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DISTRIBUTIONS OF TEMPERATURE IN AN UNDERGROUND STRUCTURE ALTERED BY HYDROTHERMAL CONDITIONS

By

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Abstract

Core samples are obtained from places from the surface to about forty meters deep during drilling works of test holes distributed on the slope of the upper side of Myōban steaming ground, where dry steam with hydrogen sulfide is ejected from a number of cracks in the ground. The method of X-rays diffraction is supplied to these samples bacause they show that the upper stratum of forty meters in thickness which rests on unaltered andesite have been almost perfectly altered by geothermal activity. The result makes it possible to distinguish two layers in the altered zone, one of which is called the Montmorillonite layer and the other of which is known as the Kaoline layer. The former layer is limited to the lower side of the cliff only and occupies relatively deeper region. Temperature in this layer is considerably high and some of the holes tapping this discharge steam. In contrast, temperature in the Kaoline layer is rather low and becomes lower higher up the slope of the cliff. This agreement between distributions of ground temperature and clay minerals supports the theory that water infiltration through a Kaoline layer changes the stratum more permeably by acid alteration under hydrothermal condition, and the temperature in the Montmorillonite layer which is occupied by steam is gradually reduced so that the layer becomes saturated by liquid water. It is assumed that such a process of reducing steaming ground may be applied to the problem as to how the area controled only by volcanic heat in ancient times has changed to the present hydrothermal system separating recharge and discharge zones as studied in the usual hot spring districts.

1. Introduction

We can often see "steaming grounds", so-called "Zigoku", locally situated around some of well-known hot spring districts in Japan. "Zigoku" means a place of remarkable geothermal activity ejecting dry or boiling steam from a number of natural fumaroles or boreholes. It is noted that most of them are found in hilly areas being highest parts of large areas where the recharge of groundwater infiltration towards a lower discharging area must be expected from the viewpoint of groundwater hydrology. Some changes or movements of such steaming grounds have been occasionally reported in spite of a relatively stable condition of thermal groundwater in the lower area. These instabilities of geothermal phenomena may originate from the variation of an interacting condition between percolating water in shallow strata and ascending dry steam through fissures of rock. Such interactions are expected to be frequently affected by the intensity of precipitation but, from the viewpoint of long time variation, changes of the ability transmissing the water percolation through geological structure must be a main cause in altering or reducing the high temperature regions occupied by underground steam.

On the other hand, history concerning the process of the formation of a hot spring district in a volcanic region may be described as follows. Geothermal activity may probably be very strong but limited locally to around the area directly controled by volcanic heat at the initial stage of hot spring action in ancient times. Then, at the later stage of the hot spring, the geothermal condition is mainly controled by groundwater stream and a rather low ground temperature is observed in the hilly area rather than in the discharging zone which is widely spread far from the center of volcano. We come to the conclusion regarding the underground thermal structure that the descending groundwater flow presses down the thermal current on the upper side of the whole region which is known as the recharge zone, and ground temperature is raised by the ascending ground water flow on the lower side situated in a valley or a coastal plain area which is called the discharge zone. During the period between the initial and later stages, infiltration of groundwater must seem to play the role of opposing and weakening the geothermal condition in the recharge zone. It is thought that a similar transitional state, i. e. from volcanic to hydrothermal activities is reconstructed on a much smaller scale in the relatively shallow structure under a local geothermal ground, the so-called "Zigoku". Hydrological researches of underground condition around such places as the "Zigoku" may therefore be considered as a valid way to gain an understanding of how the percolation of groundwater has taken place in a high temperature stratum after the initial stage of volcanic activity.

It is also well-known that surface water or shallow groundwater in or around "Zigoku" shown low pH value originating from the oxidation of hydrogen sulfide accompanied with steam from cavities in the ground. Rocks or finely divided substances are, therefore, always attacked by acid water in a shallow region where interaction between steam and water infiltration is taking place. Acid alteration brings about products consisting of opal and the process will continue until removal of the interaction zone. On the other hand, in the region where infiltration of surface water has been prevented by its high temperature or geological condition, strata have not been under acid condition but altered only by thermal conditions. It is then assumed that the distributions of variations of clay minerals in the altered zone make it possible to trace the history of the underground hydrothermal condition in the neighbourhood of the active steaming ground.

Myōban Zigoku is one of famous steaming grounds in Beppu Spä but artificial exploitation has not developed to such an extent as to disturb the original underground hydrological condition. Researches were attempted on the alteration of underground substances and its relation to present steaming activity around the "Zigoku" area, where many natural fumaroles are crowded in a relatively narrow area on the slope of the lower side of cliff.

2. Description of the steaming ground at Myōban

A hydrothermal aquifer producing hot water is extended all over the coastal square area having about six kilometers side length in Beppu City, Ōita Prefecture. Thermal activities are predominant especially along two fault lines which run on the north and south boundaries of this region and produce large amounts of hot or boiling water and steam from many fumaroles and drill-holes. The distributions are shown in Fig. 1 of the paper by Yuhara and Tomasada [1965]. Myōban hydrothermal zone is located in a hilly area situated on the north fault line. There are many cavities ejecting hot steam containing H_2S, SO_2 and CO_2 gases etc. (Koga [1965]). We found pure sulfur deposits around the outlets of those cavities. Hot acid water (whose value of pH is about 2) flowing through shallow underground strata is used for bathing at the lower region of this zone. Though this zone belongs to the area of hornblende andesite of the later volcanic period (Kasama [1953]), the whole ground surface is actually covered with browish or greyish white clay and blue clay appears on artificial sections of cliff in hilly region.

When some of the above blue clay was brought to the natural steaming ground and covered with a film of water and then covered with a straw roof, white and soft substances were observed to be crystallizing and growing. These crystals are commonly known as "Yunohana", a kind of artificial sinters, and are used in bathing.

Minami *et al.* [1966] studied the constituents of Yunohana and proved them to consist of mainly halotrichite ($FeAl_2(SO_4)_4 \cdot 22H_2O$) and alunogen ($Al_2(SO_4)_3 \cdot 16H_2O$). Koga [1965] and Minami *et al.* [1966] verified the formation process of Yunohama. They state that H_2S and SO_2 gases in the steam from cavities combine with oxygen in the surface water to form sulfuric acid. Then Fe and Al etc. elements in the clay react with sulfuric acid to form sulphates of Fe and Al etc., and these crystallize to form Yunohana. Following the separation of Fe and Al etc. from the original blue clay, the content rate of $SiO_2 \cdot nH_2O$ in the residue gradually increases and turns whitish in colour. During the above process, the Yunohana gradually changes in quality, and towards the last stage it becomes mainly alunogen in content, and simultaneously, the rate at which Yunohana forms becomes very slow. Then, towards the last stage the residue alters to opalic matter whose main element is cristobalite.

Thus considering the processes of artificial Yunohana formation and blue clay alteration, we may suppose that the above mentioned phenomena must probably happen under proper field conditions. Actually, as stated above, the white clay layer consisted of opalic matter can be found by the side of a blue clay layer on the artificial cross section in Myōban. Therefore, if we can obtain a general rule for clay and rock alterations and the information of the distributions of altered materials in a hydrothermal area, we may be able to estimate the past life of the activity of this area.

The altered character of rock or clay is generally very complicated becase of the complexity of internal and external conditions, such as the compositions of original rock, the properties of natural steam and hot water and temperature etc.. It is therefore difficult to stipulate a general rule for rock alteration under various conditions. However there is a general theory that, when natural system of steam and hot water attacking the original rock is the basic condition, it alters the rock to montmorillonite and when condition is acid it alters the rock to kaoline minerals such as halloysite or hydrated halloysite (Sudō [1954]). It is also stated that montmorillonite is able to change into kaoline minerals or opalic matter under the proper acid condition but the process may not be reversed. As halotrichite and alunogen probably produced in the course of acid alteration are soluble in water, it is thought that in field conditions they are dissolved away by precipitation or surface water and the residue is transformed to kaoline or opalic matter which is abundant in $SiO_2 \cdot nH_2O$. A knowledge of such alterations would become a valuable foundation for the investigation of the past life of a hydrothermal area assuming that we are able to obtain the distributions of underground clay minerals.

Before dawn on September 25, 1966, just after the typhoon 6624 has passed near Beppu City, a landslide occured at the hilly part of Myōban Zigoku, of width 120 m and length 80 m. In order to obtain basic data on which to base the prevention of a future disaster, thirty six test holes were drilled over an area, $6 \times 10^4 \, m^2$ by Ōita Prefectural Office for a period lasting till February 1968 and many core samples were collected. On inspection, these had obviously been altered by the effect of hydrothermal activity and become fragile. We picked

Locations of investigated holes are shown in Fig. 1 and the results X-rays diffraction are given in Table 1 with temperature observed at the bottom of each test hole. Since we cannot completely represent the quantitative relations of component minerals as only using the method of X-rays diffraction, we classified the components of minerals into four grades by judging from the heights of peaks on the diffraction records; i. e. nil, a small quantity, a large quantity and a very large quantity. The above classifications correspond to the signs of 0, +, ⧺ and ⧻ in Table 1 respectively. Minerals found relatively in general are quartz (Q), cristobalite (Cr), feldspar (F) and pyrite (Py) as rock-forming minerals and montorillonite (M) and kaoline minerals such as halloysite (H) and hydrated halloysite (H.H) as clay minerals. In addition to these, we discovered a very small quantities of hornblende and alunite in a few samples.

Table 1. Results of X-rays diffraction

No, of hole, bottom temp.	depth m	Q	Cr	F	Py	H	H.H	M	
BV. 3 105°C	1.4	0	⧺	0	+	+	+	0	
	2.3	⧺	⧻	0	+	⧺	0	0	
	4.	0	⧺	0	+	+	0	⧻	
	5.8	⧺	+	+	+	0	0	⧺	
	7.4	⧺	0	0	+	0	0	⧻	
	9.	⧺	0	+	+	0	0	⧻	
	11.	⧺	0	0	+	0	0	⧻	
	12.	⧺	0	0	+	0	0	⧻	
	13.	⧺	0	0	+	0	0	⧻	
	14.	⧻	0	0	+	⧺	0	⧺	
	21.	⧺	0	0	+	0	0	⧻	
	22.	⧻	0	0	+	+	0	⧺	
	24.	⧺	0	0	+	+	0	⧺	
BV. 8 34°C	1.2	+	⧺	⧻	+	0	0	0	
	6.	⧺	⧺	0	0	0	⧺	0	
	8.2	+	⧺	0	0	0	⧺	0	
	12.	+	+	0	0	+	0	+	
	15.	0	+	0	+	+	0	0	
	23.	0	⧺	⧺	+	0	0	0	
	30.	0	⧺	⧺	+	0	0	0	
BV. 9 24°C	4.	0	⧺	⧺	0	+	+	0	
	10.	0	⧺	0	+	0	+	0	
	16.	+	+	⧺	0	0	0	0	Hornblende +
	22.	+	⧻	+	0	0	⧺	0	
	28.	+	+	0	+	0	+	0	

up core samples of thirteen representative holes at appropriate intervals of depth, and then determined the clay composition using the X-rays diffraction process.

3. Distribution of altered matter

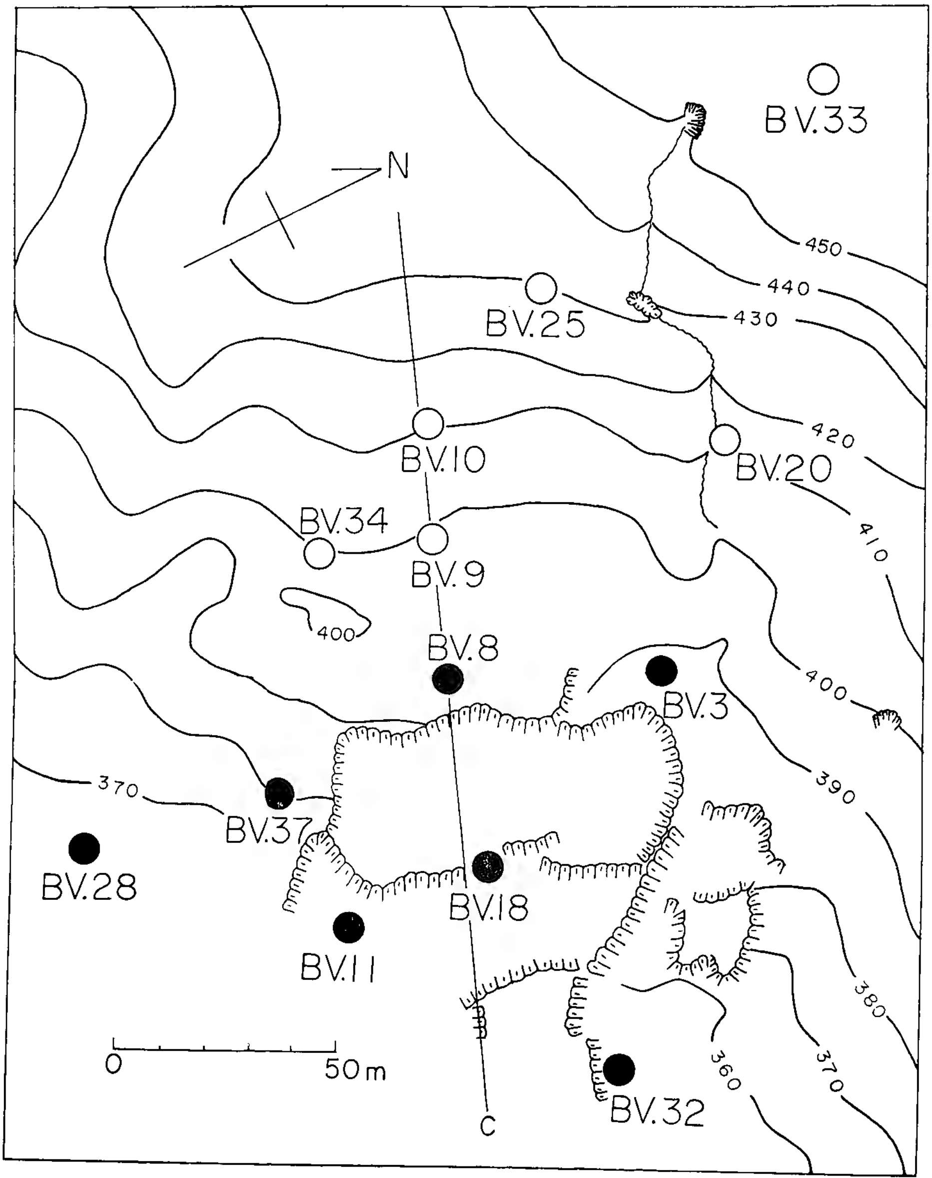

Fig. 1. Map of invegtigated area and the distribution of test holes.
● In Montmorillonite layer
○ In Kaoline layer

BV. 10	20°C	4.	0	+++	+++	+	0	+	0	
		10.	0	++	++	+	0	+	0	
		16.	0	+++	+	0	0	+	0	
		20.	+	++	+	0	+	+	0	
BV. 11	102°C	6.	+	++	0	+	++	0	0	Alunite +
		11.	+	++	0	+	+	0	++	
BV. 18	105°C	1.	+	++	+	+	0	+	0	
		3.	+	++	++	0	0	+	0	
		7.	0	+	0	0	0	++	0	
		11.	0	+	0	0	0	++	0	
		15.	0	++	++	+	+	0	++	
		17.	0	++	0	+	+	0	++	
		21.	++	0	++	+	0	0	+++	
		23.	++	0	0	+	0		+++	
		26.	++	0	0	+	0	0	+++	
		28.	+++	0	0	+	+++	0	0	
		31.	+++	0	+	++	++	0	+	
		34.	++	0	0	+	+	0	+++	
		36.	++	0	0	+	0	0	+++	
		38.5	+++	0	0	+	++	0	0	
		40.	++	0	0	+	+	0	++	
		42.	+++	0	0	+	0	0	++	
		44.	0	++	++	+	0	0	0	
BV. 20	14°C	1.	+	++	0	0	0	++	0	
		5.2	0	+	++	+	0	+	0	
		10.	+	+++	0	0	0	+	0	
		20.	+	++	0	0	0	+	0	
BV. 25	16°C	1.	++	++	+	0	+	0	+	
		5.	++	++	0	0	++	0	0	
		9.	+	++	++	+	0	0	0	
		14.	+	++	++	+	0	0	0	
		20.	+	++	+	+	0	0	0	
		25.	+	++	++	+	0	+	0	
		30.	0	+++	+	0	0	+	0	
BV. 28	103°C	1.	+	+++	0	0	0	0	0	
		5.	+	+++	0	0	0	0	0	
		10.	+	++	0	0	0	+	0	
		15.	+	+	+	+	0	0	0	
		20.	0	+	0	+	0	0	0	
BV. 32	110°C	1.	+++	0	0	0	0	0	0	Alunite +
		5.	+	++	0	+	++	0	0	Alunite +
		10.	+	++	0	+	++	0	0	Alunite +
		16.	+	++	0	+	++	0	0	Alunite +
		20.	+	++	+	+	+	0	+++	Alunite +

BV. 33	13°C	3.	+	+++	++	0	0	0	0	
		7.	++	++	+	+	+	0	0	
		11.	0	++	+++	+	0	0	0	
		18.	0	++	+	0	0	0	0	
		20.	+	+++	+	0	0	0	0	
		22.	+	++	+	+	+	0	0	
		25.	+	+	0	0	+	0	0	
		27.	+	+	0	0	0	0	0	
		29.	+	++	0	0	0	0	0	
		34.	+	+++	+	0	0	0	0	
		37.	+	++	+	0	+	0	0	
		40.	0	+	+	+	+	0	0	
BV. 34		3.	+	+++	++	+	0	+	0	
		6.	+	++	+	0	0	+	0	
		10.	+	++	++	0	0	++	0	
		15.	+	++	0	0	0	++	0	
		20.	+	++	0	0	+	0	0	
		25.	+	++	0	0	0	+	0	
BV. 37		4.2	0	++	++	0	0	0	0	Hornblende +
		12.	+	++	0	0	0	++	0	
		16.3	0	+	0	+	+	0	0	Alunite +
		22.	0	++	+	+	0	0	+++	Alunite +

Q ; Quartz, Cr ; Cristobalite, F ; Feldspar, Py ; Pyrite H ; Halloysite,
H.H ; Hydrated halloysite, M ; Montmorillonite

The main rock forming the underground strata at Myōban was found to be hornblende andesite as we stated before. Though some traces of hornblende are visible in almost all of the present core samples, only two show its existences from results of X-rays diffraction. It is therefore considered that originally andesite had been decomposed in the process of alteration. Also feldspar is hardly to be found in core samples under severe alteration. It seems to have been decomposed as hornblende.

Relations between depth and distribution of minerals are noticed in every test holes and an example in BV. 3 is expressed as follows. Samples shallower than 2.3 m depth include halloysite and hydrated halloysite as kaolin minerals and give a brownish colour, in which quantities of cristobalite are relatively large. On the other hand, almost all of samples deeper than 4 m give greyish blue and include only montmorillonite as clay mineral. Cristobalite is almost non-existant in the samples from a depth greater than 7.4 m. It is a general fact in this research area that the layer with kaoline minerals is most clearly distinguished from that with montmrillonite and the quantity of cristobalite decreases in the latter layer. It is also noted that a few samples show that halloysite reappears in deeper zone.

Based on the above mentioned classification, Fig. 2 shows the cross sectional distribution of clay minerals along line C in Fig. 1. In Fig. 2, the Kaoline layer represents the range in which main compositions are Kaoline minerals and montmorillonite does not exist at all. The Montmorillonite layer represents the whole region which contains montmorillonite irrespective of its quantity. The location, depth and bottom temperature of the test holes are also shown in the Figure. Dashes represents the piezometric level in a transient state which connects the water level measured at each hole a few days after the completion of the drilling work. We are unable to get a complete piezometric distribution because of various depths of holes (15~45 m), but an outline of hydrological condition may be made. The curved line AA′ represents the top of the rock from geological remarks and it is interesting that this line almost corresponds to the bottom of the range of kaoline minerals.

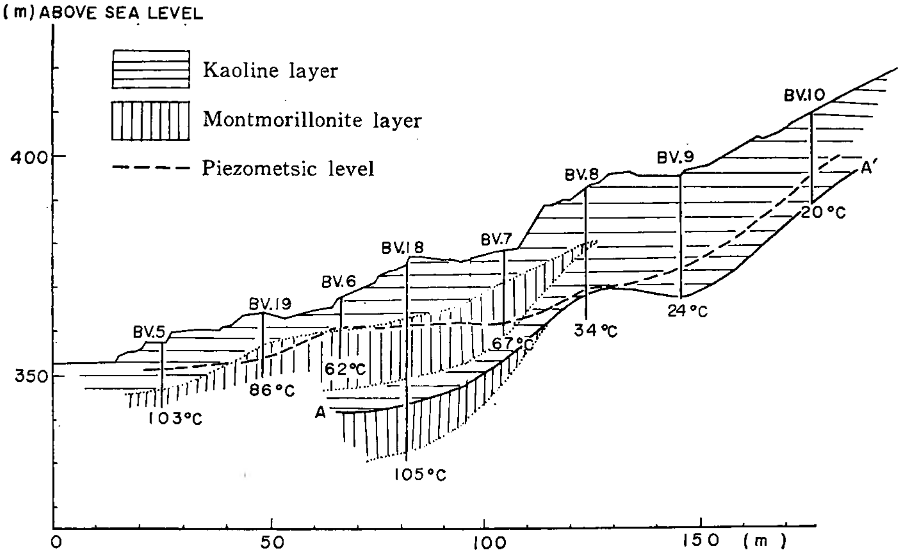

Fig. 2. A sectional distribution of clay minerals along the line C in Fig. 1.

It is characteristic that the cores in the rock below AA′ line at BV. 18 include montmorillonite, while clay minerals are not observed in this rocky region at BV. 8 located in higher part than BV. 18. Evidently from Fig. 2, the kaoline layer without montmorillonite continues to the bottom of the drillholes and the temperature is lower than 30°C in the higher region. On the other hand, we can observe a complicated stratification of the various clay layers from the surface to the bottom in the following order; Kaoline layer, Montmorillonite layer with a small quantity of kaoline minerals, Kaoline layer and Montmorillonite layer. The temperature at the bottom shows the highest value of 105°C among whole region. In the region lower than BV. 13, the Kaoline layer exists only near the ground surface and the Montmorillonite layer exists below this. The temperatures are not so high as at BV. 18 but show much higher values that at the top part of the hill. Therefore we can conclude that at present geothermal activity is still remarkable in the Montmorillonite layer.

Since BV. 8 contains a small quantity of montmorillonite in a sample at a depth of 12 m only and the temperature shows an intermediate value of 34°C, it is considered that the zone near BV. 8 shows a boundary where a Montmorillonite layer exists. This state is more clearly found in Fig. 1, where holes are classified according to whether or not they reach Montmorillonite layer.

The line representing piezometric level shows its tendency more flattened towards the lower region of the hill. It suggests a hydrological condition where groundwater infiltrates downward through the higher region of the hill and flows to the Myōban hot spring area at the foot of the hill. However water levels in some of the test holes, were observed to be more and more depressed day by day and especially, at the part of high ground temperature of BV. 18, they can no longer be observed. Such a phenomena can probably be explained by the fact that water poured into holes during drilling work gradually leaked out into the strata in hilly part or boiled away in the high temperature region. Then the piezometric level represented by a dashed line in Fig. 2 is taken as representing a transient distribution in a recharging period.

4. Hydrothermal history in the steaming ground at Myōban

Let us assume from the present condition of underground alteration that a transient process of hydrothermal activity is taking place in this region. Though such an altered condition has been probably formed under the effect of hot steam including H_2S and SO_2 gases which are observed in the present steaming ground, mineralogical differences of two layers such as Kaoline and Montmorillonite suggests that the former layer has been achieved under acid alteration but the latter has never been in an acid condition. It is ascertained that gas of high temperature still remains in the Montmorillonite layer bacause of the high temperature observed in it. Therefore active oxidation to sulfuric acid is not expected because groundwater containing sufficient oxygen has never entered such a high temperature layer. This is the reason why alteration forming Kaoline minerals has never occured in this layer. Near the boundary of this layer where infiltrating water contacts with hot steam containing. H_2S and SO_2, the same condition as that of artificial Yunohana formation is achieved, and the process of transforming montmorillonite to kaoline minerals is proceeding gradually. Such circumstances are presented by the mineral compoitions of core samples from depths of 15 to 17 m in BV. 18, in which montmorillonite co-exists with halloysite. Morever this is confirmed by the recognition of halotrichite in core samples near the boundary. Section 2 describes how halotrichite is formed as the second product in the process of acid alteration.

The history of this whole alteration zone may be explained as the advancing process of the front of which montmorillonite is transformed to kaoline minerals as visible in this boundary. This process is assumed to be as follows. In the initial stage of water infiltration to this zone, hot steam containing H_2S and SO_2 which contributed to the formation of montmorillonite mixed with water only near the surface layer where it produced surfuric acid. The Mg and Fe etc. elements in rocks were then dissolved into liquid and the residue became occupied by kaoline minerals and cristobalite. Such a kaoline layer with a more permeable character would increase the infiltration rate of water. It would cause the tendencies of a decreasing ground temperature and a pressing down of the ascending ranges of hot steam. The front of infiltration therefore advanced dounward and increased the distribution of Kaoline layer. Steaming ground, then, became limited to narrower area at the foot of the hill.

It is noted in Fig. 2 that Kaoline layer also appears in a narrow strip between two Montmorillonite layers at the lower part of the hill. This may be taken as being the trace of intruding groundwater stream, which flows along the top side of the rock after percolating through the higher region of the hill. It is expected that this narrow zone will gradually invade the high temperature zones in future.

Finally, it is concluded from distribution of ground temperature in this area that the difference of Kaoline and Montmorillonite layers corresponds to that of hydrological recharge and discharge zones respectively. Further investigations around Myōban steaming ground would be admitted to show one circumstance at the later stage in the transient state from volcanic to hydrothermal systems. It may suggest of mechanism whereby the actual distributions of hot springs are more frequently found in low ground than the volcanic uplands.

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