THE SOURCE OF THE HEAT AND THE SOURCE OF THE WATER IN THE HOT SPRINGS OF THE LASSEN NATIONAL PARK

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This paper, which forms a part of a treatise of more general scope on the hot springs of the Lassen National Park, California, is a discussion of the salient facts bearing on two questions: the source of the heat and the source of the water.

DESCRIPTION OF THE SPRINGS

There are at least eight groups of these springs occurring a few miles apart, the largest group covering an area approximately 550 × 1300 feet. Individual pools range in size all the way from a diameter of 50 feet or more down to insignificant dimensions. Though they have never been gauged, it is obvious to an observer that the discharge even from the largest springs is quite small and some springs have no visible outlet at all. In temperature there is considerable variation. The majority are hot and many are close to the boiling-point for the elevation, namely, 91° to 95.5° C., while others associated with them are only warm or rarely cold. In the spring of the year, fluctuations of temperature occur within short intervals of time, but more significant are the variations in the level and volume of the water. Some mud pots practically dry up as summer advances. The mineral content of the spring waters, varying from 0.5 gm. to 1.5 gm. per liter, consists chiefly of sulphates of the common rock bases and colloidal silica, though significant amounts of boric acid occur in a few springs. Most of the waters are practically neutral or slightly acid; a very few are slightly alkaline. None of them is depositing calcareous or siliceous sinter, but all contain more or less sediment consisting of kaolin, opal, very small amounts of pyrite, and sometimes alunite. Pyrite often accumulates in larger quantities in the little streams which form the outlets of the springs.

The Lassen springs are closely comparable in type with those in the Norris Basin of the Yellowstone Park. There are bubbling springs, spouting springs, mud pots, and mud volcanoes, but no geysers.[1]

SOURCE OF THE HEAT IS VOLCANIC

Although the volume of hot water discharged from these springs is small, the heat supply compared to the supply of the water must be large, for many springs are spouting jets of hot water sometimes of considerable size to heights of 1 to 3 feet, and a few send up jets at times to heights of 5 or 10 feet. Some fumaroles pour out considerable volumes of steam. One roaring fumarole at "Bumpass Hell" showed in 1916 a maximum temperature of 117.5° C.

A satisfactory source for this heat is not far to seek; important facts command the attention at once. Lava flows are conspicuous in the neighborhood of the springs and the kaolinized earth of the basins is mingled with débris from these lavas. All the groups are closely associated with a system of faults, and their alignment suggests that they follow two intersecting fissures (J. S. Diller). In several of the basins the springs are ranged in lines suggesting local fissures. Finally, the recent eruption of Lassen Peak in the near vicinity proves that volcanic energy there is not extinct.

In entire accord with these facts is the almost universal occurrence in the springs of volcanic gases. They consist chiefly of

[1] With the possible exception of Morgan's Springs, which have not been visited by the authors.

carbon dioxide with lesser amounts of hydrogen sulphide, hydrogen, nitrogen, and argon. The composition of the gases throughout the region, so far as examined, is singularly constant, indicative of a common source. That this source is a hot underlying magma or batholith will hardly be questioned by a student of the subject, for all igneous rocks, which at an earlier period of their history were, of course, magmas themselves, give off similar gases when heated.

The evidence appears all very clear and consistent; still there are some secondary sources of heat which should be discussed.

RADIOACTIVITY AS A SOURCE OF HEAT

While the radioactivity of the gases and waters of the Lassen springs has not been investigated, tests of this kind have been made in Iceland by Thorkelsson and in the Yellowstone Park by Schlundt and Moore, with decisive results. The amount of the emanation in both these famous hot-spring localities is considerable, but no connection was found between the amount of it and the temperature of the waters. In fact, the cold waters of the Yellowstone were slightly more radioactive on the average than the hot waters. In both localities the investigators were satisfied that radioactivity had nothing to do with the source of the heat. It is also noteworthy that mineral deposits which are most radioactive are not found associated with local high temperatures, and we conclude that further developments of importance along this line are unlikely.

HEAT DEVELOPED FROM CHEMICAL PROCESSES

Some are inclined to attribute to oxidation or other chemical processes which are supposed to be in progress near the surface of the ground a part or all of the heat supply of hot springs. In the Lassen springs there is abundant evidence of rock decomposition by sulphuric acid. This has been studied in some detail. The lavas everywhere in the hot-spring areas are in process of decomposition into kaolin, silica, the sulphates of the common rock bases, and other products in insignificant amounts. In a general way the following expression may serve to represent this process:

$$a \text{ silicates} + b \text{ sulphuric acid} = c \text{ sulphates} + d \text{ kaolin} + e \text{ silica.}$$

This expression is not a true equation for the reason that a small amount of water is absorbed from outside the system, in the formation of the kaolin, but the assumption that it is an equation is sufficiently near the truth for the purposes of this calculation. The method of calculation simply takes account of the soluble products found in a given volume of hot-spring water, from which can be estimated approximately the quantities of the other products involved in the chemical process considered. The resulting equation is then treated as a thermal equation. Although it is not possible to determine all the chemical coefficients accurately, and the thermal data are not entirely complete, it is quite possible to estimate the order of magnitude of the aggregate heat effect satisfactorily.

We select as an example the most favorable case, that of a boiling spring of the highest concentration. The soluble matter in a liter of it is easily determined by analysis; it consists of 0.4 gm. of sulphates equivalent to 0.15 gm. of rock bases (Na_2O, K_2O, FeO, etc.), some free acid which had not had time to act on the rock, and a little ammonium sulphate which is assumed to have been derived from ammonia in the magmatic gases. Included in the 0.15 gm. of rock bases are a few centigrams of alumina which is usually very low in these waters. For the sake of simplicity we shall assume that all the alumina in the original rock is transformed into kaolin, though the heat of formation of the aluminum sulphate is not disregarded.

As to the composition of the rock from which these sulphates were derived, many of the dacite andesites, the lavas in which all the hot springs occur, have been analyzed. The silica and alumina in them average about 60 per cent and 17 per cent respectively. Now, bearing in mind that kaolin contains about 40 per cent alumina and 46.5 per cent silica, we have approximately:

$$0.7 \text{ gm. silicates} + 0.3 \text{ gm. sulphuric acid} = 0.4 \text{ gm. sulphates} + 0.3 \text{ gm kaolin} + 0.28 \text{ gm. silica.}$$

The total heat effect we have to consider is the sum derived from two processes, h_2, the heat produced in the decomposition of the rock represented above, and h_1, the heat produced in the formation of the acid which decomposes the rock. The formation of the sulphuric acid involves some speculation. The evidence will not be presented here, but in our opinion it is most probably formed by the oxidation of a part of the hydrogen sulphide brought up with the magmatic gases. It is possibly formed by the oxidation of sulphur, but the order of magnitude of the heat effect is the same in both cases. The total quantity of the sulphuric acid from which the products in the spring water are derived is 0.695 gm. per liter, of which about half in this case remains undecomposed:

$$h_1=0.695\times 1.38=0.96\text{ kg cal. or }0.695\times 1.45=1.0\text{ kg. cal.}$$

where the factors 1.38 and 1.45 are simply the heats of formation in kilogram calories of 1 gm. of acid. We will call h_1 therefore 1.0 kg. cal.

In calculating h_2 we find some of the thermal data wanting, but we choose values which are within the limits of probability. Thus the heat of formation of a few synthetic silicates has been determined. These range from 2 to 3 kg. cal. per gm. Judging by heats of formation in general, it is quite unlikely that the values for rock silicates vary much from these limits, and the same is true of kaolin. The other data are known. From these we have:

$$\begin{array}{lllll} & 0.7\text{ gm. silicates} & +0.3\text{ gm. sulphuric acid} & =0.4\text{ gm. sulphates} & \\ h_2=(& -0.7\times 2.0 & -0.3\times 2.15^{*} & +0.95^{\dagger} & \\ & +0.3\text{ gm. kaolin} & +0.28\text{ gm. silica} & & \\ & +0.3\times 3 & +0.28\times 3)\text{ kg. cal.} & =0.6\text{ kg. cal.} & \end{array}$$

$$h_2=0.6\text{ kg. cal.}$$

$$h_1+h_2=1.6\text{ kg. cal.}$$

The temperature of the hot spring, the products of which are under discussion, was about 91° C. If the temperature of the ground water is taken as 10° C. it is obvious that the aggregate heat effect from the processes considered would be $\frac{1.6}{81}$ or about 2 per cent of the heat required to raise the temperature of the ground water to boiling. We have selected the most favorable case. In most

*The equation, of course, involves the heat of formation of sulphuric acid *from the elements.* This is somewhat greater than the heat effect of the oxidation of the sulphur gases.

†This figure includes a small heat effect from the neutralizatioa of ammonia—really a third effect.

springs the mineral content is much smaller and the corresponding heat effect is much less. If it is contended that there may be other chemical processes which have been left out of the discussion, we can only say there are none of which we have evidence which could contribute any important quantity of heat. Chemical oxidation, in all probability, is therefore a minor factor in the heat supply.

THE SOURCE OF THE WATER

The Lassen springs occur in small natural drainage basins in a country where, judging by records of the United States Weather Bureau for neighboring stations, the mean annual precipation must be above 40 inches. In May the snow lies deep on the mountain slopes, the valleys are watered by perennial streams, and cold pools and cold springs occur, sometimes associated with the hot ones. In all the areas there are warm pools much cooler than the boiling springs which are best accounted for by the presence of surface water. At the "Geyser," the "Boiling Lake," the "Devil's Kitchen," and "Bumpass Hell" the indubitable effects of cold streams can at times be traced through temperature variations from day to day as the spring floods diminish, and while this fact does not prove that meteoric water finds its way into the springs beneath the ground, there is obviously a considerable supply very close at hand. Quite impressive is the drop in water level in many springs and the general decline in the outflow of water from the different areas as summer advances, while boiling in the waters becomes more active or spouting increases in violence.

However, a decline in the volume of surface water may go so far as to result in *decreased* activity. Thus a number of mud pots at the "Boiling Lake" and "Devil's Kitchen," in which the water supply is always small, become practically extinct as the summer advances, a phenomenon which we compare to the drying up of an ordinary spring. Altogether the evidence for the surface origin of water in the Lassen springs is so convincing to an observer that if the hypothesis of juvenile or magmatic water had never been proposed the entire adequacy of the simpler theory to account for *all* the water would probably not have been questioned.

THE PRESENCE OF MAGMATIC WATER

Nevertheless, there are reasons for concluding that a *portion* of the water in these springs is magmatic—reasons so cogent that the conclusion appears almost inescapable. We have already found in the presence of the volcanic gases in the springs evidence of a hot magma or batholith from which the heat and the gases arise. We have concluded that a hot magma must of necessity give off volcanic gases as well as heat, because all igneous rocks, which once were magmas themselves, give off similar gases when heated. *Furthermore, heated igneous rocks almost invariably give off more steam than all other gases put together.*

Hot magmas in all probability always give off magmatic water and any hot spring which gives off volcanic gases should also contain some magmatic water. A possible step in the direction of estimating the amount of this magmatic water would be to determine the ratio of the gases to the total water in the springs and then to compare this ratio with that of the gas to the steam in fumaroles, and the ratio of gas to water in rocks. Precise determination by this means is not possible but an intimation of the proportion of magmatic water might be obtained in this way.

CONCEPTION OF THE HOT SPRING AND ITS RELATION TO THE MAGMA

As regards their view of hot springs, geologists divide into two schools. One school has held the perfectly definite notion that hot springs are produced by meteoric water circulating under the influence of gravity through hot ground. Many of this school would probably admit that some of the volatile products along with the heat were derived from a deep-seated source. The other school, approaching the subject from a study of the mineral veins and their relation to the igneous rocks, has held that the water or some of it was juvenile, though their ideas of how this water is conveyed to the surface do not appear to have been clearly worked out.[1]

[1] Gas pressure is doubtless the force which raises petroleum to the surface and it is believed to be the force or one of the forces which raises lava in craters, but the amount of gas in these springs is regarded as entirely too small to lift spring water from great depths.

Some new light on the subject we believe is to be gained by considering hot springs as one of the phases of volcanism and closely related to the fumaroles. Hot springs and fumaroles often if not generally occur together. There are fumaroles in some of the hot-spring areas under discussion, notably at "Bumpass Hell" and the "Devil's Kitchen." Whether the one or the other occurs is no doubt a question of the relation of heat supply to water supply. Near a volcanic vent or during a volcanic outbreak when the temperature is most intense, fumaroles naturally predominate, sometimes to the entire exclusion of springs. As the temperature falls, springs appear, and the two may occur together because of local differences in the heat supply or water supply. The magmatic water of a fumarole, of course, finds its way to the surface as steam. This is in entire conformity with the behavior of an igneous rock when heated.[1]

As the temperature falls, the process continues. Not until it reaches the critical temperature—strongly modified as it is by the soluble matter in the magma—would it be possible for the water to condense, and not then unless the pressure were sufficiently great. The experimental studies of G. W. Morey indicate, however, that the vapor pressure of water in the magma would be so reduced by the soluble matter that a pressure sufficient to condense the water would serve only to drive the water vapor into the magma. In other words, if water is to leave the magma at all it must do so as steam. If one is inclined to argue that some important factor has been omitted from the discussion, invalidating our conclusion, he finds himself confronted by the necessity of explaining how liquid water is raised to the surface. A force adequate to do this has so far not been suggested.

Another line of reasoning has previously led us to the same conclusion. Fumaroles commonly contain some acid gases—H_2S, SO_2, HCl, HF, as well as CO_2—while hot springs may be either acid

[1] If more direct evidence of magmatic water in fumaroles is desired, we may instance the well-known Fumarola o Vuccaloru at the foot of the Summit Cone of Aetna which gives off enormous volumes of steam even after nine months of rainless weather (observation of 1914). Its location (less than 1,000 feet below the summit) and the structure of the mountain also lead to the view that its water cannot be meteoric.

or alkaline. The presence of acid gases is easy to explain in fumaroles as the result of hydrolysis of the various sulphide and halide molecules in the complex magma into volatile products and to some extent also by other considerations; but if *liquid* water arises directly from the magma it is impossible to understand how the water could ever be anything but alkaline, for the hydrolysis of the alkali silicates bringing soluble hydroxides into the liquid phase of the system would preponderate over acid-forming reactions on account of the much greater quantities of alkalies than acid elements like sulphur and the halogens in every igneous rock.

On the other hand, if we assume that the acid gases come up with steam which is condensed by ground water, and that the sulphur gases are subsequently oxidized to sulphuric acid, the nature of the water as it emerges from the ground will depend on the conditions. If the original supply of acid is not great, if the physical and chemical nature of the rock are favorable to rapid decomposition by the acid, and if the time of contact between the two is long enough, the acid will disappear and the hydrolysis of the silicates will produce an alkaline water. Otherwise the supply of acid will be only partially used up and the water will remain acid.

It has been suggested that an alkaline water containing soluble sulphides might be transformed by oxidation into an acid water. The answer to this is that the direct oxidation product in such a case should normally be *thiosulphate*, but, whatever the conditions of oxidation might be, it is clear that for the formation of an *acid* water in this way a preponderance of sulphur over dissolved alkali carbonate must be present, while our knowledge of the composition of rocks indicates that a magma which had such a preponderance of sulphur or other strong acid elements over the elements which form soluble hydroxides and carbonates probably never existed. We are led therefore to the conception that magmatic water, in so far as it is present in hot springs, rises from the magma along with the other gases as steam, is condensed somewhere near the surface of the ground[1] by meteoric water with which it becomes mingled, and that the mineral burden which the springs contain, except for the volatile constituents, comes from a depth no greater than the ground water penetrates.

[1] That is to say, *near* as compared to the depth of the magma or batholith.

THE MEANS BY WHICH HEAT IS CONVEYED TO THE SURFACE

If we accept the view that the Lassen hot springs contain magmatic water and that this water rises from the magma as steam, it is clear that the condensation of this steam would supply a relatively large amount of heat. On the assumption that all the heat is supplied in this way and that none of it is lost to the surroundings, 1 kg. of steam at an initial temperature of 100° C. would raise about 6.5 kg. of ground water from an initial temperature of say 15° to 95° C. (the boiling-point, as previously stated, varies here with altitude from about 91° to 95.5° C.), and the mixture would contain about 13 per cent of magmatic water. Furthermore, since the steam must have an initial temperature higher than the boiling-point of the spring, for each additional 100° in the initial temperature the heat supply would be increased about 10 per cent, but the quantity of magmatic water required for the heating would thereby be lowered less than 1 per cent.

Assuming still that all the heat of the springs is derived from the condensation of magmatic steam, it is obvious that the foregoing figures for the percentage of magmatic water would have to be raised in consequence of the loss of heat to the ground through which the waters percolate. After a time an equilibrium would be established in which this loss would be represented by the heat loss from the surface of the ground outside the springs. At present this quantity is impossible to estimate. Temperatures at the surface itself in the hot-spring areas here under discussion seem to be near the normal except close to the borders of the pools. A few feet below the surface of the ground it is sometimes quite hot at long distances from the springs. In such cases, steam always seems to be present. Though we are inclined to the conclusion that the heat lost in this way is less than that carried off by the hot water, the very large area of the surface through which some heat escapes as compared to the area of the springs themselves is a factor which may raise the heat loss in question to an unsuspected magnitude. A further amount of heat is lost in evaporation.

Whatever the magnitude of these corrections may be, it would seem a safe conclusion from this line of reasoning alone that the surface water should be in excess over the magmatic water, especially where the water is barely boiling, or is below boiling temperature.

But there are facts which are difficult to explain by the assumption that volcanic heat is transmitted to the surface entirely by magmatic steam. For example, there is strong evidence that the fumaroles of the Katmai region, Alaska, carry with the magmatic gases much steam originating from surface water. Gases from very hot fumaroles carry sometimes as much steam as those several hundred degrees lower in temperature. To assume that the heat is supplied entirely by the magmatic steam would lead to an initial temperature of the gases and of the magma absurdly high. But if the water is not all magmatic one must assume some other source of heat to vaporize the surface water.

In so far, of course, as heat is supplied to the spring waters by any other means, our estimate of the quantity of magmatic water must be reduced.

Only one other means for the transfer of heat from a batholith to the surface has yet been suggested, so far as we are aware; namely, conduction through the rock. It is difficult to see how heat could be conducted through the rock fast enough to keep up the temperature of boiling springs, especially springs of great volume like those of the Yellowstone. If it is possible at all, it must be accomplished by the circulation of the water through a labyrinth of cracks and crevices which brings a given volume of water into contact with a very great surface of rock, for rock is a poor conductor of heat, and shattered rock, such as would commonly be found in the upper strata of the Earth's crust, especially poor.

Some recent experiments of Jaggar offer good evidence that at least in these upper strata it is not chiefly by conduction that heat is transferred. In 1922 Jaggar sunk several drill holes in or near the crater of Kilauea. One of these was bored in the bottom of the crater within half a mile of the Lake of Fire where a high temperature gradient was expected. At a depth of 80 feet a temperature of 62° C. was found. As a matter of fact there was no gradient at all; the temperature was equalized by a rising stream of volcanic gases. The maximum temperature found in any of the boreholes was the boiling-point of water for that altitude, namely, 96° C.

The gases here are mostly steam, 96–97 per cent in the samples analyzed, which for reasons previously stated is doubtless partly magmatic. But much of it is certainly surface water, for the rainfall there is very high and the lava remarkably porous.

Jaggar's experiments tend to confirm our ideas of heat convection by steam, and they suggest further that surface water as well as magmatic water may have a part in the transfer. Circulating ground water receives heat from magmatic steam which rises through crevices cutting the path of the ground water. Very narrow cracks offer a ready passage to the steam, but are less accessible to liquid water. We may suppose, however, that some surface water finds its way through and into a zone where it is not stable but where the temperature may or may not be much above boiling, according to varying conditions in different places. For every point in the path of the circulating ground water, there is of course a depth below which gravity cannot bring it again to the surface. If the water falls below this depth it will continue to fall until it is vaporized, when it will again rise carrying its latent heat toward the surface. In this way another portion of heat may be transferred from the rock to the surface water. This process seems the more likely to happen because it is difficult to believe that fractured rock which permits the passage of steam would not also give access to *some* liquid water, though in particular cases it is possible that the pressure of escaping steam might practically prevent it. One limitation to the transfer of heat by this means is obvious. Since the heat in question is withdrawn from the rock by a change of state in the water, the process cannot be operative below the depth which liquid water can reach. From the magma or batholith up to that level, it would seem that conduction must afford the only means of transferring heat excepting that by means of magmatic steam. As to the fraction of ground water which may be instrumental in the transfer of heat, it is clear from the previous discussion that only a comparatively small amount would be required as an intermediary to heat all the water to boiling even if there were no magmatic steam at all.

If any additional amount of ground water were vaporized, it would persist as uncondensed steam which, according to conditions, might seek for itself a shorter route to the surface, or accompanying the hot water to the spring orifice might, in its escape, give rise to the pulsation or spouting so commonly observed in these springs.

While this line of reasoning seems to lead independently to the conclusion that meteoric water in the Lassen springs is in excess of the magmatic, we rely rather on the more obvious evidence of the field which we have previously described. This leaves no doubt in our minds of the correctness of the conclusion.

CONCLUSION

As a result of our studies in the Lassen National Park we conclude that the hot springs are fed chiefly by surface water which drains the basins in which they lie, and that the variation in the volume of this water locally and seasonally accounts for the variations in volume and for the greater part of the variations in temperature which we find in the springs. Another portion of water, probably much smaller in amount, is derived from an underlying magma or batholith. Rising in the form of steam along with other volcanic gases through clefts in the rock, it is condensed by the ground waters and becomes mingled with them. The amount of this magmatic water varies in different springs and at different times in the same springs, not so much because of inconstancy in the emanation as because of variations in the volume of ground water.

Some of the heat, probably a large part of it, is derived from the magmatic steam. Another portion conveyed by conduction through the lower depths of the rock is carried through the upper strata by the evaporation of a fraction of the ground water in a manner which has been explained.

Whether the spring waters descend throughout their whole course, or whether they ascend in the latter part of it as do artesian waters, we do not know, but according to our view the *liquid* water comes from no greater depth than the ground water penetrates, and the mineral content of the waters, excepting the volatile portion or the portion which was *once* volatile, is all derived from the rock above that level.