.76	32.83	0.07	(0.07°)
1804	10.05	7.65	33.30	33.22	0.08	(0.08)
1849	10.31	7.73	33.64	33.67	0.03	(0.04)
1894	10.56	7.81	33.97	34.06	0.09	(0.08)
1942	10.83	7.89	34.32	34.49	0.17	(0.16)
1994	11.13	7.98	34.71	34.94	0.23	(0.22)
2042	11.41	8.05	35.06	35.33	0.27	(0.16)
2093	11.69	8.11	35.40	35.61	0.21	(0.19)
2134 (= 7000f)	11.91	8.16	35.67	35.94	0.27	(0.24)
2192	12.25	8.22	36.07	36.50	0.43	(0.35)
2243	12.53	8.26	36.39	36.77	0.38	(0.27)
2293	12.82	8.30	36.72	37.22	0.50	(0.33)
2341	13.10	8.33	37.03	37.66	0.63	(0.42)
2390	13.38	8.36	37.34	38.11	0.77	(0.52)
2440	13.67	8.38	37.65	38.61	0.96	(0.71)

H. Jeffreys, who considers the conductivity as about 0.008 where the gradient is $30^0 \cdot 10^{-5}$, writes: "Thus the rate of transfer of heat outwards to the surface is about $2.4 \cdot 10^{-6}$ cal./cm^2. sec., and this would be supplied by the radioactivity of 18 km. of granite with modern data. Of the various possible ways of reconciling the known radioactivity of rocks with the gradient of temperature in the crust, the most probable seemed to be that the radioactivity was confined to a surface layer with the thickness of the order of tens of kilometres." (The Earth 2 d ed. p. 144.) Where the gradient has the said magnitude the conductivity might generally be only half so great, and the thickness of only 9 km. (granite) woul be required. Further if half of the amount of heat at the surface is subtracted for the increase of the temperature below the layer, we come down to the thickness of it as 4.5 km.

There cannot be any doubt that the disintegration, the atomic changes, is a phenomenon going on only at the surface and into a surface layer, but experiments in a deep mine have not been made in order to state if a radioactive substance really acts ionizing of the air at great depth as it does at the surface.

The energy of the cosmic rays and of the shower of secondary rays raised by them is stated to cause atomic bursts, and the rays are able to pass through 75 feet of lead. (W. F. G. Swan, J. Franklin Inst. 1936). Yet some circumstances —

as the scintillation — makes it not probably that the cosmic rays are the cause of the disintegration.

The cause of the disintegration of atoms must be an hithereto unknown action, penetrating through the rocks, and as it more probably that it is able to cause atomic bursts down to 2000 m. depth than to 3000 m. the values found above for g_i, giving D as about 2000 m. are the more probable, or for the Rand 7⁰. Thus 7/12 of the heat at the surface and 5/12 = 42 % of it generated into the rocks. If the rocks deeper down in the crust have lower conductivity, we can consider the increase to great depth to be 8⁰ *per km.*

In the Boliden mine, Sweden, temperatures have been measured in drill holes in the walls as 6.5⁰ at 210 m. depth and 9.6 at 410 m. The gradient at about 300 m. depth thus $13^0 \cdot 10^{-5}$. The conductivity of the rocks deeper down — granites and gneisses — might be the same as that of the rocks at the mine, thence if the amount of heat decreases to 60 % of that at 300 m., the increase of the temperature below the heat generating layer will — also her — be 8⁰ *per km.*

Temperatures measured in deep bore holes are higher than of the penetrated rocks. Statements in deep bore holes do not show downwards decreasing gradients, and when the penetrated rocks and their probable conductivities are known, the calculated amount of heat below the wet*) rocks is generally obtained greater than in the uppermost part of the borehole. There cannot be any doubt that the rocks contain radioactive heat generating atoms, why the heat must decrease downwards, and thus that the temperatures measured deep down are erroneous. The opinion — based on statements in bore holes — of 30⁰—32⁰-increase per km. of the temperature even to great depths must be wrong.

The cause of the error is evidently that heat has been generated into or near the bore hole. Heat generation by the mechanical work during the boring is the most common cause to the error, but measurements made so long time after the boring was finished that this cause must have disappeared give too great amount of heat, why there must be other causes.

The work of the gravitation and of capillary effect transformed into heat can contribute to the error, when water from the bore hole is absorbed into dry porous rocks.

Concerning measurements in a dry bore hole we find in Kleins Jahrb. der Astr. und Geoph. (II, S. 172) not the measured temperatures, but only the following: "Das Temperaturwachstum in dem — *trockenen* — Bohrloche von Wheeling, Westvirginien, war nur im unteren Teile ein ziemlich rasches, weiter oben

*) Sedimentary rocks, originally containing much water are below 500 m. depth. generally very dry, because during geological times the water has destilled against the lower vapour pressure i. e. upwards. (This maintainance yet not valid for late volcanic regions.) The absorbtion of water into dry rocks can be so considerable that water must be pumped into the bore hole during the boring, when tubes hinders the flowing down of water from the wet rocks, and some years after the boring was finished the bore hole can be found to be emty of water.

ein langsames." Thus downwards *increasing* gradients. The error by the absorbtion of water of the rocks can scarcely have been up to 4^0, and so many years have gone from the boring to this measurements that this cause to error might nearly have disappeared.

From oil-boring in North Dakota has been reported that the increase of the temperature in a bore hole was near the surface 1^0 C for 34.5 m., but at 1150 m. depth it was 1^0 for 19.5 m. The gradients had downwards increased from 29^0 to $51^0 \cdot 10^{-5}$.

It used to be thought that the temperature in a bore hole was rising more rapid than else, when the boring was approaching an oil-bearing layer, and thence the temperature was measured during the boring. In Germany this was left off some years ago, because it had been stated that the said more rapid increase occured even where no oil existed.

The increase of the gradients and of the amount of heat in deep bore holes indicates a considerable heat generation by which the measured temperatures are impaired with a considerable error. The cause can scarcely be any other than that *heat generating emanations move against the bore hole,* thus that the rocks at great depths are so filled up with He, formed during hundreds of millions of years, that there existing emanations have a pressure forcing them against the lower pressure at and into the bore hole.

Some statements, made at the bottom of almost horizontally 38 to 45 m. deep bore holes at different depths in village Deep mine, may be of interest. The statements are cited in table 6.

Table VI

Depth m.	Temperatures measured		Differences
	in 8 feet holes	in 125–150 feet holes	
1894	34.06° C	34.06° C	0° C
2243	36.77	37.60	0.83
2293	37.22	38.28	1.06
2341	37.66	38.77	1.11
2390	38.11	39.28	1.17

The bore holes were made and the temperatures measured before the air cooling plant was in use.

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*) In the very deepest bore hole (in which no oil was found) named Mc. Elroy 103 in upton Co, Texas, was measured 149^0 F = 65^0 C at 10542 feet = 3213 m. and the same temperature was measured the following day at 3231 m. The bottom of the bore hole is at 12786 feet = 3896 m., and near it was measured 182^0 F = 83.3^0 C. (These temperatures are certainly both too high.) The surface temperatures is about 15^0 C, the increase to 3222 m. is 50^0, thus the average gradient $15.5 \cdot 10^{-5}$. The increase from the said depth 18.3 for 676 m. or the gradient $27.1 \cdot 10^{-5}$. Estimeted conductivities of 8 kinds of rocks, penetrated in the upper part of the hole, averaging as 0.0074 and of 5 kinds of rocks, penetrated in the lower part averaging as 0.007. Gradients times conductivity $11.5 \cdot 10^{-7}$ cal./cm^2. sec. for the upper part and $19 \cdot 10^{-7}$ for the lower part.

The differences in temperature between 1.3 and ($42 \cdot \sin 33^0 =$) 23 m. distances from the footwall has been ascribed to cooling by the ventilation air, but as said above this air is during the greater part of the year warmer than the walls of the mine. Supposing that cooling was the cause, and that the temperature of the footwall originally were 1.5^0 higher than that of the air, and that the depth of the mine has increased 20—25 m. per year, then, according to trial calculations, the temperature difference after ($2 \cdot 10^7$ seconds) about 7 years, measured as 0.83^0, would have been less than 0.3^0. It seems more probably that the differences are due to outflow of heat generating emanations, slowly decreasing with decreasing difference in pressure between 23 and 1.3 m. from the footwall.

The heat generating substances into the rocks. The contents of U and Th into granites are according to H. Jeffreys U $= 0.0009\,\%$ and Th $= 0.002\,\%$, and their heat generation $22 \cdot 10^{-14}$ cal./g. sec. of U and $14 \cdot 10^{-14}$ of Th, thus $96 \cdot 10^{-14}$ cal./cm^3. sec. [Any heat generation of K is not probable, as even into a great mass of pure Sylvanite (= KCl) there would be scarcely perceivable raised temperature (Koenigsberger) and further its heat generation is caused by isotop-change which can have occurred millions of years ago.] With Ra/U $= 3.4 \cdot 10^{-7}$ the content of U as 0.0009 corresponds to Ra $= 3.06 \cdot 10^{-12}$ g. per g. rock, which might be too high according to later Ra-determinations*). Known heat generating atoms into the rocks cannot be considered to generate more than $0.6 \cdot 10^{-12}$ cal./cm^3. sec., but from statements in Village Deep Mine we calculated $2.34 \cdot 10^{-12}$. From 1/2 to 3/4 of the heatgeneration into rocks seems to be due to atomic heat generations which have remained unknown because they changes are rayless. Concerning rayless changes Rutherford wrote already year 1905: "In a rayless product the α-particle may be expelled with a velocity less than $1.5 \cdot 10^9$ cms. per second and so fail to produce much electrical effect."

In a rock the content of Ra seems to be the same in every part of it. If this occurrence were caused by its formation of emanation, able to penetrate all parts of the rock, it is possibly that one or some of the elements Rb, Cs, Ga, Sc or Zr with similar occurrences are formed of emanations with considerable heat generation. Their quantities into the crust are about one million times greater than that of Ra, why it is probably that unknown atomic changes can produce more heat into a rock than its contents of U and Th.

The supposition above of heat generation at great depths in bore holes by emanations flowing against them would be untenable, if there not existed rather great quantities of emanations of unknown kinds.

For the question of the increase downwards of the temperature the heat generation per cm^3. is of importance, as the greater it is the more rapid the decrease of the gradients and the less the thickness of the heat generating layer.

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*) C. Snowden Piggot obtained Ra $= 0.98 \cdot 10^{-12}$ as average in 11 granites, in two granites with visible uranophan 3.39 and 3.81, in one gneis 0.64 in two shists 0.98 and 0.49. (Geoph. Lab. 729.) This determinations seems to be more accurate than older ones.

The problem, the increase downwards of the temperature has above been attacked in conformity to the law for conduction of heat, and thence it could appear that temperatures measured at great depths into bore holes are erroneous, higher than that of the rock before the hole was made.

The effect of the heat generation into the surface layer, generally neglected, must be downwards diminished increase of the temperature, as the cause of the increase, heat transferred in opposite direction, must diminish downwards.

Above has been shown that when the heat generation into the rocks was assumed to be little more or less than the half of the heat at the surface, calculated temperatures corresponded so closely to those measured at different depths in the walls of Village Deep mine from 1230 to 2243 m. that the average difference was only 0.2^0. These results indicate that the heat generation per cm^3. — on which the calculation was based — might be almost correct, although 4 times greater than could be expected with the probable contents of radioactive elements in the rocks, why it indicates that unknown atomic changes contribute to the said heat generation.

Coarse-grained granites and gneisses are as good conductors of heat as quartzites, and in the deeper parts of the crust the decrease of the conductivity by the raised temperature can be more than balanced by its increase by the rock-pressure.

With the amount of heat, transferred from the interior of the earth, as 7 or $8 \cdot 10^{-7}$ cal./cm^2. sec. the increase of the temperature below 2 or 3 km. depths in continents can be considered to be 8^0 or 9^0 per km. instead of 30^0 — 32^0 as generally considered. If the average depth to the bottom of the crust, i. e. to the magma, were 40 km., the temperature would there be about 400^0*), why magma cannot be conceived as molten rocks but as concentrated aqueous silicate solution, as real solution with exceedingly great depression of its vapour pressure**).

It has remained impossibly to formulate an answer to the fundamental question in volcanism, namely, What is the mechanism of a volcano? but the cause of volcanic outbreaks as well as of their progress and of the stated increase of basicity of the products during the eruption can be explained when proceeding from low temperature of the magma. (The present author has shown this in the paper "Volcanic Events, when Magma is considered to be a Solution", published in Extrait du Bul. Volcanologique, Napoli, 1928.)

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*) According to Heiskanen the thickness of the crust is 35 km. in southern Norway.

**) The temperature of lava flowing out of a volcano has been stated to be 1000^0 to 1200^0, thus while magma is rising through a volcano, there must be a heat generation of 500 — 600 cal./g. of lava. — A solution with temperature as 400^0 and pressure as 10000—12000 kg./cm^2. might be extreemely ionized, partly to single-atomic ions, and when the solvent evaporates and the ions combine to great (silicate) molecules, there will be great heat generation, but there might also be heat generation of unknown kind. There might be such a one in the liquid lava forming a lake in the volcano Mauna Loa, Havaii, as in spite of enormeous lose of heat during decennies no change has been stated. ,,Never has any important explosion been reported from Mauna Loa." Dr. Friedlaender, B. Nat. Res. Council, Volcanology.

The cause of the earth's magnetism has been said to be a mystery, but with a more correct opinion on the increase of the temperature, we must not consider the demagnetizing temperature of magnetite (569^0) to be at 20 km. depth into the rocks, but rather deep down into the magma.

The question can be seen from following points of view. All kinds of rocks are formed of magma. The primary magma is (according to the opinion in present time) basaltic, with the iron contents of basalt, about 10 %. As the average content of iron of the rocks, at least down to known depths, is low, only a few procent, the greater part of the iron of the magma, which has formed the rocks, must have stayed below the crust, probably as Fe_3O_4 = magnetite, which has sunk into the magma till increased viscosity stopped the sinking. Thus we may believe that there exist into the magma enormeous masses of magnetite, partly above the (present) depth to its demagnetizing temperature, giving rise to the earth's magnetism.

Falun, Sweden, May 1938.

Beiträge zur Theorie des Erdaufbaus

Von **H. Lorenz.** — (Mit 3 Abbildungen)

1. Ableitung allgemeiner Bedingungen für die Dichteverteilung im Erdinnern. 2. Beweis für die Schollennatur der festen Kruste und Ermittlung der Dicke der Simaschicht aus der geothermischen Tiefenstufe. Entscheidung für einen gasförmigen Erdkern. Bestimmung der Dicken des Meeres- und Festlandblockes aus Messungen der Schwerezunahme mit der Tiefe und der Gesteinsdichten mit Rücksicht auf das Schwimmgleichgewicht (Isostasie). 3. Diskussion einiger Potenzgesetze für die Dichteverteilung; Entscheidung für den Helmertschen Ansatz und Bestimmung der Beiwerte aus den allgemeinen Bedingungen, der mittleren Erddichte und dem Trägheitsmoment. Allgemeingültigkeit der dimensionslosen Dichteformel für alle oberflächlich erstarrten kugelförmigen Weltkörper.

1. Allgemeine Grundlagen. Unter Vernachlässigung der Fliehbeschleunigung gegenüber der Schwere, sowie der Annahme des Erdaufbaues aus konzentrischen homogenen Kugelschalen ändert sich die Dichte δ nur mit dem Radius r derart, daß die Masse einer Schale von der Dicke dr durch $dm = 4\pi\,\delta r^2\,dr$ gegeben ist. Mit der Gesamtmasse innerhalb des Radius r und der Erdmasse $m_0 = \frac{4}{3}\pi\,\delta_m\,a^3$ mit der mittleren Dichte δ_m, dem Erdhalbmesser a, sowie der Oberflächenbeschleunigung g_a folgt dann die zu r gehörige Beschleunigung g aus

$$\frac{g}{g_a} = \frac{m}{m_0}\,\frac{a^2}{r^2} = \frac{3}{a r^2 \delta_m}\int_0^r \delta r^2\,dr \quad \ldots \ldots \quad (1)$$