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T C. CHAMBERLIN

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T. C. CHAMBERLIN
University of Chicago

To the geologist the center of interest in the phenomena of radioactivity lies in the spontaneous evolution of heat attending atomic disintegration. This interest is the more piquant because the source of the internal heat of the earth is one of the oldest of its problems and the discovery of radioactivity brings into the study an unexpected element. During the last century there was a rather general consensus of opinion that the earth's internal heat was derived from the condensation of the nebula from which the earth was then commonly supposed to have taken its origin. This nebula was usually regarded either as a gaseous body or as a quasi-gaseous meteoritic swarm, and in either case its condensation was thought to have given rise to intense heat. The primitive gaseous or quasi-gaseous earth-mass was held to have passed later into a molten globe, and the subsequent incrusting of this to have entrapped in the interior the heat supply of subsequent ages. This older view was still in general possession of the field when the apparition of radioactivity forced a new line of thought. But there was also an alternative view built on the belief that the earth grew up gradually by the slow accession of discrete orbital matter in distinction from the direct condensation of a gaseous or quasi-gaseous mass. In this view, the internal heat arose mainly from the self-compression of the earth-mass as it grew.

This view had its origin in the grave cosmogonic difficulties that had been discovered in the gaseous and quasi-gaseous theories of the earth's origin. Of the two rival views thus already in the field, the one postulated a plethora of heat at the outset and a gradual loss in all later time, the other postulated at the outset a more limited supply of heat which was increased as compression progressed. The adequacy of such compression to give a sufficiency of heat was a subject of debate from the inception of the view.[1] To the interest that naturally attaches to the discovery of a wholly unexpected agency, already acute because of the agent's singular qualities, there was thus added piquancy in view of its inevitable bearings on the thermal problem of the earth's interior and on the hypotheses of the earth's origin.

An even more fundamental though less imminent interest was awakened by the discovery that some of the atoms of the earth-substance are undergoing spontaneous disintegration and that all atoms may possibly be doing so and that even the permanency of terrestrial substance may be brought into question. However, matters of this ultra-radical nature cannot be discussed with advantage as yet, for little light has been shed on the broad question whether all terrestrial substance is in process of disintegration, and on the complementary question whether atoms are somewhere and somehow undergoing integration.

If the general tenor of the studies thus far made is to be trusted, nothing in the field of common experience seriously inhibits the dissolution of the radioactive substances. It does not appear that even the greatest heightening or lowering of temperature or pressure that can be brought to bear either stays or hastens, in any material measure, the progress of atomic disintegration. Nor do any known changes of chemical union or disunion, of concentration or diffusion, or of freedom or confinement seem materially to retard or accelerate the spontaneous dissolution. There is probably no warrant for an unqualified affirmation that neither temperature, pressure, concentration, exposure, nor combination

[1] The status of the problem of the earth's heat as it stood near the opening of the twentieth century is sketched more fully in *Year Book No. 2*, Carnegie Institution, 1903, 262–65, and in *Geology*, Chamberlin and Salisbury, I (1904), 533–47.

affects the progress of radioactive decomposition, but no specific effects of a critical value have been certainly disclosed by experimentation. These conditions that so much qualify most geologic processes must apparently be regarded as negligible for the present so far as radioactivity in the earth's crust is concerned. It is thought by the leaders in radioactive science permissible to treat radioactive substances as undergoing disintegration persistently and uniformly under all known terrestrial conditions. In the thermal problem of the earth radioactive particles may be dealt with tentatively as centers of heat-generation whose efficiency and endurance are conditioned simply by their atomic constitutions and their mass values. In so far as these remarkable deductions from experimentation may be thought to fall short of full warrant, weakness in equal degree must of course be held to enter into the geological inferences based on them; and in view of the radical nature of the conclusions to which they lead, we cannot perhaps too constantly bear in mind that the postulate of immunity to conditions is the main basis of the geologic contributions credited to radioactivity. But the remarkable verifications of skill and accuracy that have followed the multiplication of tests furnish an ample warrant for a serious discussion of present deductions. There is strong presumption that future tests will further substantiate present conclusions so far as their main bearings on immediate terrestrial problems are concerned, whatever interrogations one may be disposed to indulge in regarding ulterior problems.

The clue to this extraordinary tenacity of radioactive dissolution in spite of conditions that profoundly influence most terrestrial processes, probably lies in the fact that the action springs from the internal motions of the atomic constituents and that these are of such intense nature and are actuated by such prodigious energies that the influences of ordinary chemical and physical conditions are relatively insignificant.

At the same time, the radioactive substances show a decided aptitude to enter into chemical combination under common conditions. None of the parent radioactive metals is known to occur in the earth in a native state. In the form of compounds they have become widely distributed over the face of the globe in the course of the surface changes it has undergone. Radioactive substances have freely entered into solution in the natural waters and have thus been carried wherever the hydrosphere reaches, and in turn they have been deposited therefrom. Their singular property of passing spontaneously from certain states into gaseous forms (emanations) and then back into the solid or liquid form, on definite time schedules, has caused them to be given forth freely into the atmosphere, and, drifting in this, to be later precipitated in the solid or liquid form, and this has naturally been dispersive in an extreme degree. Radioactive matter is therefore found in practically all the rocks of the surface of the earth, in practically all the waters, and in practically all the atmosphere.

But this highly diffusive distribution has not been uniform. There have been special tendencies toward concentration running hand in hand with the general tendencies to diffusion, and these concentrative tendencies constitute a critical element in this discussion.

So far as the accessible part of the earth is concerned, the igneous rocks may be taken as the original source of the radioactive substances. How the igneous rocks themselves came to have their present content will be considered later. Whence the radioactive substances came still more remotely is problematical. There may be even now accessions of radioactive substances from without the earth for aught that is known, and indeed this is probable; but, except in the form of meteorites whose content appears, from the few tests made, to be relatively meager,[1] such accessions are not yet demonstrated.

The cycle of distribution on the earth's surface is simple. From the igneous rocks the radioactive substances are dissolved and disseminated through the waters and carried wherever they go; while from both the rocks and the waters the emanations are given forth into the atmosphere. From the air and the waters in turn the radioactive derivatives are reconcentrated into the earth, except as their disintegration becomes complete and they pass permanently, in the form of helium, into the atmosphere or are lost from the atmosphere into the cosmic regions outside.

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[1] Strutt, *Proc. Roy. Soc.*, LXXVII A, 480.

The special distribution of the radioactive substances among the different kinds of igneous rocks is no doubt full of meaning, but as yet the determinations have not been sufficient to justify more than a few broad generalizations, and these must be held subject to revision.[1] It may be said safely that the igneous rocks carry a higher ratio of radioactive substance than the average sediments. The reason for this is simple. The sediments are derived from the igneous rocks, and in the process of derivation some of the radioactive matter inevitably goes into the waters and into the atmosphere, and this diversion leaves the content in derivative rocks lower than that of the original rocks. If all the radioactive matter that is lost into the waters and the air were gathered into the derivative rocks, their content should equal that of the igneous rocks from which they came, if no account be taken of the loss by dissolution.

The earlier determinations of the amounts of radium in the igneous rocks by Strutt seemed to show that the acidic class hold more radioactive matter, on the average, than the basic class, and a portion of the later determinations seem to support this generalization, but the determinations of Eve and Joly, which have been important, seem to bring the richness of the basic class into somewhat near equality with that of the acidic, and even to make the preponderance of the one class over the other doubtful. The point of special interest here lies in the inference that, if the liquefaction and eruption of the igneous rocks is dependent on the heat derived from radioactivity, the distribution of radioactive substances in the erupted rocks should be inversely proportional to

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[1] The larger number of determinations of radioactivity in rock have been made by Strutt: *Proc. Roy. Soc.*, LXXVI A (1905), 88 and 312; LXXXVII A (1906), 472; LXXVIII (1906–7), 150; LXXX A (1907–8), 572; Eve: *Phil. Mag.*, September, 1906, p. 189; February, 1907, p. 248; August, 1907, p. 231; October, 1908, p. 622; *Am. Jour. Sci.*, XXII, (December, 1906), 477; *Bull. Roy. Soc. Con.*, June, 1907, pp. 3 and 9; July, 1907, p. 196; Joly: *Nature*, January 24, 1907, p. 294; *Phil. Mag.*, March 1908, p. 385; *Radioactivity and Geology* (1909), general treatment with references; Elster and Geitel: *Phys. Zeit.*, II (1900–1901), 590; III (1901), 76.

For the physics of radioactivity see J. J. Thomson: *The Conduction of Electricity through Gases;* E. Rutherford: *Radioactivity;* (1904); *Radioactive Transformations* (1906); *F. Soddy: Radioactivity* (1904); *The Interpretation of Radium* (1909); R. J. Strutt: *The Becquerel Rays and the Properties of Radium* (1904); and the papers of Boltwood, McCoy, and many others.

their temperatures of mutual solution or of fusion. But it must be observed that even if such a casual distribution prevailed in the rock-matter when first it took the liquid form, this distribution might not persist indefinitely, for selective segregation has apparently taken place during the later processes. It is quite clear that the radioactivity is concentrated in some constituents rather than others, as for example in zircon, pyromorphite, apatite, and some other minerals, and in pegmatite and some other rocks. The pegmatitic material, in segregating from a granitic magma, seems to have gathered into itself an unusual proportion of the radioactive substance of the parent mass. In the details of final distribution, therefore, the different parts of the segregated rock-material may rationally be expected to differ from one another and from the parent magma in radioactive content. The determinations thus far made, though not adequate to demonstrate this, seem to be in consonance with it. Much interest will therefore gather about the forthcoming determinations as they multiply and contribute their quota of evidence bearing on the radioactive qualities of the various species of igneous rocks.

Among the derivative and sedimentary processes it seems clear that there are modes of concentration also which have given to different sediments different contents of radioactive substances. It appears from the determinations already made that the radioactive substances are leached out of the parent igneous rocks faster than the average minerals of those rocks, for weathered igneous rocks are found to carry less radioactive matter than fresh rocks. This is in accord with the aptitude for chemical change already noted; and yet soils which are almost the type of ultra-weathered material still retain notable radioactivity, but a part of this is probably a redeposit from the atmosphere. In general, it appears that the clayey element carries more radioactive material than the quartzose sands or the calcareous derivatives.

In the deep-sea deposits radioactive matter is higher than in the deposits of the shallow parts of the ocean. In the red clays and radiolarian oozes of the abysmal depths the content is markedly greater than in the land-girting muds and sands, or the calcareous oozes of mid-depths. This is assigned in part to the removal by solution of the lime from the original matter of the abysmal deposits, leaving them residual concentrates, and in part to the collection in the depths, in relatively high proportions, of phosphate-bearing relics (teeth, bones, etc.) with which radioactive substances are associated. It is a suggestive fact that the phosphatic nodules of the great deeps are highly radioactive compared with ordinary sedimentary material. A part of this is clearly due to the concentration of the radioactive substances after the phosphates were deposited, for fresh phosphatic material is notably less radioactive than fossilized phosphates.[1]

It appears then that the radioactive substances on the surface of the earth are subject to special agencies that lead in part to greater concentration and in part to wider distribution, and that these act co-ordinately with the general dispersing agencies that give radioactivity to the derivative rocks, to the waters, and to the air.

If it were permissible to reason from what is known of surface phenomena, particularly from the broad fact that radioactivity increases as we go from air to water, from water to sediment, and from sediment to igneous rock, it might be inferred very plausibly that radioactivity would be found to reach its maximum concentration in the heart of the earth, and certainly that the deeper parts would be as rich as the superficial ones. This presumption might very justly be felt to be strengthened by the fact that the atoms of uranium, radium, and thorium are among the heaviest known and that if the earth were ever gaseous or liquid, these heavy atoms might naturally be expected to be concentrated toward its center unless the viscosity of the fluid mass were too great to permit this, in which case the distribution should be either equable or indifferent to depth.

But Strutt[2] early called attention to the fact that if such an increasing abundance exists toward the center of the earth, or if there were an equable distribution in depth, the heat gradient as the earth is penetrated would be higher than observation shows it to be. By computations on the data then available he

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[1] Strutt, *Proc. Roy. Soc.*, LXXX A, 582.

[2] *Proc. Roy. Soc.*, LXXVII A (1906), 472; LXXVIII A, 150.

concluded that a distribution of radioactive substance equal to that of the surface rocks for a depth of only 45 miles would give the rise of heat actually observed in wells, mines and other deep excavations. Later data and closer scrutiny seem to confirm the general soundness of Strutt's inference, and to make the limitations even more narrow. Joly, approaching the problem from the geological as well as the physical point of view, and with the advantage of later data, reached the conclusion that radioactivity of the amount observed at the surface, if continued to a depth ranging from 27 to 37 kilometers (17.2 to 23.5 miles), would give rise to heat equal to that implied by the loss at the surface.[1] According to Joly, however, a complete concentration of radioactivity in a shell of this depth does not meet the apparent requirements of igneous phenomena if this be assigned to radioactivity. A deeper distribution of a part of the radioactive matter and a less concentration in the outer part of the crust is felt by Joly to be required and he was led to this final statement: "If we said that the richer part of the crust must be between 9 and 15 kilometers deep, we cannot be far from the truth. This appears to be the best we can do on our present knowledge."[2] It is to be noted that these deductions are reached on the supposition that all the internal heat given out arises from radioactivity; no margin is left for any original heat or for secular heat from any other source. On the other hand, the computations seem to take no account of loss of heat by means of igneous extrusions.

These remarkable deductions raise two questions of radical import:

(1) If supplies of heat are generated currently by radioactivity in such abundance that it is necessary to put these severe limits on the distribution of radioactive substances, must we abandon entirely all further consideration of supposed supplies handed down from a white-hot earth or from any other form of the primitive earth?

(2) Is there among the internal processes previously postulated any that provides a way in which such a concentration at

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[1] *Radioactivity and Geology* (1909), 175.

[2] *Ibid.*, 183.

the surface might naturally have taken place, or must we find a new geological process to fit the new thermal difficulty?

The rigor of the dilemma is softened somewhat by noting that the deductions of Strutt, Joly, and their colleagues are based simply on comparisons between the heat-generating power of radioactive substances in the crust and the conductive power of the crust. The functions of igneous extrusion as a mode of transfer of internal heat do not seem to be taken into account. This is not unnatural since the heat carried out by extrusive matter and by waters heated by igneous intrusions has not usually been regarded as an important factor in reducing the high temperature inherited by the earth under the older view. But the movement of igneous matter and of waters and gases heated by it has been made to play an essential part in the working concepts that have been based on the planetesimal hypothesis. There will be occasion to return to this critical difference of view.

When the apparent excess of thermal riches arising from the new source was first realized an escape from the dilemma raised by it was sought in the natural supposition that the disintegration of uranium and thorium was restrained by pressure in the depths of the earth, and that, though present there, their activity was greatly subdued or possibly inhibited altogether. This plausible explanation was diligently tested; but the general tenor of experiments on the effects of pressure, notably those of Eve and Adams[1] in which the pressures were carried to intensities sufficient to cover earth-pressures to the depths supposed to limit radioactivity and beyond, showed no appreciable restraint on the disintegrating process. It seems necessary, therefore, in the present state of evidence, to accept the inference that the radioactive substances are really concentrated toward the surface, and that the radioactive content in the depths of the earth is of a much lower order.

It does not fall to me to adjust the new requirements to the older view of the earth's internal temperatures based on a molten earth, for other considerations led me to the abandonment of this view before the advent of the new issue. I must leave it to those who hold to the molten hypothesis to battle with its new perils.

[1] *Nature*, July, 1907, p. 269.

With such a plethora of heat at the start as a molten earth implies and with a new agency whose current production of heat would seem to be excessively great if its prevalence were not constructively minimized, it is not with regret that I feel absolved from the task of finding a reconciliation between this venerable view and the requirements of juvenile discoveries.

The discussion of Professor Joly,[1] though not explicitly based on the theory of a molten earth, is sympathetic with the general tenets associated with such an earth, and his treatment may be taken as offering the best approach to a reconciliation that seems now possible.

It is interesting to note, however, that when Professor Joly reached the critical question of a possible mode by which the surface concentration of radioactivity could have come about (*Radioactivity and Geology*, 184) he turned to the accretion or planetesimal hypothesis. While he indicated the central line of action on which the concentration might have been accomplished he left without elucidation the line of reconciliation between the heat gradient postulated by the planetesimal view and the gradient he deduces from radioactivity.

It is the chief purpose of this paper to set forth what seems to me to be the true harmony between the new light shed by radioactivity and the tenets of the planetesimal view as shaped by me before the discovery of radioactivity and to show the co-ordination of the planetesimal and radioactive agencies in jointly leading to the results observed. To this end it is necessary to sketch with some care the thermal features of the planetesimal view in the form to which preference was given from the start so that it may be clear just what part radioactivity plays in the assigned co-operation.

On the assumption that the earth grew up by the accession of planetesimals, whatsoever heat arose from the condensation of the nucleus about which the growth took place centered in the innermost parts and can affect present surface phenomena only by transfer. The infalling matter that is supposed to have built up the earth to its mature size must have generated much heat by

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[1] *Radioactivity and Geology*, 154–82.

its impacts, but as the infall is held to have been slow and as this heat was superficial, it may be assumed that it was largely radiated away before it became so deeply buried as to be permanently retained, and so the most of the heat of impact may be regarded as negligible.[1] In the original shaping of the planetesimal hypothesis (before the discovery of radioactivity) the main source of internal heat was made to spring from the compression which the deeper parts of the earth underwent by the increase of its mass as the planet grew to maturity. This chief source was supposed to be abetted by heat springing from the rearrangment and recombination of molecules within the mass as time went on. Changes in the distribution of the heat after it was developed were supposed to follow by means of conduction and especially by the transfer of hot fluid matter carrying latent heat.

It is important to the present discussion to note that the heat generated by pressure did not affect the outer part and that it began to be sensible only when those depths were reached at which the rocks suffered appreciable compression from the weight of the rock-mass above them. Thus the heat gradient so generated would rise only slowly in the outer part of the earth and faster in a systematic way toward the center for a considerable depth, if the compressibility of the rocks remained uniform to indefinite depths. If the compressibility fell off as compactness increased the rate of thermal rise toward the center would have been slower. Compressibility at the surface seems to be nearly proportional to pressure, but the compressibility of rocks after they have been compacted by such pressures as are attained at considerable depths is unknown, and it is necessary to proceed here by alternative hypotheses. The extrapolation of the curve found under experimental pressures is of course entitled to precedence and this alternative was used as the basis of the first approximation to the heat curve of the earth's interior. For the other factors, such as specific heat, necessarily taken into account in the computation, assumptions as near to known facts as possible were made. On these assumptions it was found that the heat generated between the surface and the center of the earth may be represented by a curve

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[1] Chamberlin and Salisbury, *Geology*, I, 533.

which rises at a very low rate near the surface and is followed by a slowly *increasing* rate for about one-third the distance to the center, beyond which it rises at a *decreasing* rate to the center; or, if traced from the center outward, this computed curve of temperature declines faster and faster at every step for about two-thirds of the distance and then declines less and less rapidly to a vanishing-point near the surface. Hence if conductivity be assumed to be the same at all depths, the outward flow of heat on such a gradient would increase in rate from the center to the two-thirds point and then grow slower toward the surface, from which it follows that, on these assumptions of uniform compressibility and uniform conductivity taken by themselves, the internal heat should have been progressively lowered in the deep interior and raised in the more superficial parts. The conductivity of rocks is so very slow, however, that its effects at the surface under the conditions named cannot have been large up to the present unless the earth is much older than even radioactivity seems to imply.

This first approximation to a theoretical curve of heat, even when modified by conduction, has not been supposed to represent the actual distribution of heat at the present time, for reasons that follow.

There is ground to think that compressibility falls off as increased degrees of compactness are attained. In working out the curve which was published in *Geology*, I, 566 (Chamberlin and Salisbury), Dr. Lunn used as a guide the Laplacian law of density which postulates that density varies as the square root of the pressure. This distribution of density harmonizes fairly well with such astronomical tests as are available and gives a mean density for the earth which is near that required by the earth's total weight. The assumption that the increased density of the interior is all due to compression, however, makes no allowance for the probable transfer of lighter matter to or toward the surface by extrusive action which would tend to increase the mean specific gravity of the residue. The curve of Dr. Lunn may be regarded as a second approximation.[1] But this, as noted, does

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[1] *Year Book No. 3*, Carnegie Institution of Washington, 1904, p. 156; also "Geophysical Theory under the Planetesimal Hypothesis," Section II of "Tidal and Other

not take into consideratiion the effects of liquefaction and extrusion and these in the planetesimal view are of the first order of importance. The theoretical curve mathematically deduced by Dr. Lunn is, however, an indispensable basis for a third approximation in which the effects of liquefaction and extrusion are taken into account.

Before passing on to consider liquefaction and extrusion, it is well to note that the Lunn curve based on the Laplacian law of density also is low near the surface and that its rate of rise is much below that of the temperature gradient observed in wells and mines. Dr. Lunn, on assumptions carefully specified in his discussion in the paper cited, found the rise in the first 200 miles only 330° C.

This low development of heat in the outer part of the earth seemed at first thought to present a difficulty of a rather serious nature, but it was believed to be met by the effects of liquefaction and extrusion, and these were made the chief basis of an additional approximation to the actual temperature curve (Chamberlin and Salisbury, *Geology*, I, 265–67). It was held that the rising heat of the interior would reach the temperatures of fusion or of mutual solution of some ingredients in the mixed material much earlier than that of other ingredients, and that the ascent of the portion that became molten carrying its latent as well as sensible heat into the cooler outer zone would necessarily raise the temperature of that zone. It was held that the continuation of this process served as a constant influence tending to retard the rise of temperature in the deeper zone where the partial liquefaction was in progress while it progressively raised that of the outer zone into which the liquid rock was intruded, whether it lodged in the crust or passed through it to the surface. This extrusive process was supposed to have continued to the present day and to have resulted in a permanent adjustable working curve of accommodation between thermal, fluidal, and mechanical conditions. This curve, except in the cool crust, was essentially identical with the fusion-

Problems," *Publication No. 107*, Carnegie Institution of Washington, 1909, pp. 169–231; for a summary and figure of curve see also Chamberlin and Salisbury, *Geology* (1904), I, 566.

solution curve, whatever that might happen to have been for the time being under the local conditions of pressure, state of strain, nature of material, means of escape, and other properties that affected liquefaction and extrusion. It was regarded as essentially *a curve of equilibrium between solidity and liquefaction* accommodated to the conditions present at each depth and at each stage and was *maintained automatically. The actual curve as thus assigned continued always to be essentially the liquefaction curve after that was once attained.*[1] The view excludes automatically all internal temperatures higher than the local liquefaction temperatures and of course excludes all pervasive gaseous conditions except that of the interspersed and occluded gases of the mixed mass. These interspersed gases assisted extrusion and hence were among the parts most freely extruded. All theoretical inferences based on temperatures higher than the temperatures of liquefaction are excluded from consideration under this view by its very terms.

Certain structural conditions postulated by the planetesimal hypothesis greatly favored this automatic action. The infalling matter was assumed to have built itself up in a very heterogeneous manner with the result that the mass of the earth was an intimate mixture of all the kinds of material that made up the spiral nebula from which it was supposed to have been gathered. As this mixed matter was heated by compression, some parts of it must certainly have reached temperatures at which they could go into mutual solution or into fusion while as yet other closely associated parts had not reached temperatures that permitted such action, and as the rise of temperature was very slow by the terms of the hypothesis the passage of successive parts into liquefaction was widely separated in time. Fluid parts thus came temporarily to be intimately mixed with solid parts. These fluid parts, in the act of passing into solution or fusion, absorbed the necessary energy of liquefaction at the expense of the increasing supply. On their ascent into the crust they heated it. If they lodged there and resolidified they gave up their heat of liquefaction. If they reached the surface the residue of heat, both sensible and latent, was lost. By such liquefaction and transfer these portions served

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[1] *Op. cit.*, 567.

to protect the residue in the deeper parts from liquefaction for the time being and the continuation of the process extended the protection to such residue as continued to persist.

It is not necessary to offer evidence that ascent of liquid rock took place in great quantities in the early geologic ages and has been more or less active in all ages down to the present. One of the extraordinary facts of the Archaean terranes is the extensive lodgment of liquid rock in the crust, and even in later ages batholitic phenomena have attained surprising magnitudes. The extrusion of molten rock at the surface was a very pronounced phenomenon as late as the Tertiary and is still an active process. As this extrusive action was widely distributed over the surface at various altitudes and at various stages through great lapses of time and yet was never really very massive when measured in terms of earth-volumes at any one time or place, it is of critical value here to note that the view built on the planetesimal hypothesis appeals to a special set of conditions of liquefaction and extrusion which are peculiarly favorable for selective work in small masses and unfavorable for *general* liquefaction. In this respect the conditions it assigns stand somewhat in contrast with the conditions usually assumed to be the natural inheritances from a general molten condition. The inference that *general* liquefaction would take place on any general rise of heat is natural enough in a case in which the whole mass has been solidified from a previous molten state, for such a mass might be presumed to return massively into its former state on a reversal of conditions; but the heterogeneous condition of the mixed matter of the interior postulated by the planetesimal view is not favorable to a simultaneous fusion of the whole mass or any large continuous part of it unless extrusion be restrained until a high temperature is attained. Such restraint is here held to be dynamically inconsistent with the mechanism and the stress conditions of the earth-body. In addition, therefore, to such a mixed state of material in the interior as peculiarly to invite selective liquefaction as the temperature slowly rose, the planetesimal view postulates a set of stress agencies that worked co-operatively to effect extrusion as fast as liquid matter accumulated in workable volume.

In considering stress effects, it is necessary scrupulously to distinguish between *hydrostatic* stresses which operate equally on all sides of a given unit and so only produce compressive and like effects, and *differential* stresses which promote movement and change of form. The effect of differential stresses on the solid parts of the earth is primarily to produce strains; the effect on liquid parts is primarily to produce flow and relocalization. And so by reason of this difference of effect, a general differential stress on any large part of the earth is apt to become locally subdifferentiated when solid and liquid parts are intermixed, especially if the liquid and solid states of these parts are partially interchangeable because their temperatures lie so close to the line of equilibrium between solidity and liquidity. Tensional strains promote liquefaction in bodies constituted as most rocks are; compressive strains resist liquefaction in such bodies. And so general differential strains co-operate with temperature in promoting or in restraining the passage of matter from the one state to the other according to the nature of the strain and thus have some influence in directing and facilitating movement as well as in forcing it.

Some of the differential stresses in the earth are essentially fixed and constant, such as the direct pressures that arise from the action of gravity. These stresses range from one atmosphere at the surface to about three million atmospheres at the center. Such pressures tend to force lighter bodies toward the surface while heavier bodies seek the center in ways so familiar that we need not dwell on them, nor on the fact that, since molten rock is usually lighter than the same rock in a solid state, this static differential stress of gravity presents a general condition that favors the ascent of liquid rock. So also the incorporation or generation of gases in liquid rocks tends to lessen the specific gravity and increase the mobility and hence the gaseous element adds another general influence that favors ascent.

In addition to these very general and persistent stresses, more special differential stresses have arisen at various times from inequalities of accession, from transfers of matter, from loss of heat, and from other varying agencies, and these have been present, in one form or another, at nearly all times in the earth's history. They have often been cumulative until they reached diastrophic intensity and manifested themselves in impressive deformations. That these have been effective agencies in forcing the movement of liquid parts within the earth in the lines of least resistance and of best accommodation to existent conditions is scarcely debatable.

In addition to the simple stresses of gravity and to the diastrophic stresses, there have been superposed at all times a series of stresses of a rhythmical pulsatory nature acting throughout the body of the earth. The nature and function of these has not been so generally recognized. These stresses are derived from the differential action of the gravity of neighboring bodies, particularly that of the moon and of the sun. Tidal and tidelike stresses and strains have swept through the earth's body in a constant cycle bringing to bear on each part a perpetual succession of compressive and tensional stresses and strains alternating with one another. The effect may be pictured as that of a minute kneading of the earth-body. There is not only a superposition of pulsating strains on the more static strains but a superposition of pulsating strains on pulsating strains. The pulses of the twelve-hour body tides are overrun by tides of longer periods and these are attended by shifts of direction of strain, all of which tend to knead the mixed matter to and fro and promote insinuation of the liquid parts along the lines of escape.

Underlying all these rhythmical strains there has been ever present a variation in intensity from center to surface. Sir George Darwin has shown that the tidal stresses generated by the moon at the earth's center are eight times as great as those at its surface. Each compressive strain squeezes the lower part of each liquid vesicle or thread more than the upper part.

The coexistence of these pulsatory and periodic strains with the simple static stresses of gravity and the less constant diastrophic stresses sufficiently implies their co-operative nature. All these three classes are either differential stresses or have factors or phases that are differential, and so, in specific local application, they are all transformed into sub-differentiational effects on the liquid and solid parts.

Under the planetesimal view the joint effect of these differential stresses and their resulting strains has been at all times to force toward the surface liquefied rock as fast as it gained workable volume. Much aid in insinuating itself along liquid lines and in fluxing a more open path until the fracture zone was reached, is assigned to the mixed nature of the material and to the local strains imposed by the stress agencies. The whole picture centers on the fundamental dynamic proposition that *energy in mobile and expansive embodiments seeks the surface, while its fixed embodiments are forced more firmly together toward the center.*

The extrusion is held to have begun as soon as the susceptible matter took the mobile form. Possible exception is admitted in the case of matter that may have been too dense to be forced to the surface. However, a high density of small masses enmeshed in masses of less density could only contribute to an average effect so long as a high state of viscosity was retained, and a relatively high viscosity for the small mobile masses, naturally arose from the close balance between the liquid and solid states. Such a condition seems equally to be implied by the remarkable mixtures of dense and light matter often seen in the igneous rocks.[1]

The matter forced early to the surface is held to have been buried by further accretions to the growing planet, later to have been subject to a second liquefaction and extrusion, a second burial, and so on. Progressive selection and reselection are postulated until the growth essentially ceased. Since then a more complete selection and concentration of the eutectic material at the surface has been in progress as far as further generation of internal heat has furnished the actuating agency.

Now if this picture in its working details and in its rather sharp antithesis to the older view is clearly in mind, the part which the radioactive substances may be supposed to play in co-operation with this mechanism without changing the general conception is little less than self-evident. The radioactive particles are sources of self-generated heat. Under the planetesimal view the radioactive substances were promiscuously scattered through the mixed mass as it was gathered in heterogeneously from the nebula

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[1] Chamberlin and Salisbury, *Geology*, II, 121–22.

by the crossing of the planetesimal orbits. No original segregation of this class of matter more than of any other heavy material is assignable. The relative amount of the radioactive matter, at least of the classes now known to be radioactive, must have been extremely small and its influence on the specific gravity of the matter with which it was mixed must have been negligible. The self-heating effects of these disseminated particles were necessarily expended first upon themselves and next upon adjacent matter, and, other things being equal, this homemade heat should have given these parts precedence in passing into the mobile state. Normally the mixed units that inclosed a radioactive particle should have been as susceptible of partially passing into the liquid state as similar units that were free from radioactive matter. The special source of heat should have turned the balance in favor of the unit immediately surrounding the radioactive particle. Thus the radioactive matter normally became involved in the mobile matter and passed with it to or toward the surface.

With every stage in the growth of the earth and with every reburial of the radioactive material a second similar preferential action should have followed. On the essential completion of the growth of the earth a more complete concentration of the self-heating matter should have followed, for additional weighting by accretion had essentially ceased and compression had become essentially static while the self-heating competency of the radioactive matter, though no doubt somewhat reduced by consumption, was probably more efficient *relatively* in the production of heat than it had been during the more active stages of growth.

It seems clear, therefore, that at all times after the volcanic process was well under way radioactivity should have been relatively most active in the outer part of the earth and should have become especially so in the latest stages of the earth. It is therefore not too much, perhaps, to claim that a specific basis in favorable conditions and a definite working mechanism for an effective concentration of self-liquefying matter at the surface was postulated in a singularly apt way before radioactivity was discovered, and quite irrespective of the dilemma which its discovery has involved.

Reciprocally radioactivity greatly eases the burden laid on compression in the outer part of the earth where it is least competent and where resort was had to igneous intrusions from below to give the crust its observed temperatures. With the addition of the new thermal agency the extrusions are presumed to play much the same part as before but more actively, as they must now be supposed to meet the liquefying effects both of compression and of radioactivity. If there was ground before to question the efficiency of compressional heat, aided by such other sources as were formerly assignable, to give rise to the high degree of igneous activity that marked the Archaean ages and to sustain the lesser igneous action of later periods down to the present, this doubt is amply resolved by the combined efficiency of compression and radioactivity. In any case it is certain that a large amount of energy has been brought to the surface and radiated into space.

Radioactivity also comes to the aid of other agencies of extrusion in the peculiar service it renders in opening a path for the outward movement of the liquid matter. In the liquefying process, as we have seen, the radioactive particles should have been gathered by their self-heating action into the liquid vesicles and have been forced outward with them. The self-heating property thus became an endowment of the liquid and gave to it thermal efficiency in dissolving and fluxing its way. This efficiency was continually renewed by the progressive disintegration of the radioactive atoms. It is not improbable that the liquid threads were thus aided in a very special way in boring upward, for it seems obvious that the part of the liquid which carried most of the self-heating constituent would come to have the highest temperature, the lowest specific gravity, and the largest gaseous factor—for the disintegration produced gas emanation and helium in addition to the gases generated by the heat alone—and hence would take the uppermost position and bring its liquefying influences to bear on the solid matter which lay between it and the surface toward which it was pressed. The very mechanism may thus have kept the most effective part at the point most critical to its ascent.

While this outline falls far short of an adequate discussion of the relations of radioactivity to the planetesimal hypothesis, it will perhaps suffice to point out the line of co-operation of the new thermal agency with the new genetic hypothesis. The two seem to co-operate happily. Jointly they seem to furnish a promising basis for a revised thermal geology in harmony with accumulating geologic data in various lines and with the growing evidence of the elastic rigidity of the earth-body as a whole. At least the concentration of the radioactive substances at the surface seems to be aptly explained, and the mechanism that conserves the solidity of the earth falls into consonance with the new experimental evidence of an elastico-rigid body-tide which seems scarcely less than decisive.

There is perhaps one further point, among the many remaining, that should be briefly touched here lest there seem to be an outstanding incongruity in the present distribution of vulcanism. If there is a progressive supply of heat in the earth's crust springing from radioactivity and if it is this that actuates vulcanism, why are not volcanoes more uniformly distributed over the face of the globe? A general sub-uniform distribution is a natural deduction from the postulates. The distribution of pits on the moon, assuming that they are volcanic craters, fairly fits the picture that normally arises from the action of such an agency. Especially is this true if vulcanism is effected in so selective and so individual a way as we have indicated. Why has not such a distribution persisted on the earth? It will perhaps be conceded that the prevalence of vulcanism in Archaean times fairly satisfies the terms of the case. But at present volcanoes are rare in the primitive shields that form the nuclei of the continents while volcanoes are concentrated about the borders of the continents and in the deep basins and are particularly abundant where the great segments of the crust join one another. The primitive shields are indeed intimately scarred and shotted with igneous intrusions of the early ages, but they are almost immune now.

There seem to be two lines of plausible explanation. These old embossments have suffered denudation from an early date and the matter removed has been carried to the borders of the adjacent basins. According to the hypothesis of concentration at the surface, this lost matter carried a relatively high proportion of radioactive substance. When this was in the state of a mechanical sediment it was chiefly deposited on the borders of the basins; when it was in solution it mixed with the waters of the oceans and was later largely concentrated in the oceanic precipitates. Thus the prolonged process of denudation cut away the radioactively richer part of the shield and added it to the undenuded crust of the continental borders and the oceanic basins, thinning the one and thickening the other in a special radioactive sense. Besides this the lower crust in the denuded area was lifted relatively toward the cold surface, while in the depositional area it was relatively depressed beneath a growing radioactive mantle.

The rise of the denuded embossments of the crust was attended by elastic expansion of the whole sector of the earth beneath, since the gravitative pressure was lessened throughout. A lowering of the melting-points indeed attended this and doubtless a change also of the mutual-solution conditions, but this was anticipated by the elastic expansion and its instantaneous cooling effects, a point usually overlooked.

In addition to this immediate expansional effect, it is held by some geologists, with whom I am glad to associate myself, that the protruding portions of the continents tend to lateral creep and that this carries with it tensional effects as well as some further elastic expansion. At the same time, the penetration of surface-water is promoted and this aids effectively in carrying off the heat of the outer crust. It may be observed that while meteoric circulation penetrates to considerable depths beneath land surfaces there is little reason to think that there is any effective circulation to appreciable depths in the ocean beds.

One further agency is believed to co-operate with these at a lower horizon but this can be touched only with reserve as it involves joint studies yet in progress upon which I do not feel at liberty to draw further than may be necessary merely to indicate their bearing on this particular problem.[1] In a previous part of

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[1] The studies are common to my son, Rollin T. Chamberlin, and myself and in the particular here applicable the junior partner is the leader in pursuance of lines of inquiry growing out of his studies on "The Appalachian Folds of Central Pennsylvania," *Journal of Geology*, XVIII, No. 3 (April-May, 1910).

this paper the selective influence of strains on fusion and solution was cited. There seems little doubt that a similar influence is exerted by the great zones of strain that are developed in the earth by diastrophic agencies. Among the tentative distributions of these under study, a specific system seems more probable than others and this is of such a nature as to direct fluid matter, particularly any that may arise at considerable depths, toward the lines that are affected by volcanic extrusions.