17. On the Heat Generated by the Deformation of the Earth Crust.

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Introduction.

Any inelastic deformation of the earth crust is accompanied with the generation of heat, which must be taken into account in any problem concerned with the thermal conditions of those parts of the crust subjected to sensible deformations. For example, it may be inquired whether the heat of some hot springs may not be supplied, at least partly, from such a source. Another example may be cited which is related with the hypothesis of continental drift; namely, the heat generated by the supposed slow displacement of the continental crust relative to the substratum may or may not affect the facility of such a motion.

Heat of Hot Spring.

The origins of the heat of hot springs have been repeatedly enumerated and discussed by generations of geologists. Besides the volcanic sources, the radioactive and chemical origins have been frequently dwelt upon. In the meanwhile, the possibility of a mechanical origin of heat seems to have be unduly neglected, though the present author was yet unable to make an exhaustive survey of the literatures.

In Saghalien, Honsyû, Formosa, Corea and also in China[1] we may point out numerous examples of a system of hot springs which are arranged along some conspicuous fault line, but could not be associated with any apparent volcanic activity of the region in question. In such cases, it is usual to attribute the heat of springs to the juvenile origin of the water. Even if such be the case, it will make an important difference whether the fault zone through which the juvenile water emerges is additionally heated by the mechanical cause or not.

1) Some of the papers consulted by the author are referred to at the end of this note.

For a rough estimation, we will assume that the deformation is limited to a region bounded by two parallel planes at a distance h from each other. One of the boundary plane, and the mass beyond it, moves parallel to the plane with a uniform velocity v relative to the other boundary plane. The region between the two planes is sheared uniformly on account of this relative motion of the boundary planes, behaving meanwhile as if it consisted of a viscous fluid with its coefficient of internal friction η. Let the motion continue for an interval of time τ. Then the total work done, which is mainly converted to heat, is

$$Q = \eta \left(\frac{v}{h}\right)^2 \tau \text{ erg/cm.}^3 = \eta \left(\frac{v}{h}\right)^2 \tau / 4{\cdot}18 \times 10^7 \text{ cal./cm.}^3$$

Assuming $\eta = 10^{13}$, for instance, with Wegener, we have

$$Q = \left(\frac{v}{h}\right)^2 \tau \times 2{\cdot}4 \times 10^5 \text{ cal./cm.}^3$$

Suppose a fault takes place of which the total displacement $s = 10$ m. is completed in $\tau = 1$ minute. If the deformation is uniformly distributed within a zone of thickness $h = 100$ m. and if it went on with the uniform velocity $v = s/\tau$, we obtain $Q = 40$ cal. The temperature rise is $\theta = Q/\sigma$, where σ is the specific heat. If we assume $\sigma = 1/4$, we have

$$\theta = 160^\circ\text{C}.$$

which cannot be neglected in any case. If we assume $\eta = 10^{12}$ instead, then $\theta = 16^\circ$C., which may still be of importance in the problem of hot springs at least.

The temporary excess of temperature in the zone of deformation will fall down due to the conduction into the external regions on both sides of the disturbed zone. For the present estimation, we will neglect the effect of the earth's surface, an effect which will decrease with the increasing depth, and consider the simplest one-dimensional case. Let the initial distribution of the temperature v be given by

$$v = f(x) \qquad \text{for } t = 0.$$

From the usual equation

$$\frac{dv}{dt} = k \frac{d^2 v}{dx^2},$$

we have

$$v = \frac{1}{2\sqrt{\pi k t}} \int_{-\infty}^{\infty} f(x') \, e^{-\frac{(x-x')^2}{4kt}} dx'.$$

Assume

$$f(x) = T_0 \, e^{-px^2},$$

as this may roughly represent the state immediately after the process of deformation as discussed above. Then, the subsequent course of matter goes on according to

$$v = \frac{T_0}{\sqrt{4kpt+1}} \, e^{-\frac{x^2}{4kpt+1}}.$$

If we put $p=1/b^2$, b will represent the effective *breadth* of the disturbed region and may roughly correspond to the thickness h above quoted. Take, for instance. $b=100$ m., i.e. $p=10^{-8}$ and $k=10^{-2}$ which is an approximate value for granite. Then the time, t_0, at which the temperature excess v at $x=0$, falls down to $1/\sqrt{2}$ will be given by

$$t_0 = \frac{1}{4kp} = 0{\cdot}25 \times 10^{10} \text{ sec.} \fallingdotseq 79 \text{ years},$$

which is of an order of 100 years. If b be increased to 1000 m. t_0 will be accordingly increased to

$$t_0 = 7900 \text{ years.}$$

On the other hand, the heat must be estimated which is carried away by the spring water from the subterranean source to the earth's surface. Let V be the volume output of the spring in cm^3. per sec., then the heat carried away is $cV\theta'$ cal./sec. where θ' is the temperature rise due to the heat source and c is the specific heat of the water, $\fallingdotseq 1$. The water, either juvenile or meteorological, will have acquired the temperature proper to the undisturbed region before entering the zone of disturbance and then be heated up to the excessive temperature of the hot zone on leaving that zone.

Assuming, for example, $V=10^4$ or 10 litre/sec. and $\theta=80$°C., the heat loss is 8×10^5 cal./sec. For 1000 years, this will amount to a total loss of $2{\cdot}52 \times 11^{16}$ cal.

The excess heat content of a rock with the specific heat of 1/4, heated 80° above the normal temperature, for a cube with its side of L km., is $2L^3 \times 10^5$ cal. Thence, if L be a little more than 2, the amount of the heat content will suffice to answer for the above calculated amount of the heat loss for 1000 years.

If the zone of deformation, as the heat source, has a thickness of $h=100$ m., while its areal extent is 10×10 km^2., its volume$=10$ km^2. is just of the same order of magnitude as above assumed. Thus, in short, a single spring of the assumed output will be able to exhaust the heat source of the above described extent and temperature during the lapse of time of an order of 1000 years. This is obiously a kind of lower limit of the time, as the rate of the heat loss decreases with the falling temperature.

An alternating way of estimating the heat produced by faulting is to regard the phenomenon as a simple slide along an ideal plane of contact with a definite coefficient of friction. If F be the force of friction per unit area, we may assume for the present purpose that F is of the same order of magnitude as the maximum breaking stress of rock materials. Put $F=s \times 1000$ kg/cm. If the total slip is l m., the work done per unit area in thermal unit will amount to $sl \times 2{\cdot}4 \times 10^3$ cal/cm. Taking $l=10$ m., for example, this is $2{\cdot}4\,s \times 10^4$. If this heat be distributed uniformly within a prism of 100 m. height, with the unit area as its base, the heat content per unit volume will be 2·4 s cal., which will be equal to 40, i.e. the value estimated in the previous paragraph, if s be taken as 17. Ordinary compression tests in laboratory give s for usual hard rocks the values between 1 and 3. It is conceivable however, that the *effective* F in the present problem is much larger than the "strength," as the process of faulting is by no means that of a simple slipping, but involves the fracture of the adjoining zones.

The above estimations will show at least that the mechanical source of heat cannot be always put out of account in some problems concerning hot springs. It cannot be exactly said that any spring of importance might have derived its supply of heat through ages, solely out of the "mechanical fuel" as above discussed. It seems, however, quite probable that some springs might have undergone modifications in their thermal conditions by some processes as above considered.

There are many records of the cases in which the temperatures of springs were changed, temporarily or permanently, after destructive earthquakes. Rise as well as fall of the temperature are reported. It is, indeed, well known that the temperature of a hot spring is greatly influenced by the change in its output, so that any change in the system of subterranean water circulation caused by the seismic crustal disturbances may affect the temperature of hot springs to a coniderable amount and thus completely eclipse the effect of the mechnical heat as above considered, even if the latter may be sensible. It seems, therefore, at first sight hopeless to discriminate the latter from the former. The situation will be, however, not so bad, if we could be furnished with an ample supply of data comprising the results of systematic observations regarding the temperature, output as well as the chemical constituents of water, for all the springs situated in the region where a conspicuous tectonic disturbance has been experienced. For the present, however, it will be scarcely worth while to develop here the feasible methods of analysis. What is urgently needed is an well-organised systematic observation, instead of a mass of fragmentary and temporary gleaning.

In passing it may also be suggested that the mechanical heat of the kind here considered could have played some rôle in the genetical process of petroleum.

Heat due to Continental Drift.

Consider a *sima* layer with the depth h, and suppose that its top-layer is moved with a uniform velocity v relative to the bottom layer which is assumed as fixed. The work done per unit time per unit volume is $\eta(v/h)^2$, where η is the coefficient of viscosity, as before. If $h=H\times 100$ km. and $v=V$ m/year and $\eta=10^{13}$, the heat produced is

$$Q \doteqdot \left(\frac{V}{H}\right)^2 \times 0{\cdot}24\times 10^{-9} \text{ cal./cm}^3\text{. sec.}$$

On the other hand, the rate of heat production due to the radioactivity of plutonic rocks is, according to Holms,

$$Q' = 6{\cdot}4\times 10^{-13} \text{ cal/cm}^3\text{. sec.}$$

Since H and V above defined are probably of the order of unity, the mechanical heat Q is safely negligible in comparison with the radioactive heat Q'. This holds even if $V=100$ and $H=1$.

In the case when a very thin layer is sheared with a sensible velocity, it may occur that the temperature is abnormally raised and result in a considerable reduction of viscosity, in which case the drifting motion may be accelerated. As for an illustration take $V=10$ and $H=10^{-3}$, i.e. only 1 m. Then, $(V/H)^2=10^8$ and $Q \fallingdotseq 2{\cdot}4\times10^{-12}$, which decidedly exceeds Q'. As it is known that the plastic deformation of some material is frequently localized in a quite narrow zone of disturbance, for example "slip-plane", such an extreme case as above assumed may not be entirely excluded beyond the margin of possibility.

On the other hand, the mutual displacements of minor geotectonic units, i.e. "blocks", may involve the thermal process as above supposed. Slow gliding of two blocks along a common boundary zone may sometimes result in an accumulation of the mechanical heat and consequently to the acceleration of the motion, leading thus to a catastrophal acute disturbance. This idea, though crude enough, seems to harmonize with many observed facts concerning the relation between the chronic crustal motion and the occurrence of severe earthquakes.

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17. 地殼の變形に因る熱の發生

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地殼の非彈性的變形が局部的に集中して起る時は其爲に發生する熱の爲に局部的の高温を生じ得る。斷層の生ずる時の温度上昇を概算して見ると、場合によつては、此れが温泉の温度等に影

響し得る程度のものとなる。故に溫泉の熱源を論ずる際には、此點も考慮に加へる必要がある。

大陸移動說に於て考へらるゝやうな大陸と下層との間の相對運動の爲に、中間層に發生する熱は放射能性岩石の發する熱に比して小さいであらうと考へられる。併し陸塊相互の滑動の際に其境界層に發生する熱は必しもさうでない。此れは場合によつては其滑動を助長し急變を促がす効果があるかも知れない。

以上の如き熱源が從來余り注意されなかつたやうであるから、玆には唯極めて概略的な見積りをして、此方面の研究に注意を喚起したいと思つた迄である。