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On the Distribution of Strain in the Earth's Crust Resulting from Secular Cooling; with Special Reference to the Growth of Continents and the Formation of Mountain Chains

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VII. *On the Distribution of Strain in the Earth's Crust resulting from Secular Cooling; with special reference to the Growth of Continents and the Formation of Mountain Chains.*

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Communicated by Professor T. G. Bonney, *D.Sc., F.R.S.*

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(1) The reasoning of this paper is based upon the results of Sir W. Thomson's and Professor G. H. Darwin's well-known and independent researches on the rigidity of the Earth, upon Sir W. Thomson's investigation on the secular cooling of the Earth, and, lastly, upon the beautiful contraction theory of mountain evolution which these researches lead up to and support. Its objects are to determine the distribution of strain in a solid globe resulting from secular cooling, and to examine the effects which this distribution must have upon the form of the great features of the Earth's surface.

In the first part of the paper I shall suppose the Earth to be bounded by a smooth spherical surface, and to be made up of a very great number of very thin concentric spherical shells, each shell being so thin that the loss of heat throughout it may be considered uniform. In the latter part the effects of inequalities on the Earth's surface upon the results so obtained will be alluded to. The argument urged against the contraction theory by the Rev. Osmond Fisher will also be incidentally considered.

I. *The Distribution of Strain in the Earth's Crust resulting from Secular Cooling.*

(2) In his memoir on the secular cooling of the Earth, Sir W. Thomson works out the case of the conduction of heat in "a solid extending to infinity in all directions, on the supposition that at an initial epoch the temperature has had two different constant values on the two sides of a certain infinite plane," and he shows that, for "a globe 8000 miles in diameter of solid rock, the solution will apply with scarcely sensible error for more than 1,000,000,000 years." The solution he gives is

$$v = v_0 + \frac{2V}{\sqrt{(\pi)}}\int_0^{x/2\sqrt{(\kappa t)}} dz \,.\, \epsilon^{-z^2};$$

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where "κ denotes the conductivity of the solid, measured in terms of the thermal capacity of the unit of bulk; V, half the difference of the two initial temperatures; v_0, their arithmetical mean; t, the time; x, the distance of any point from the middle plane; v, the temperature of the point x at time t."*

(3) Differentiating v with respect to t, we obtain

$$\frac{dv}{dt} = -\frac{V}{2\sqrt{(\pi\kappa)}}\frac{x}{t^{\frac{3}{2}}}\cdot\epsilon^{-x^2/4\kappa t},$$

the rate of cooling at the point x at time t. Differentiating this expression with respect to x, we find

$$\frac{d^2v}{dx\,dt} = \frac{V}{2\sqrt{(\pi\kappa)}}\frac{1}{t^{\frac{3}{2}}}\left(\frac{x^2}{2\kappa t} - 1\right)\epsilon^{-x^2/4\kappa t}.$$

Hence $d^2v/dx\,dt$ is equal to zero when $x = \sqrt{(2\kappa t)}$. In other words, at any given epoch, the rate of cooling is a maximum at the depth for which x is equal to $\sqrt{(2\kappa t)}$.†

Hence the rate at which any shell parts with its heat increases to a certain depth below the Earth's surface, where it is a maximum, after which it decreases towards the centre, and the depth of the surface of greatest rate of cooling is continually increasing, and *varies as the square root of the time that has elapsed since the consolidation of the globe.*

(4) Consider any two consecutive spherical shells below the surface of greatest rate of cooling. Since the upper shell cools the more rapidly, its inner surface would, if free, contract more than the outer surface of the shell below; but, being forced to remain of the same radius as the latter after its contraction, it follows that the upper shell must be stretched or rent in order to rest upon the lower. Owing to the great pressure at that depth, and also to the slow rate of cooling, there can be little doubt but that the upper shell will be stretched and not rent.

Consider, again, two consecutive shells above the surface of greatest rate of cooling. In this case the lower shell cools the more rapidly; the inner surface of the upper shell, if free, would not therefore contract so much as the outer surface of the shell below. The upper shell must then either be stretched less than the lower, or must be crushed and folded in order to rest upon it. It will be shown afterwards that, above the surface of greatest rate of cooling, the amount by which each shell is being stretched gradually diminishes towards the surface of the Earth, until at a certain depth it is zero (the shell at this depth being now unstrained through cooling), and that, outside this depth, every shell is being crushed or folded.

* 'Edinb., Roy. Soc. Trans.,' vol. 23, 1864, pp. 161–162; THOMSON and TAIT'S 'Natural Philosophy,' App. D., §§ (l), (o).

† This paragraph is the substance of a letter by Professor G. H. DARWIN on "The Formation of Mountains and the Secular Cooling of the Earth," published in 'Nature,' Feb. 6, 1879 (vol. 19, p. 313). If t be taken as 98,000,000 years, the depth at which the rate of cooling is greatest is about 53 miles.

Hence *folding by lateral pressure takes place only to a certain depth below the Earth's surface; at this depth it vanishes, and, passing through it downwards, folding gives place to stretching by lateral tension.**

(5) In order to find the depth at which folding by lateral pressure vanishes, I propose to solve the following problem:—

A globe, of radius r, is surrounded by a number of concentric spherical shells, called A_1, A_2, A_3 . . ., of thicknesses a_1, a_2, a_3 . . ., respectively. The globe remaining at its initial temperature, the shell A_1 is cooled by $t_1°$, the shell A_2 by $t_2°$ in the same time, and so on. The linear coefficient of expansion being e, and the same for all the shells, it is required to find the distribution of strain resulting from this method of cooling.

[(6) Consider the shell A_1. If the globe were absent, the radius of its inner surface would become $r(1 - et_1)$. It is, however, obliged to remain of radius r, and it must, therefore, be stretched. Assuming the stretching to be uniform throughout the shell, and expressing the fact that the volume of the shell after cooling $t_1°$ is equal to its original volume multiplied by $1 - 3et_1$, it will be found that the radius of the outer surface of the shell is

$$r_1 - \frac{r_1^3 - r^3}{r_1^2} et_1,$$

where

$$r_1 = r + a_1.$$

Proceeding in a similar manner with the other shells, and remembering that the radius of the inner surface of any shell after cooling must be the same as the radius of the outer surface of the shell below after its cooling, then the radius of the inner surface of the shell A_{n+1} becomes

$$r_n - \frac{(r_n^3 - r_{n-1}^3)\,et_n + (r_{n-1}^3 - r_{n-2}^3)\,et_{n-1} + \ldots + (r_1^3 - r^3)\,et_1}{r_n^2}.$$

Now, let $a_1 = a_2 = \ldots = a$; also let $t_1 = \delta t_0$, $t_2 - t_1 = \delta t_1$, . . ., $t_{n+1} - t_n = \delta t_n$. If the shell A_{n+1} had been allowed to contract, as if the globe and n interior shells were absent, the radius of its inner surface would have been $(r + na)(1 - et_{n+1})$. Hence the amount by which a great circle of the inner surface of this shell is stretched is proportional to

$$\frac{e}{(r+na)^2}\left[(r+na)^3\,\delta t_n + (r + \overline{n-1}\,.\,a)^3\,.\,\delta t_{n-1} + \ldots + r^3\,.\,\delta t_0\right],$$

that is, if the shells be supposed infinitely thin and infinitely great in number, to

$$\frac{e}{(r+na)^2}\int_r^{r+na} z^3 \frac{dt}{dz}\,dz.$$

* Whilst folding and crushing by lateral pressure must be accompanied by a development of heat, as pointed out by Mr. R. MALLET and others, stretching by lateral tension, on the other hand, must be accompanied by a cooling of the masses stretched.

If this expression for any shell be negative, then that shell will be folded and not stretched.]*

(7) Comparing the above with the notation used by Sir W. THOMSON, it will be seen that t is proportional to his dv/dt; his x corresponds to $c - z$, where c is the radius of the Earth, and z is the distance of any point from the centre of the Earth. Hence the dt/dz of the preceding paragraph is proportional to $-(d/dx)(dv/dt)$ in Sir W. THOMSON'S notation.

Now

$$\frac{d}{dx}\left(\frac{dv}{dt}\right) = \frac{V}{2\sqrt{(\pi\kappa)}} \cdot \frac{1}{t^{\frac{3}{2}}}\left(\frac{x^2}{2\kappa t} - 1\right)\epsilon^{-x^2/4\kappa t}.$$

Substituting in the integral in § (6), we have

$$\delta_{n+1} = \frac{\mu}{t^{\frac{3}{2}}(r+na)^2} \cdot \int_{c-r}^{c-r-na} (c-x)^3 \left(\frac{x^2}{2\kappa t} - 1\right)\epsilon^{-x^2/4\kappa t}\,dx,$$

where μ is a constant.

No practical use can be made of this expression, and we are, therefore, obliged to return to the last expression in § (6), in order to find the radius of the shell which experiences no strain through cooling.

(8) If, in the expression for dv/dt in § (3), we put $x = 2\sqrt{(\kappa t)}\,z$, we find that, at any given time, the rate of cooling is proportional to $z\epsilon^{-z^2}$. At the depth where the rate of cooling is greatest (for which $z = 1/\sqrt{2}$) the value of $z\epsilon^{-z^2}$ is ·42888. Again, at the depth for which $z = 4·00$, the value of this expression is ·00000045014. Hence, at any time, the rate of cooling at the latter depth is about one-millionth of its value where it is greatest. For our present purpose I shall, therefore, assume that below the depth for which $z = 4·00$ the rate of cooling is practically insensible, and it will be seen afterwards that the quantities neglected do not appreciably affect the results.

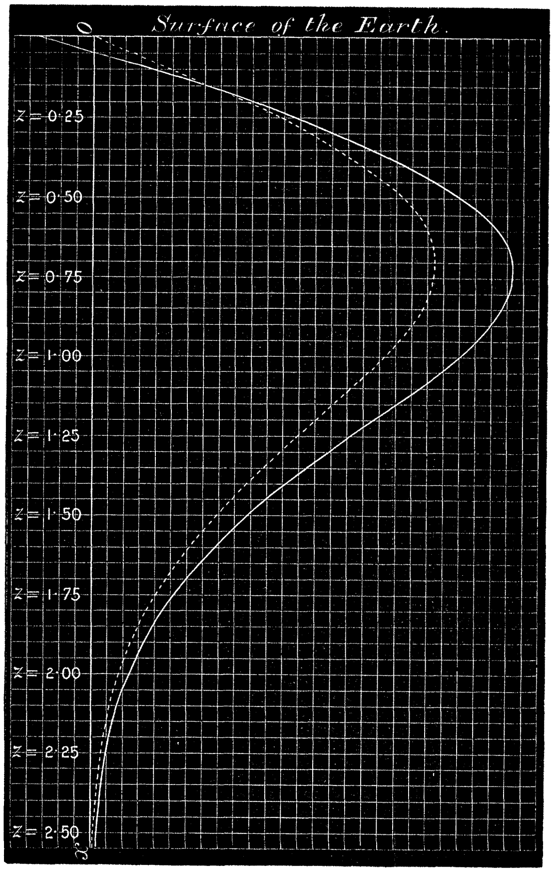
If the temperature of melting rock be 7000° F., the consolidation of the globe may have taken place about 98,000,000 years ago; but, as Sir W. THOMSON remarks, "we are very ignorant as to the effects of high temperatures in altering the conductivities and specific heats of rocks, and as to their latent heat of fusion. We must, therefore, allow very wide limits in such an estimate as I have attempted to make; but I think we may with much probability say that the consolidation cannot have taken place less than 20,000,000 years ago, or we should have more underground heat than we actually have, nor more than 400,000,000 years ago, or we should not have so much as the least observed underground increment of temperature."†

* The paragraphs within square brackets (added June 21, 1887) are abridged from the proof contained in the original paper communicated to the Society, partly because the proof there given was unnecessarily long, and partly because another and more elegant proof is given, in the note following this paper, by Professor G. H. DARWIN.

† 'Edinb. Roy. Soc. Trans.,' vol. 23, pp. 160–161; 'Natural Philosophy,' App. D., §§ (j), (l).

If the time that has elapsed since consolidation be taken as 174,240,000 years, the depth for which $z = 4 \cdot 00$ is 400 miles. For simplicity, let us adopt this value for the present.

(9) The radius of a sphere equal to the Earth in volume being about 3959 miles, I therefore suppose the Earth at the present time to be made up as follows :—A central globe, 3559 miles in radius, at a temperature of 7000° F., which as yet has not sensibly cooled; surrounded by 400 concentric spherical shells, each one mile in thickness, the rate of cooling in each shell being uniform throughout, and equal to its value at the outer surface of that shell. On these assumptions I have calculated, from



the last expression in § (6), the proportional amounts by which the four hundred shells are stretched or folded.

The results of the calculation are shown in the accompanying figure, in which the dotted curve represents the rate of cooling, at the time considered, from the surface down to the depth for which $z = 2 \cdot 55$, and the continuous curve represents, at the same time, the amount by which a great circle of any shell is being stretched or folded, the folding by the part of the curve to the left of the axis Ox, and the stretching by the part to the right.

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(10) The continuous curve also represents approximately the volume that, in a given time, is stretched or folded of any shell. For, let r be the radius of the internal surface of any shell, a its thickness; let r' and a' be what these values would naturally become by cooling if the shell were isolated; and let $r' + \delta$ be the radius of the globe on which this shell is obliged to fit, δ being small compared with r'. If the shell were isolated, its volume after cooling would naturally be $4\pi r'^2 a'$. But the volume of the shell of radius $r' + \delta$ and thickness a' is $4\pi a' (r'^2 + 2r'\delta)$. Hence the amount of the shell that is stretched or folded is equal to $- 8\pi a' r' \delta$, the shell being stretched or folded according as δ is positive or negative. This expression, at a given time, varies nearly as δ, and therefore the continuous curve of the figure may be considered to represent very fairly the amount of rock stretched or folded at any depth.

(11) Without attributing much weight to the numerical results of these calculations—for, on account of our ignorance on many points, they are given rather for their qualitative than their quantitative value—the following conclusions may be deduced from them, taking t provisionally at 174,240,000 years :—

1. Folding by lateral pressure changes to stretching by lateral tension at a depth of about 5 miles.

2. Stretching by lateral tension, inappreciable below a depth of about 400 miles, increases from that depth towards the surface; it is greatest at a depth of 72 miles, that is, just below the surface of greatest rate of cooling;* after this, it decreases, and vanishes at a depth of about 5 miles.

3. Folding by lateral pressure commences at a depth of about 5 miles, and gradually increases, being greatest near the surface of the Earth.†

(12) Since, at the depth at which folding by lateral pressure vanishes, the thin spherical shell cools and naturally contracts without straining, it follows that the folding of the outer crust is exactly the same as it would be if the whole globe beneath the unstrained shell were to cool uniformly throughout, and at the same rate as at the unstrained surface.

It will be seen, in the next paragraph, that the depth of this surface increases with the time since consolidation. Hence a part of the crust at one time stretched by lateral tension may at some later period be folded by lateral pressure.

* If $t = 174{,}240{,}000$ years, the depth of the surface of greatest rate of cooling is about 71 miles. As the surface of greatest stretching should be just below the surface of greatest rate of cooling, this close approximation indicates the degree of accuracy of the assumptions made in § (9).

† The limited depth to which crust-folding extends may, perhaps, be considered as an argument against the contraction theory on the hypothesis of solidity, inasmuch as room is apparently not afforded for the accumulation of sediment to the estimated thicknesses of 40,000 feet in the Alleghany Mountains and 60,000 feet in the Rocky Mountains. But, assuming such estimates to be correct, it should be remembered that the depth of the unstrained shell has been calculated on the supposition that the surface of the Earth is smooth and spherical; and it is probable that the existence of the surface inequalities would account for folds amply large enough to bury the thickest known masses of sediment.

(13) Let us suppose, for a moment, that the rate of cooling is always inappreciable at the depth for which $z = 4{\cdot}00$, *i.e.*, for which $x = 2\sqrt{(\kappa t)}\,.\,4{\cdot}00$. This depth is continually increasing, and varies as the square root of the time that has elapsed since the consolidation of the globe. Dividing the crust above this depth always into the same number of spherical shells, the thicknesses of these shells therefore increase in proportion to the square root of the time. Now, the rates of cooling of any two particular shells have at any time the same proportion to one another, and therefore the proportional values of δt_0, δt_1, δt_2, . . . , in § (6) are always the same. But the cubes of the radii of the shells above the surface of greatest rate of cooling diminish in a less ratio, as the time increases, than the cubes of those below that surface; so that the depth of the unstrained surface would increase in a proportion rather greater than the square root of the time. On the other hand, the rate of cooling of any particular shell varies inversely as the time;* and, although at any time, the rate of cooling at the depth for which $z = 4{\cdot}00$ is always about one-millionth of its rate at the depth where it is greatest at that time, yet in early periods the rate of cooling might be sensible at a depth greater than that for which $z = 4{\cdot}00$. This would have the effect of slightly diminishing the proportion alluded to above. Hence, within certain limits, it is true that *the depth of the unstrained surface increases as the square root of the time that has elapsed since the consolidation of the globe.*

From the value given in § (11) we can therefore determine approximately the depth of the unstrained surface at any other time.

If we assume, as is generally done in the theory of the Conduction of Heat, that κ, the rate of conductivity, is independent of the temperature, then the rate of cooling of any particular shell varies only when the time changes, and therefore the depth of the unstrained surface is, at any time, independent of the initial temperature of the globe.

(14) Making use of the conclusion of the last paragraph, we can also determine approximately the law according to which the amount of rock stretched or folded in a given time changes. Considering any shell above the unstrained surface, the amount of it folded in a given time has been shown, in § (10), to be $8\pi a' r' \delta$. Now, approximately, r' may be considered constant, δ to vary inversely as the time, and a' directly as the square root of the time; so that $8\pi a' r' \delta$ varies nearly inversely as the square root of the time. This is the case with every shell above the unstrained surface, and therefore with the total folding of all such shells. Hence *folding by lateral pressure was effected most rapidly in the early epochs of the Earth's history, and, since then, the total amount of rock folded in any given time decreases nearly in proportion as the square root of the time increases.*

(15) The same law being approximately true of the total amount of rock stretched by lateral tension, it follows that the ratio of the amount of rock stretched to the

* For $dv/dt = -\mathrm{V}/\sqrt{\pi}\,.\,z\,\epsilon^{-z^2}\,.\,1/t$, which varies as $1/t$, since z is a constant for any particular shell.

amount folded in a given time is very nearly constant, but in reality slightly diminishing as the time increases.

Hence the ratio of the areas contained by the parts of the continuous curve in the figure with the axis Ox, to the right and left of that axis, may be considered to represent roughly the ratio of the total amount of rock stretched to the total amount folded since the earth solidified.*

II. *The Rev.* O. FISHER'S *Argument on the Insufficiency of the Contraction Theory.*

(16) It may be well here to refer to the objection urged against the contraction theory by the Rev. O. FISHER, an objection which has by some been considered conclusive against either the contraction theory, as usually held, or the assumptions on which that theory is founded. In its latest form this argument will be found in a paper in the 'Philosophical Magazine' for February, 1887.† Briefly it may be summed up as follows:—

Mr. FISHER'S argument is based on the assumptions that, initially, the Earth was practically solid, its surface spherical, and its whole mass at the high temperature of 7000° F. throughout; and that it cooled down from this condition to that implied by Sir W. THOMSON'S solution. Further, he takes the case which he considers most favourable to the advocates of the contraction theory, and supposes that each spherical layer, in sinking down by reason of the cooling of the mass beneath, maintained its horizontal extension, so that the whole of the compression, introduced by its having to fit on the shrunken nucleus, was rendered available for producing corrugations. He thus finds that "if all the elevations which would have been produced by compression, through the contraction of the Earth cooling as a solid, were levelled down, they would form a coating of about 900 feet in thickness above the datum level, which would be the surface, had the matter of the crust been perfectly compressible, so that compression would not have corrugated it." He concludes, therefore, that, "if we take into consideration the land and the ocean-basins, the existing inequalities of the surface are greater than can be accounted for by the theory of compression through contraction by cooling of a solid globe, even upon the too highly favourable suppositions made in the present paper."‡

This argument seems to me inconclusive on several grounds.

* Roughly, this ratio is about 340 to 1. But this relates only to folding resulting directly from secular cooling, the surface of the Earth being smooth and spherical. The total amount of rock-folding must, of course, be far in excess of that indicated by this ratio; see footnote to § (23).

† "On the Amount of the Elevations attributable to Compression through the Contraction during Cooling of a Solid Earth," 'Phil. Mag.,' vol. 23, 1887, pp. 145–149. The original form of the argument is contained in a paper "On the Inequalities of the Earth's Surface viewed in connection with the Secular Cooling," 'Cambridge Phil. Soc. Trans.,' vol. 12, 1879, pp. 414–433, and in 'The Physics of the Earth's Crust' (1881), chaps. v. and vi. See also a letter to 'Nature,' Nov. 23, 1882 (vol. 27, pp. 76–77).

‡ 'Phil. Mag.,' vol. 23, 1887, pp. 148–149.

(17) First, the problem investigated is not one according to nature. For it takes no account of the time during which the cooling has taken place; and, therefore, being independent of the time, the effect must be the same as if the cooling were suddenly accomplished. But sudden cooling involves the impossible supposition that κ, the rate of conductivity, should be infinite.

(18) But, again, let us for a moment imagine that the temperature of the Earth's crust (supposed solid) did suddenly change from a uniform one throughout to its present condition as given by Sir W. THOMSON's solution. Let us further assume the Earth's surface to have been initially spherical, and the Earth to be divided into a very great number of very thin shells by spheres concentric with the Earth; the shells being so thin that the cooling throughout each may be considered uniform.

Then the loss of heat experienced by any one of these shells is $V - v$, where V was its initial and v is its present temperature. And, as v increases with the depth from the surface, it follows that $V - v$ diminishes as the depth increases.

Consider any two consecutive shells. Since the upper shell is cooled by the greater amount, its inner surface would, if free, contract more than the outer surface of the shell below; but, being forced to remain of the same radius as the latter after its contraction (and straining), it follows that the upper shell must be stretched in order to rest upon the lower.

The same reasoning applies to every pair of consecutive shells from the greatest depth at which $V - v$ is a sensible quantity to the very surface of the Earth. Hence, on the assumption of sudden cooling throughout the whole of the Earth's crust that has so far undergone cooling, there ought only to be crust-stretching by lateral tension, and not any crust-folding by lateral pressure.

But, as shown above in § (11), lateral pressure, brought into action by secular cooling, does produce folding in the Earth's crust—to a limited depth, it is true, and in rock that may already once have been stretched by lateral tension.

I maintain, therefore, that an argument built up on the virtual hypothesis of a sudden cooling of the globe, however favourable to the contraction theory the other data employed may be, loses its force when we consider the natural process of a continuous and gradual cooling.

(19) Lastly, even if it were to be proved that the volume of rock folded by lateral pressure due to secular cooling is insufficient to produce the existing inequalities of land and ocean-basin, it would in no wise follow that the mountain-chains alone could not be so produced. And it should be remembered that this is all that is generally asserted by the advocates of the contraction theory. Mr. FISHER's argument assumes that the Earth's surface was initially spherical. But Professor B. PEIRCE * and Professor G. H. DARWIN † have shown that vast wrinkles would be formed on the

* "The Contraction of the Earth," 'Nature,' Feb. 16, 1871 (vol. 3, p. 315), reprinted from the 'Proceedings of the American Academy of Arts and Sciences,' vol. 8.

† "Problems connected with the Tides of a Viscous Spheroid," 'Phil. Trans.,' 1879 (Part 2), pp. 539–593.

surface of a once viscous Earth by "the diminution of oblateness arising from the diminished velocity of rotation upon the axis" resulting from tidal friction; wrinkles that would be amply large enough to form the foundations of the continental masses. In order to prove the insufficiency of the contraction theory, it is necessary, therefore, to show that folding by lateral pressure, both directly and indirectly, by acting on vast masses of sediment, is incapable of producing, not the average height of the inequalities of the Earth's surface, but the total amount of rock-folding in all past and present mountain-chains.

III. *The Effects of Crust-Stretching and Folding on the Evolution of the Earth's Surface-Features.*

(20) It has been already stated that much weight cannot be attached to the numerical results obtained in this paper. They are evidently dependent on the assumptions made at the commencement. It should also be remembered that the coefficient of expansion (e) has been supposed constant at whatever temperature the loss of heat takes place, and there is reason for believing that this is not strictly true. And again, it was assumed that, on solidifying, the surface of the Earth was a smooth sphere, although by the interference of tidal friction there must previously have been raised up masses forming the nuclei which, by continual growth of folded rock and mountain-range along their borders, have developed into our present continental areas. Clearly the existence of these great masses from the very beginning must have had an all-important influence on the subsequent evolution of the Earth's surface-features.

(21) "In the case of the Earth," says Professor G. H. DARWIN, "the wrinkles would run north and south at the equator, and would bear away to the eastward in northerly and southerly latitudes; so that at the north pole the trend would be north-east, and at the south pole north-west. Also the intensity of the wrinkling force varies as the square of the cosine of the latitude, and is thus greatest at the equator, and zero at the poles. Any wrinkle when once formed would have a tendency to turn slightly, so as to become more nearly east and west than it was when first made.

"The general configuration of the continents (the large wrinkles) on the Earth's surface appears to me remarkable when viewed in connection with these results."

And again, indicating a physical cause of continental permanence, he says, "But, if this cause was that which principally determined the direction of terrestrial inequalities, then the view must be held that the general position of the continents has always been somewhat as at present, and that, after the wrinkles were formed, the surface attained a considerable rigidity, so that the inequalities could not entirely subside during the continuous adjustment to the form of equilibrium of the Earth adapted at each period to the lengthening day. With respect to this point it is worthy of remark that many geologists are of opinion that the great continents have always been more or less in their present positions."*

(22) Now, soon after the formation of these wrinkles, that is, in the initial period of the Earth's history as a solid, or nearly solid, globe, the unstrained shell must have been very close to the surface of the Earth, and the surface of greatest stretching also so near to it that stretching by lateral tension must have affected the form of the surface features. But, owing to the pressure of the continental wrinkles, the amount of stretching under them must have been very much less than under the great oceanic areas. Thenceforward, therefore, *crust-stretching by lateral tension must have taken place chiefly beneath the ocean-basins, deepening them and intensifying their character.* And, in leading to the continual subsidence of the ocean-bed, it is evidently a physical cause of the general permanence of oceanic areas: a cause, it is true, continually receding from the surface, and diminishing in intensity with the increase of time, but probably even now not quite ineffective.

(23) Again, the amount of crust-stretching by lateral tension being greatly in excess of the amount of crust-folding by lateral pressure due to secular cooling, it follows that folding beneath the ocean-bed will do little but diminish its rate of subsidence. The effects of folding in changing the form of the Earth's surface features will therefore be most apparent in the continental areas, especially in those regions where the change of vertical pressure above the folded layers diminishes most rapidly, *i.e.*, near the coast-lines where the slope towards the ocean depths is greatest. It is perhaps worthy of remark that these are the districts where earthquake and volcanic action are now most prevalent.†

In the coast regions, moreover, the products of continental denudation are chiefly deposited, and the rock-folding due simply to secular cooling produces in vast masses of sediment still more crushing and folding.‡ The direction of the folds will be perpendicular to the average slope of the surface above them, *i.e.*, they will generally be parallel to the coast-line. Hence *the continents will grow by the formation of mountain chains along their borders.*

(24) In a given time, the amount of rock-folding resulting from secular cooling was greatest in the first epochs of the Earth's history, and diminished as the time increased. It does not necessarily follow that the early mountain ranges were the loftiest and most massive, but probably they were; and very possibly also the displacement, by crushing and folding, of two neighbouring portions of rock was greatest in early times. But,

* 'Phil. Trans.', 1879, pp. 589, 590.

† Professor J. Milne, "Note on the Geographical Distribution of Volcanoes," 'Geol. Mag.,' vol. 7, 1880, pp. 166–170.

‡ Professor J. D. Dana thus summarises the history of the Alleghany and other mountain-chains:— "First, a slow subsidence or geosynclinal .... and, accompanying it, the deposition of sediments to a thickness equal to the depth of the subsidence; finally, as a result of the subsidence, and as the climax in the effects of the pressure producing it, an epoch of plication, crushing, &c., between the sides of the trough." 'Phil. Mag.,' vol. 46, 1873, p. 49.

taking into consideration the whole surface of the globe, *the process of mountain-making diminishes with the increase of the time, and so also does the rate of continental evolution.*

(25) It cannot be said that the contraction theory on the hypothesis of solidity is entirely free from objections. Two very obvious ones have already been alluded to in the course of this paper, namely (1) The small calculated depth of the unstrained surface, especially in early geological periods; and (2) The small proportion of folded rock to stretched rock directly produced by secular cooling. But I do not think that these objections are by any means fatal to the theory. Assuming the Earth to be practically solid, and to have been originally at a high temperature throughout, I believe it may be concluded that the peculiar distribution of strain in the Earth's crust resulting from its secular cooling has contributed to the permanence of ocean-basins, and has been the main cause of the growth of continents and the formation of mountain chains.

VIII. *Note on Mr.* Davison's *Paper on the Straining of the Earth's Crust in Cooling.*

By G. H. Darwin, *LL.D., F.R.S., Fellow of Trinity College, and Plumian Professor in the University of Cambridge.*

Received June 15,—Read June 16, 1887.

Mr. Davison's interesting paper was, he says, suggested by a letter of mine published in 'Nature' on February 6, 1879. In that letter it is pointed out that the stratum of the Earth where the rate of cooling is most rapid lies some miles below the Earth's surface. Commenting on this, I wrote :—

"The Rev. O. Fisher very justly remarks that the more rapid contraction of the internal than the external strata would cause a wrinkling of the surface, although he does not admit that this can be the sole cause of geological distortion. The fact that the region of maximum rate of cooling is so near to the surface recalls the interesting series of experiments recently made by M. Favre ('Nature,' vol. 19, p. 108), where all the phenomena of geological contortion were reproduced in a layer of clay placed on a stretched india-rubber membrane, which was afterwards allowed to contract. Does it not seem possible that Mr. Fisher may have under-estimated the contractibility of rock in cooling, and that this is the sole cause of geological contortion?"

Mr. Davison works out the suggestion, and gives precision to the general idea contained in the letter. He shows, however, that there is a layer of zero strain in the