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REPORT No. 225

GEOLOGICAL SURVEY OF JAPAN

**HYDROTHERMAL ROCK ALTERATION OF THE
MATSUKAWA GEOTHERMAL AREA,
NORTHEAST JAPAN**

By

Kiyoshi Sumi

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Hydrothermal Rock Alteration of the Matsukawa Geothermal Area, Northeast Japan

By

Kiyoshi SUMI *

Abstract

In the Matsukawa area, where hydrothermally altered rocks are extensively distributed, three-dimensional sections of the altered aureole were obtained by several core drillings.

The rocks of the altered mass originate from the volcanic rocks of three kinds, i. e. dacite welded tuff and andesite welded tuff in Miocene age, and pyroxene andesite in Pleistocene age.

The altered aureole can be divided into six zones based upon the stability range of minerals. Four zones of them are aligned from margin to center, as saponite zone (or chlorite zone), montmorillonite zone, kaolin zone and alunite zone. Besides them, pyrophyllite zone is distinguished.

The formation of such a zonal arrangement is considered to be controlled by the increasing of pH value from center to margin. The pyrophyllite zone only is formed under higher temperature than other five zones.

The compositional rocks in each zone are tabulated below :

(Zones)	(Compositional rocks)
Saponite zone.....	Weakly altered andesite containing saponite.
Chlorite zone	Chlorite-laumontite rock, chlorite-montmorillonite-calcite rock and anhydrite-calcite-chlorite rock.
Montmorillonite zone.....	Calcite (or anhydrite)-montmorillonite-quartz rock.
Kaolin zone.....	(Anhydrite-) kaolin-quartz rock.
Alunite zone.....	Quartz alunite rock.
Pyrophyllite zone.....	Diaspore-zunyite-pyrophyllite rock, andalusite-pyrophyllite-quartz rock and anhydrite-pyrophyllite-quartz rock.

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I. Introduction

The Matsukawa geothermal area (latitude $39^{\circ}52'$, longitude $140^{\circ}55'$) lies about 25 km northeast of Morioka city, and is situated at the southern end of the Hachimantai National Park (Fig. 1). Since 1956, investigations to exploit natural steam for electric power have been promoted. In Oct. 1966, the generation of electric power of 20,000 kw was inaugurated.

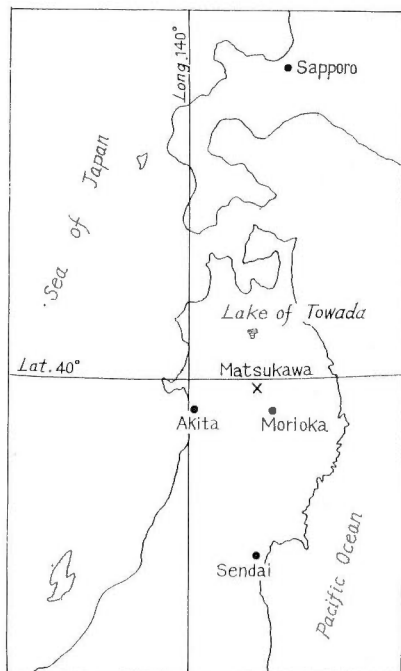


Fig. 1. Location of the Matsukawa geothermal area.

Geological studies on hydrothermally altered rock mass at active geothermal area are rare in Japan. Fortunately, in this area a number of core drillings brought us many useful informations on the studies of underground alteration, and three dimensional sections of the altered mass were obtained.

In this report, the writer focuses his attention on the zonal mapping of the altered mass underground as well as on the earth's surface. The extent of zonal mapping was limited to the part shallower than 600 m in depth because of three reasons as follows:

- 1) In the shallower part of less than 600 m, only two or three kinds of volcanic rocks are found as original rocks.
- 2) On the contrary, in the deeper part of over 600 m various sedimentary and volcanic rocks are predominant.
- 3) In the still deeper part than of over 1,000 m the rocks are suffered from regional alteration of Miocene age and converted into the so-called "Green tuff" in the Inner Zone of Northeast Japan.

For this study, three hundred specimens collected from outcrops and drilling cores are studied under the microscope. Two hundred specimens of them are examined with X-ray diffractometer. Clay minerals separated from sixty rock

samples are studied with X-ray diffractometer and electron microscope. Eighteen rock samples are analyzed chemically.

II. Geology

The geology of the Matsukawa geothermal area has been already reported in other paper (NAKAMURA and SUMI, 1961). In this paper, the outline of geological sequence is described briefly. The geological map of this area and its environs is shown in Fig. 2.

The Yamatsuda formation is the oldest. It is composed of black shale, sandstone and conglomerate. The last two yield marine molluscan fossils of late Miocene. The formation is 470 m in thickness.

The Tamagawa welded tuff covers conformably or unconformably the Yamatsuda formation. It consists of lavas, welded tuffs and pyroclastic rocks of andesite or dacite. Thin layers of mudstone and conglomerate are sometimes intercalated in them. The Tamagawa welded tuff is assumed to be late Miocene or early Pliocene in age.

Quaternary volcanic rocks overlying unconformably the Tamagawa welded tuff are widely distributed in the environs of the Matsukawa area.

Matsukawa andesite, the lowest member of the volcanic rocks, is a thick pile of pyroxene andesite lavas. It is assumed to be the ruins of a large shield volcano.

The Marumori volcano covering the Matsukawa andesite is the composite volcano of a somma and a central dome. The caldera of the somma is 3 km in diameter. The Matsukawa river divides the caldera into northern part and southern part. The main part of the Matsukawa geothermal area is situated on the bottom of the caldera, and extends along the valley of the Matsukawa river in ENE-WSW direction.

On the earth's surface of the geothermal area, the Matsukawa andesite crops out. Judging from the results of drillings, the sequence of strata of the Matsukawa area is presumed as follows:

- 1) From earth's surface to about 160 m in depth
..... Matsukawa andesite.
- 2) From about 160 m to 930~960m in depth
..... Tamagawa welded tuff.
- 3) Deeper than 960 m in depth
..... Yamatsuda formation and older strata.

Stratigraphic section of the Matsukawa geothermal area is shown in Fig. 3.

The original rocks of altered zones described in this paper are members, Tw 5 and Tw 6 of the Tamagawa welded tuff, as well as Matsukawa andesite.

The member Tw 5 is dacite welded tuff. It is white in color and massive. Large phenocrysts of quartz (1~5 mm in size) are characteristically predominant.

The member Tw 6 is andesite welded tuff and lava. The welded tuff is pale green macroscopically. Deep greenish parts, which are altered products after the fragments of glass, are sporadically found. Some greenish parts are welded. The lava is hard, dark greenish and shows porphyritic texture with plagioclase and a small amount of quartz. The aspects of the andesite resemble to the Matsukawa andesite but occasionally glassier than the andesite.

The Matsukawa andesite is dark green-colored, compact andesite. It does not associate with pyroclastic rocks.

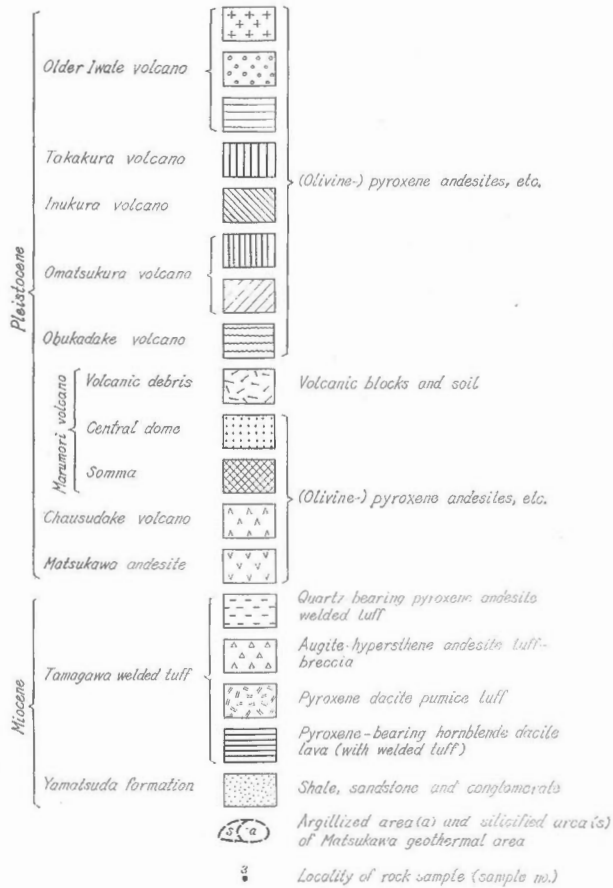
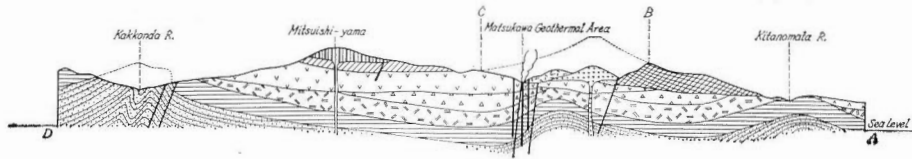


Fig. 2. Geological map of the Matsukawa

III. Zonal Arrangement of Altered Rocks

III. 1 General remarks

In the Matsukawa geothermal area, merely two or three hot springs have been discovered. But, hydrothermal altered rocks formed by hot spring action are widely distributed. This fact proves that fumarolic action was strongly active in the past.

The altered area extends, as a whole, over 7 km in ENE-WSW direction, and about 1~1.5 km in width.

In 1961, NAKAMURA and SUMI reported for the first time the zonal mapping

of the altered rocks in this area, based upon the megascopic features of rocks on the earth's surface.

They considered that such features are genetically related to the grade of



geothermal area and its environs.

concentration of silicon component, or leaching of some other elements.

The altered area was divided into four zones, i. e., weakly altered zone, clayey zone, compact siliceous zone and porous siliceous zone, from outside to inside (Fig. 4).

On the outside of the weakly altered zone, the volcanic glass and primary minerals of andesites remain fresh. The secondary minerals are scarcely found.

The rocks of weakly altered zone are characterized by dark greenish color. Plagioclase and augite are slightly altered, and hypersthene is mostly altered. This zone is transitional to the fresh zone with intervals of several meters to several ten meters.

The rocks of clayey zone are soft, white or bluish gray due to the impreg-

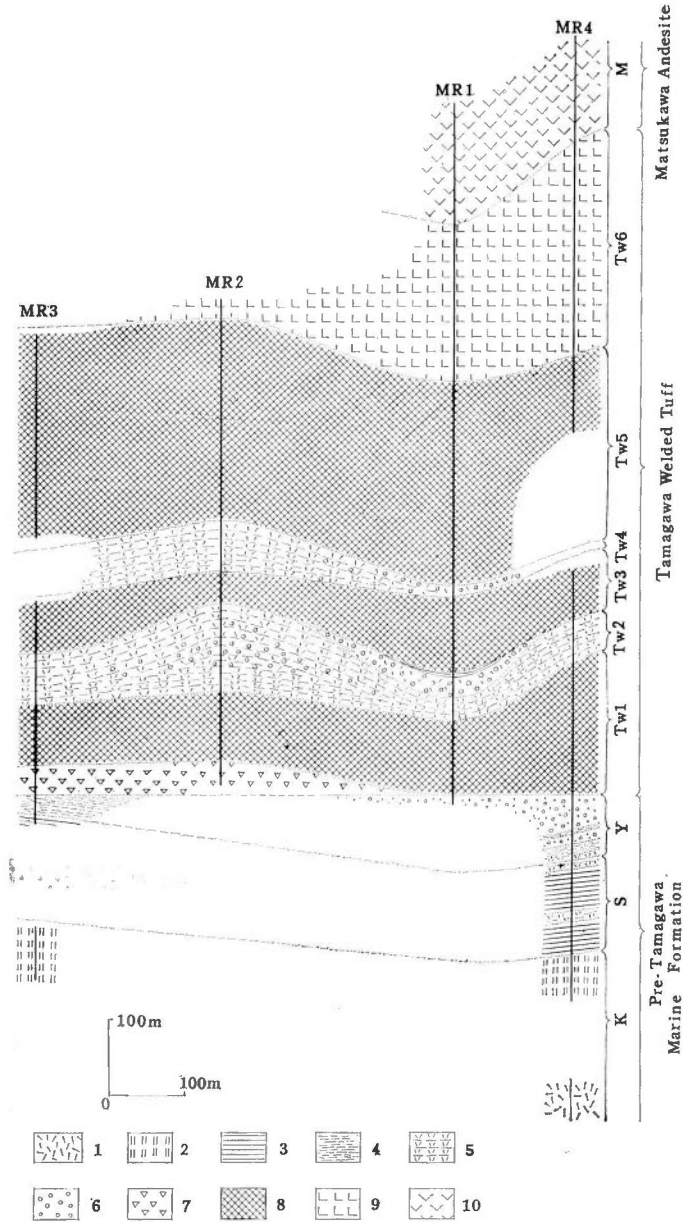


Fig. 3. Stratigraphic section of the Matsukawa geothermal area.
 1 : Mafic tuff breccia, 2 : Rhyolite volcanic breccia, 3 : Siliceous shale, 4 : Black shale, 5 : Sedimentary tuff, 6 : Conglomerate, 7 : Accidental tuff breccia, 8 : Dacite welded tuff, 9 : Andesite welded tuff and lava, 10 : Andesite lava, Y : Yamatsuda formation.

nation of fine-grained pyrite.

The compact siliceous zone is gray to white in color. Transition from this zone to the clayey zone is generally abrupt.

The porous siliceous zone occurs in the higher mountainous area west of the Matsukawa area. Beneath this zone, the compact siliceous zone is usually developed. This porous siliceous zone is characterized by silicified porous rocks which are gray to white and very frequently brown due to limonite stain. It is possible that the porous siliceous rocks were formed by leaching of acid solution near the earth's surface.

III. 2 Scheme of zonal mapping

The hydrothermally altered rocks in this area can be divided into five

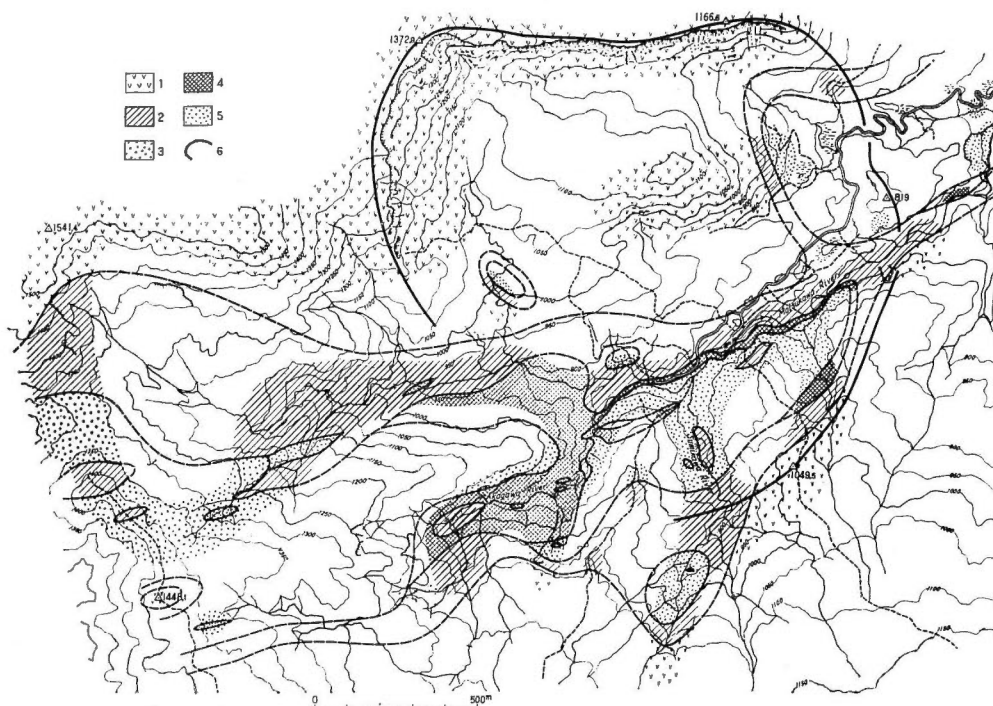


Fig. 4. Zonal mapping of altered rocks based upon the megascopic features (After NAKAMURA and SUMI, 1961).
 1 : Fresh zone, 2 : Weakly altered zone, 3 : Porous siliceous zone,
 4 : Compact siliceous zone, 5 : Clayey zone, 6 : Caldera.

zones based upon the stability range of minerals recrystallized. They are arranged, from margin to center, as saponite zone, chlorite zone, montmorillonite zone, kaolin zone and alunite zone. Besides them, pyrophyllite zone is distinguished. The boundaries of each zone are in accord with lines from which a critical mineral begins to disappear or appear. The transition of mineral associations between zones are briefly given as follows:

- 1) Saponite zone → chlorite zone
disappearance of saponite.
- 2) Chlorite zone → montmorillonite zone
disappearance of chlorite.
- 3) Montmorillonite zone → kaolin zone
 disappearance of montmorillonite.
- 4) Kaolin zone → alunite zone
disappearance of kaolin.
- 5) Pyrophyllite zonepresence of pyrophyllite (relic probably).

The general aspects of the zonal mapping are indicated in Table 1 (a and b) in which the phenomena of the shallower part (a) and deeper part (b) are separately shown.

Besides the minerals mentioned above, the altered rocks comprise also other minerals—laumontite, hydromica, mixed-layer minerals, quartz, anhydrite, calcite,

Table 1 a. Summary of mineral association in the altered zones of shallow part.

Zones	Saponite zone	Montmorillonite zone	Kaolin zone	Alunite zone	Pyrophyllite zone
Minerals					
<i>Saponite</i>					
<i>Sericite</i>					
<i>Montmorillonite</i>					
<i>Calcite</i>					
<i>Kaolin</i>					
<i>Alunite</i>					
<i>Pyrophyllite</i>					
<i>Andalusite</i>					
<i>Diaspore</i>					
<i>Zunyite</i>					
<i>α-Cristobalite</i>					
<i>Quartz</i>					
<i>Pyrite</i>					

Table 1 b. Summary of mineral association in the altered zones of deep part.

Zones Minerals	Chlorite zone	Montmorillo- nite zone	Kaolin zone	Alunite zone
Chlorite	—————			
Laumontite	-----			
Hydromica		-----		
Mixed-layer of ser.-mont.	-----	—————		
Mixed-layer of mont.-chl.	-----			
Calcite	-----	—————		
Montmorillonite	-----	—————		
Anhydrite	-----	—————	—————	
Gypsum	-----	—————	-----	
Kaolin			—————	
Alunite				—————
Quartz	—————	—————	—————	—————
Pyrite	—————	—————	—————	—————

rutile, pyrite, diaspore, andalusite or zunyite. The presence of these minerals is not respectively limited in the restricted zones. The quantity of these minerals is distinctively variable, and is probably influenced by the amounts of fluid materials circulated within the alteration mass, as a function of depth. Accordingly, the assemblages of alteration minerals are classified by the depth at which the minerals are crystallized. The mineral assemblages are shown in Table 2 (a and b), sample locality, in Fig. 5 (a and b), and approximate percentages of clay minerals in the deeper part, in Fig. 6.

The zonal mapping of the altered rocks on the earth's surface is shown in Fig. 7 and their underground distribution, in Fig. 8. These figures indicate a clear zonal arrangement, from margin to center:—Saponite zone (or chlorite zone)—→montmorillonite zone—→kaolin zone—→alunite zone. Three boundaries among them never intersect with each other, and, therefore, the cause of forming such a zonal arrangement is not multiple but simple. The distribution of the pyrophyllite zone only, however, overlaps on the other three zones—the montmorillonite zone, kaolin zone and alunite zone. Moreover, the boundary between the saponite zone and chlorite zone is oblique to the general trend of the zonal arrangement. It must be considered that these two exceptional obliquities may be caused by some other processes.

Conclusively, the alteration zones mentioned above can be classified upon the characteristic features of arrangement:

- A. A series of montmorillonite zone—kaolin zone—alunite zone.
- B. Saponite zone and chlorite zone.

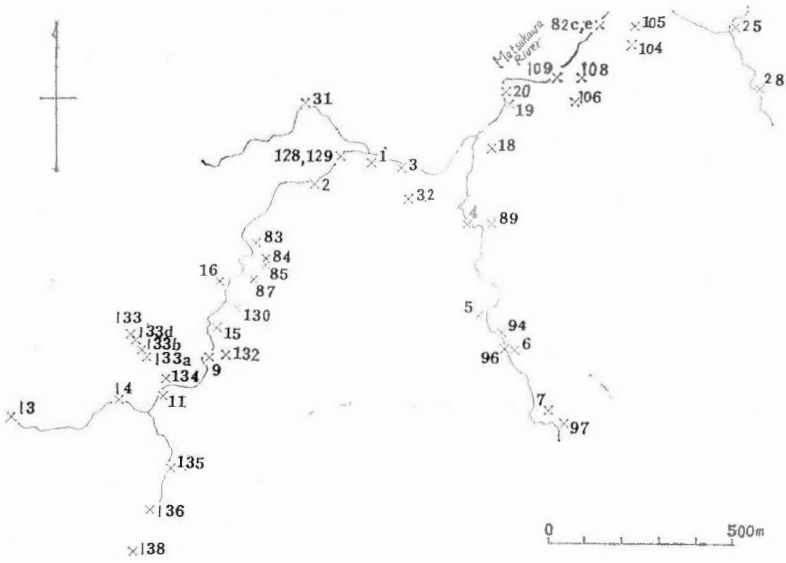


Fig. 5 a. Localities of samples. Sample numbers of this figure are omitted their prefixes, "Cl" (nos. 1~31) or "HF" (nos. 82~138).

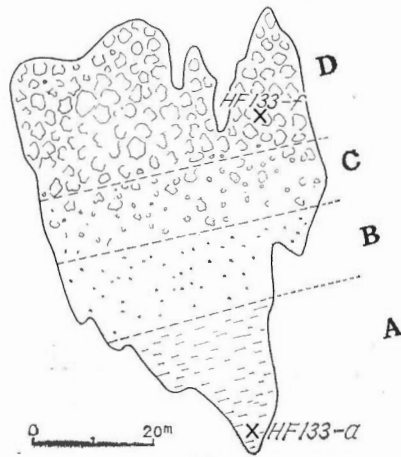


Fig. 5 b. Localities of samples (HF 133 a and f).

This figure shows a large vertical outcrop where two samples are collected, west of the Matsukawa area.

- A: Compact siliceous rock, B: Clay-bearing siliceous rock,
- C: Sulphur-bearing siliceous rock, D: Limonite-bearing siliceous rock.

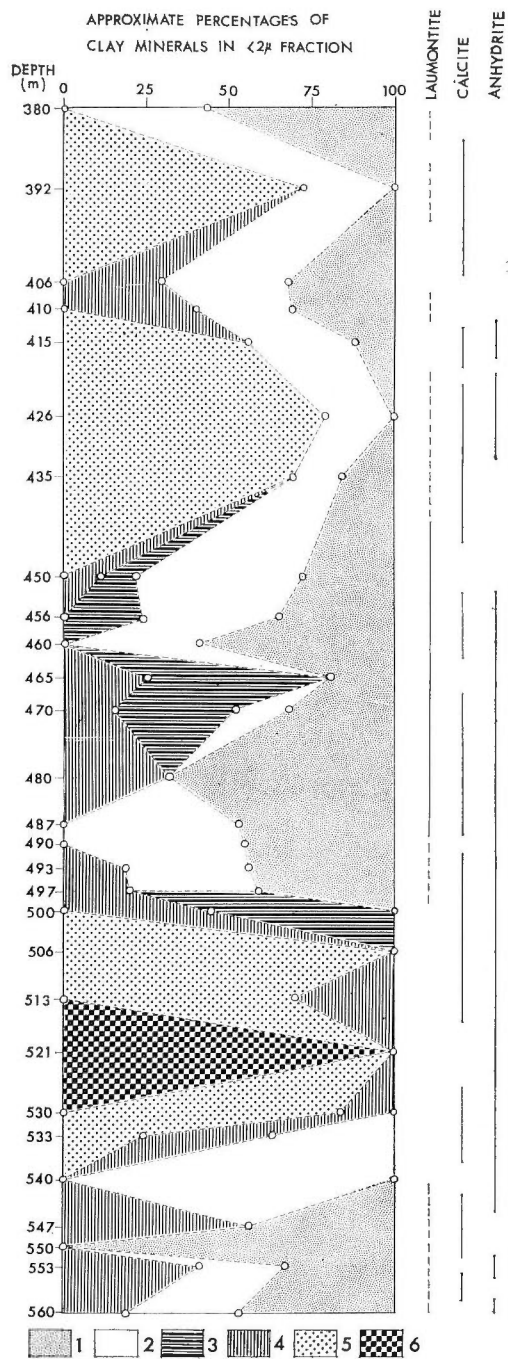


Fig. 6. Semi-quantitative modal percentage of clay minerals from cores of the drilling BR 2. 1: Chlorite, 2: Hydromica, 3: Mixed-layer mineral of montmorillonite-chlorite, 4: Mixed-layer mineral of sericite-montmorillonite, 5: Montmorillonite, 6: Kaolin. Open circle: Points where the percentages are measured.

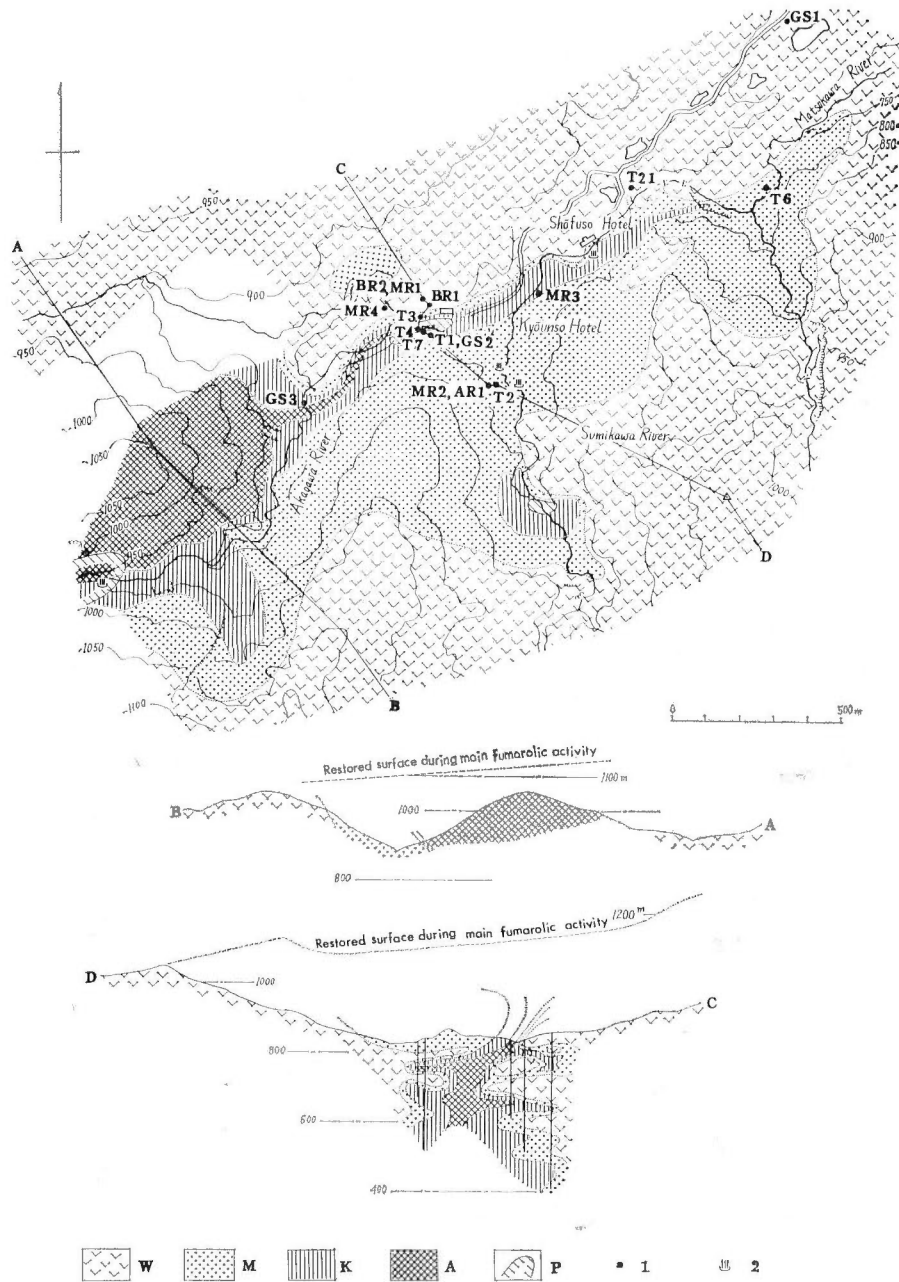


Fig. 7. Distribution and schematic sections of alteration zones in the Matsukawa geothermal area.

W: Saponite zone, M: Montmorillonite zone, K: Kaolin zone, A: Alunite zone, P: Pyrophyllite zone, 1: Locations of drillings, 2: Hot springs,

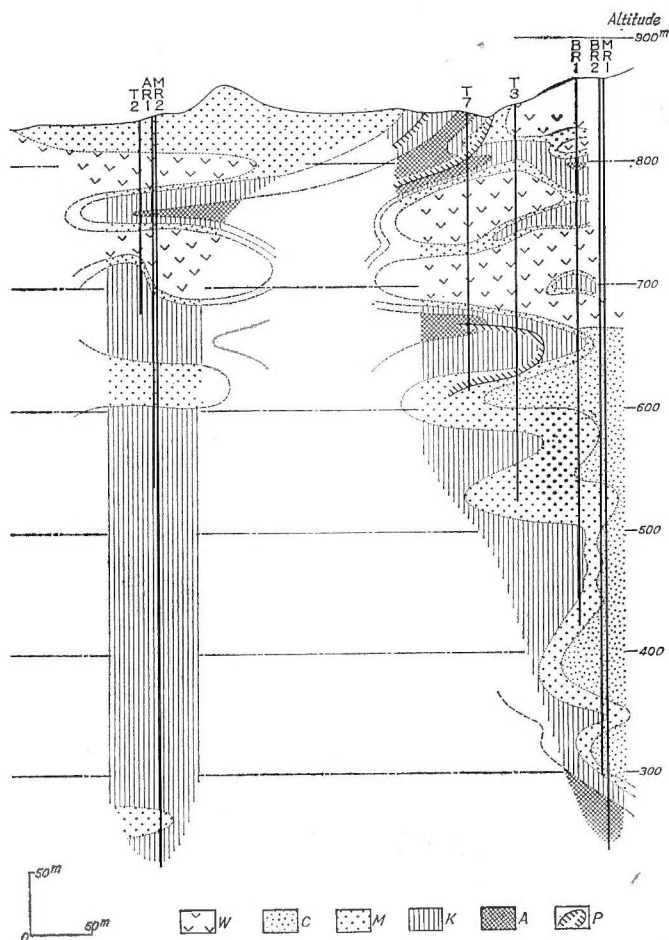


Fig. 8. Section of alteration zones in the Matsukawa geothermal area.
 W : Saponite zone, C : Chlorite zone, M : Montmorillonite zone,
 K : Kaolin zone, A : Alunite zone, P : Pyrophyllite zone.

C. Pyrophyllite zone.

The chemical and physical conditions of formation of the rocks in these zones may be inferred from several synthetic experiments (ALTHAUS, 1966, LEONARD, 1927, NOLL, 1936, ROY and OSBORN, 1954), as follows:

- 1) The value of pH decreases gradually from the montmorillonite zone to alunite zone in the zone-series A.
- 2) The pyrophyllite zone is formed under higher temperature than the zone-series A.

The time sequence of formation among the zones of A, B and C can be inferred as follows :

- 1) The formation of C is older than that of A, because the present temperature measured at C is lower than the temperature required to the crystallization of pyrophyllite.

- 2) The formation of B is older than that of A, as described in later chapter.
- 3) The relation between B and C is not known.

Correlation between the zonal mapping in this paper and that of NAKAMURA and SUMI (1961) is listed below:

This paper	Paper of NAKAMURA and SUMI (1961)
1) Saponite zone	Weakly altered zone
2) Montmorillonite zone	Greater part of clayey zone
3) Kaolin zone	A part of clayey zone and a part of compact siliceous zone
4) Alunite zone	Porous siliceous zone, greater part of compact siliceous zone and a part of clayey zone

III. 3 Distribution of altered zones and its relation to geologic structure

The distribution of the altered zones is remarkably elongated in the direction of ENE-WSW along the Matsukawa river. This fact probably indicates that the supplies of fumarolic gas and hydrothermal solution took place along the fissures having this direction. Although these fissures cannot be confirmed by the geological survey of the earth's surface, they give some characteristic features to topography, i. e. the somma of the Marumori volcano is divided into southern and northern parts (after the oral communication of Prof. H. KUNO).

Selective alteration due to the difference of original rock types is remarkable. Acid alteration zones, alunite zone and kaolin zone, are conspicuously developed in the part deeper than 160 m in depth. On the contrary, in the part shallower than 160 m, saponite zone and montmorillonite zone develop (Fig. 8).

The depth of 160 m corresponds to the boundary between Matsukawa andesite and Tamagawa welded tuff. The former is rather compact and the latter, relatively porous. These differences are probably due to the differences in the permeability of original rocks to gas or solution.

IV. Minerals in Altered Rocks

Mineral constituents are identified by X-ray measurements. Basal reflections are measured by the observation of well-oriented aggregate, and prismatic reflections are measured by that of random-oriented one. Heating and pre-treatment with ethylene glycol or 1 : 1 solution of hydrochloric acid are commonly used.

The methods of separation and pre-treatment are referred as follows:

1) Separation of clay:

Clay fraction is separated by Stokes' method. Clay or crushed rock (less than sixty mesh) is dispersed by stirring in distilled water. This dispersed system is left for eight hours, then the dispersed part is taken at 10 cm in depth. Dispersed particles (less than two microns) are separated by centrifugal force.

2) Preparation of well-oriented aggregate of clay:

A half of pasty samples (less than two microns) is dispersed in small amounts of distilled water by the ultrasonic vibrator. The water suspended with clay is dropped on slide glass and/or silica glass (for heat-treatment), and is naturally dried.

3) Preparation of random aggregate of clay:

Another half of pasty samples (less than two microns) is dried at room temperature. Samples dried are milled in mortar and are stuck with acetone on the slide glass stirring the samples with a needle.

4) Heat-treatment:

The well-oriented aggregate stuck on the silica glass is heated at temperatures of 300°C, 500°C and 700°C respectively for two hours. Immediately after cooling, X-ray measurement is examined.

5) Treatment with ethylene glycol:

The specimens stuck on the glass are saturated with ethylene glycol and left in that condition for about thirty minutes, then, an extruded portion by swelling is cut off, and the extended face is made smooth.

X-ray data were obtained with a X-ray diffractometer, "Geigerflex" made by Rigakudenki Co. The conditions of experiments are as follows: Radiation $\text{CuK}\alpha$, Ni filter, count full scale 400 c/sec, time constant 4 sec., scanning speed $1/4^\circ 2\theta/\text{min.}$, chart speed 1 cm/min., glancing angle 5° , divergence and soller slits $1/2^\circ$, receiving slit 0.15 mm., internal standards used are silicon and/or cholesterol (KITTRICK, 1960). The mean error of 2θ is 0.007° under these conditions.

IV. 1 Saponite

In X-ray diffraction pattern, the 15\AA reflection and its subsequent orders are observed. The X-ray diffraction data for the sample separated from the specimen of sample no. (HF8) is listed in Table 3.

Table 3. X-ray diffraction data for saponite separated from weakly altered andesite (HF 8).

d(Å)	I	
14.8	100	Sp
4.57	9	Sp
3.77	13	
3.34	21	Q
3.20	18	Pl
3.01	15	
2.55	8	
2.52	8	Pl
1.54	6	Sp

Sp: Saponite
Q: Quartz
Pl: Plagioclase

The 15\AA reflection shifts to 17\AA one by the treatment with ethylene glycol. The 1.54\AA reflection of (060) plane shows that this mineral is trioctahedral.

IV. 2 Chlorite

The powder of this mineral is greenish to the naked eye.

In X-ray diffraction pattern, the 14Å reflection and its subsequent orders are observed. These reflections show no change by the treatment with ethylene glycol, but disappear by the treatment with hydrogen chloride. The X-ray diffraction patterns of the representative sample separated from the drilling core of sample no. (BR2-550m) are shown in Fig. 9. The basal spacing does not shrink by heat-treatment at 700°C.

The 1.55Å reflection of (060) plane shows that this mineral is trioctahedral.

IV. 3 Laumontite

Table 4 shows X-ray diffraction data for the laumontite which is separated

Table 4. X-ray diffraction data for leonhardite.

1		2		
d (Å)	I	d (Å)	I	Indices
9.45	100			
7.62	12			
6.86	76	6.88	6	200
.....	...	6.21	2	201
5.06	6	5.07	2	111
4.74	19	4.75	1	220
4.50	11	4.51	3	221
4.16	71	4.18	10	130, 201
3.77	11	3.77	< 1	131
3.66	23	3.67	4	401
3.50	27	3.52	10	221, 002
3.41	10	3.42	< 1	400, 131
3.36	19	3.36	1	312
3.27	29	3.28	3	040
3.20	32	3.21	2	331
3.15	21	3.16	1	330
3.03	30	3.09	< 1	402
2.94	5	3.04	4	420, 112
.....	...	2.95	< 1	240
2.83	14	2.88	3	511
2.80	5	2.80	2	
.....	...	2.73	< 1	
.....	...	2.64	< 1	
2.573	15	2.58	3	
2.520	4	2.52	2	
.....	...	2.46	1	
2.438	13	2.440	4	
.....	...	2.394	< 1	
2.362	8	2.361	2	
2.268	5	2.272	1	
2.217	3	2.216	2	
2.181	4	2.183	1	
2.152	12	2.155	3	

1 : Leonhardite separated from chlorite-laumontite rock (BR 2-480 m).

2 : Leonhardite from Hungary (COOMBS, 1952).

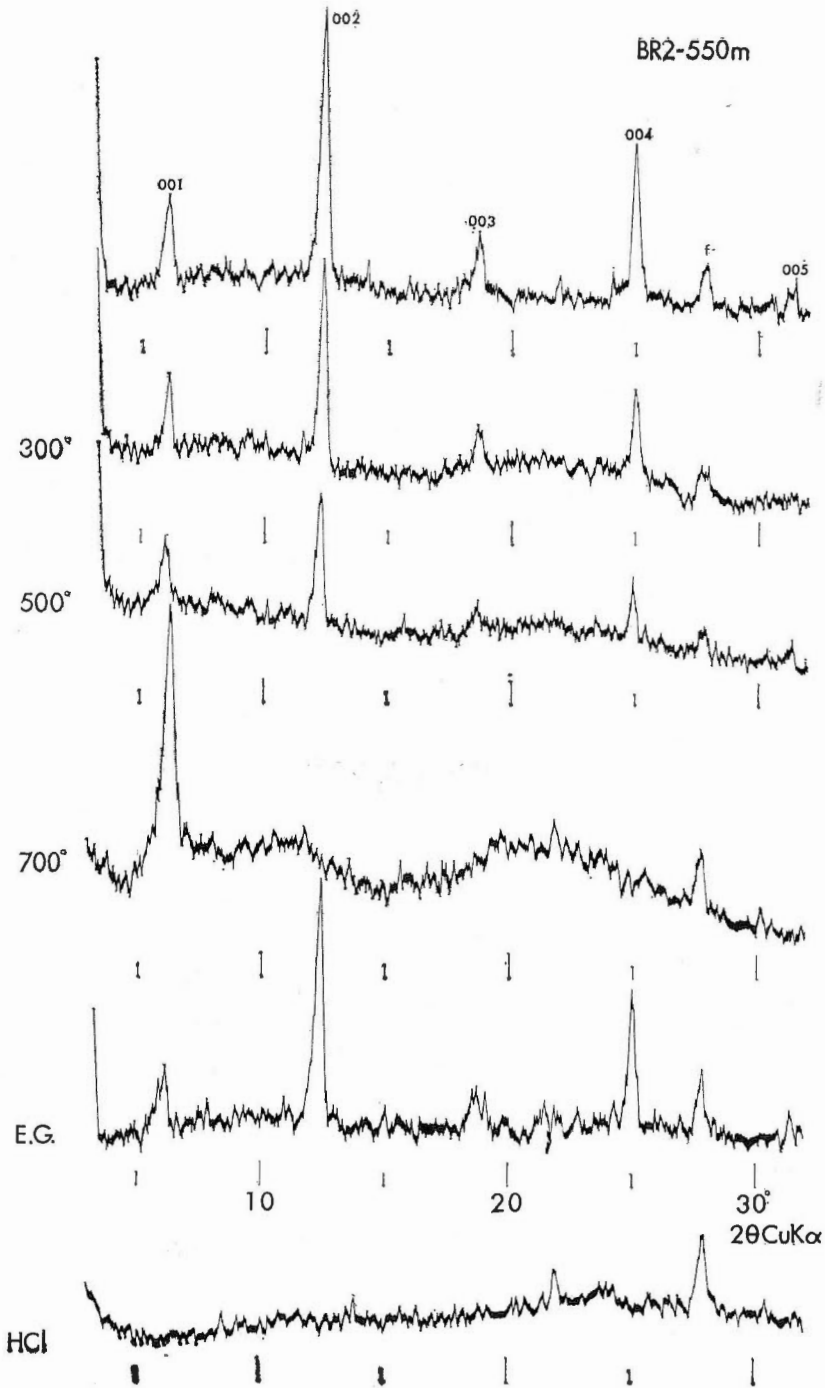


Fig. 9. X-ray diffraction patterns of chlorite separated from chloritized dacite (BR2-550m).
 f : Plagioclase, E. G. : Ethylene glycol, HCl, : Hydrogen chloride.

from the drilling core of sample no. (BR2-480 m) and is dried in the air for two days. These data are coincide to those for leonhardite partially dehydrated product from laumontite, reported by COOMBS (1952). According to him, when the laumontite is transformed into leonhardite, the lattice spacings of (100) and (010) are distinctly changed as follows:

	(100) lattice spacing	(010) lattice spacing
Leonhardite (this paper)	13.64 Å	13.08 Å
Leonhardite (COOMBS, 1952)	13.68 Å	13.10 Å
Laumontite (COOMBS, 1952)	13.86 Å	13.17 Å

IV. 4 Hydromica

In X-ray diffraction pattern, a broad peak from 10Å (the basal reflection of mica clay mineral) to lower angle side is observed, and its intensity gradually decreases from high angle to lower angle side. The X-ray diffraction patterns for the samples separated from the drilling core of sample no. (BR2-460 m) are shown in Fig. 10a.

The broad pattern of 10Å is not changed by treatment with ethylene glycol, and becomes sharp toward 10Å by heat-treatment.

It is noticed that one or two reflections (10.6Å and/or 11.3Å) appear overlapping with the broad peak in some cases as shown in Fig. 10b. Those two peaks are slightly displaced to lower angle side by treatment with ethylene glycol, and disappear by heat-treatment. These features are coincide with those of hydromica from the Kamikita mine (SUDO, 1959, p. 132). Examples of X-ray diffraction pattern are shown in Fig. 10 b.

For some specimens, the reflection of approximate 9.6Å appears (Fig. 10b). This reflection does not change either by the treatment with ethylene glycol or by the heat-treatment. However, it is not yet possible to determine from which mineral the reflection appears. The reflection of (060) plane is about 1.50 Å.

IV. 5 Montmorillonite

In X-ray diffraction pattern, the 15Å reflection and its subsequent orders are observed. The X-ray diffraction patterns for the sample separated from the drilling core of sample no. (BR2-530 m) are shown in Fig. 11.

The 15Å reflection shifts to 17Å by the treatment with ethylene glycol, and shrinks to 14Å by the heat-treatment, but does not disappear by the treatment with hydrogen chloride.

The 1.50Å reflection of (060) plane shows that this mineral is dioctahedral.

IV. 6 Kaolin

In X-ray diffraction pattern, the 7 Å reflection and its subsequent orders are observed. Their reflections are not changed by the treatment either with ethylene glycol or with hydrogen chloride.

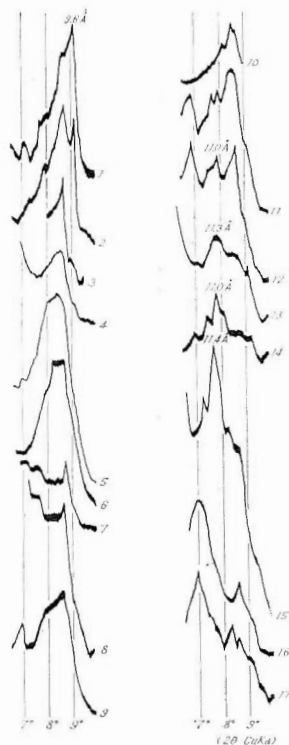


Fig. 10 b. X-ray diffraction patterns of hydromica overlapped by reflection of 11\AA and/or 9.6\AA .

1 : Sample no. (BR2-450m), 2 : (BR2-490m), 3 : (BR2-370m),
 4 : (BR2-435m), 5 : (BR2-460m), 6 : (BR2-456m), 7 : (BR2-392m),
 8 : (BR2-410m), 9 : (BR2-497m), 10 : (BR2-487m), 11 : (BR2-493m),
 12 : (BR2-406m), 13 : (BR2-426m), 14 : (BR2-380m), 15 : (BR2-415m),
 16 : (BR2-470m), 17 : (BR2-533m).

The 1.49\AA reflection of (060) plane shows that this mineral is dioctahedral.

IV. 7 Alunite

Table 5 shows the X-ray diffraction data of the sample separated from the drilling core of sample no. (T2-78 m).

IV. 8 Pyrophyllite

In X-ray diffraction pattern, the 9.2\AA reflection and its subsequent orders are observed. Their reflections are not changed by the treatment either with ethylene glycol or with hydrogen chloride.

The 1.49\AA reflection of (060) plane shows that this mineral is dioctahedral.

Table 5. X-ray diffraction data for alunite.

1		2		
d (Å)	I	d (Å)	I	Indices
.....	...	5.77	30	003
5.69	16	5.72	14	101
4.93	65	4.96	55	012
3.49	27	3.49	20	110
2.97	100	2.99	100	113
2.85	9	2.89	100 ?	006
.....	...	2.477	6	024
2.259	20	2.293	80	107
2.207	8	2.211	6	122
.....	...	2.038	2	018
.....	...	2.022	2	214
.....	...	1.926	70	009
1.898	24	1.903	30	303
.....	...	1.762	2	208
1.745	6	1.746	16	220

1 : Alunite separated from quartz-alunite rock (T2-78 m)

2 : Alunite (A. S. T. M. card 14-136).

IV. 9 Mixed-layer mineral of montmorillonite-chlorite

In X-ray diffraction pattern, the 29Å reflection and its subsequent orders are observed. The X-ray diffraction data and pattern for the representative one of the samples from the drilling core of sample no. (BR2-470 m) are shown both in Table 6 and Fig. 12. The mean value of basal spacing calculated from the higher order reflections is 28.5Å.

The 28.5Å reflection is changed into 30.8Å one by the treatment with ethylene glycol.

Table 6. X-ray diffraction data for mixed-layer mineral of montmorillonite-chlorite separated from chlorite-laumontite rock (BR2-470 m).

ℓ	Natural			Complexes with ethylene glycol		
	d(00l) (Å)	I	d(00l) (Å)	d(00l) (Å)	I	d(00l) (Å)
1	29.4	98	29.4	31.0	87	31.0
2	14.6	100	29.2	15.5	100	31.0
3	.....	.....	.....	.....	.....	.....
4	7.16	59	28.64	7.69	39	30.76
5	.....	.....	.....	.....	.....	.....
6	4.77	57	28.62	5.15	68	30.90
7	.....	.....	.....	.....	.....	.....
8	3.55	47	28.40	.....	.....	.....
Mean			28.55			30.84

The results are closely coincide with the data (29.0Å and 31.5Å) reported by EARLY et al. (1956). The sample is 1:1 regular mixed-layer probably.

IV. 10 Mixed-layer mineral of sericite-montmorillonite

In X-ray diffraction pattern, the 25Å reflection and its subsequent orders are observed.

The X-ray diffraction data and pattern for the representative one of the samples separated from the drilling core of sample no. (BR2-500 m) are shown

Table 7. X-ray diffraction data for mixed-layer mineral of sericite-montmorillonite separated from anhydrite-calcite-chlorite rock (BR2-500 m).

l	Natural			Complexes with ethylene glycol		
	d(00l) (Å)	I	d(00l) (Å)	d(00l) (Å)	I	d(00l) (Å)
1	24.9	100	24.9	27.2	100	27.2
2	12.5	66	25.0	13.5	61	27.0
3	.....	.....		8.93	21	26.79
4	.....	.....		6.68	10	26.72
5	5.03	16	25.15	5.37	15	26.85
6		.....		.....	.....	.....
7		.....		.....	.....	.....
8	3.15	19	25.20	3.34	16	26.72
Mean			25.12			26.81

both in Table 7 and Fig. 13. The mean value of basal spacing calculated from the higher order reflections is 25.1Å.

The 25.1 Å reflection is changed into 26.8Å one by the treatment with ethylene glycol.

The 1.49Å reflection of (060) plane shows that this mineral is dioctahedral.

The first order reflection of 25Å is found in the powder from the montmorillonite zone, but does not found in the powder from the chlorite zone.

According to the theoretical calculation of MACEWAN et al. (1961), the 25Å reflection does not appear in case of his formulae $P_{AA} \geq 0.3$; here the P_{AA} means probability which A succeeds A, when minerals A and B are at random interstratified in equal proportion. Moreover, in case of the minerals in which the first order reflection is not observed, the second order reflection of 12.5 Å is not so sharp. Then, the regularity of the mixed-layer mineral from montmorillonite zone is probably larger than that from chlorite zone.

IV. 11 Other minerals

Other accessory minerals are anhydrite, gypsum, calcite, rutile, pyrite, diaspore, andalusite and zunyite.

Table 8 shows the X-ray diffraction data of anhydrite from vein in the drilling

core of sample no. (MR2-842 m). Table 9 shows the X-ray diffraction data for rutile separated from the drilling core of sample no. (T3-199 m).

Table 8. X-ray diffraction data for anhydrite.

1		2	
d(Å)	I	d(Å)	I
3.87	2	3.87	6
3.50	100	3.498	100
3.12	2	2.118	3
3.85	7	2.847	33
2.80	1	2.797	4
2.473	2	2.473	8
2.327	5	2.328	22
2.208	4	2.208	20
2.183	4	2.183	8
2.086	2	2.086	9
1.993	4	1.993	6
1.938	1	1.938	4
1.868	4	1.869	15
1.852	2	1.852	4
1.750	8	1.749	11
1.747	9	1.748	10
1.648	3	1.648	14
1.594	1	1.594	3
1.564	2	1.564	5

1 : Anhydrite, vein in dacite welded tuff
(MR 2-842 m)

2 : Synthetic anhydrite (A. S. T. M. card 6-0226).

Table 9. X-ray diffraction data for rutile.

1		2		
d(Å)	I	d(Å)	I	Indices
3.25	100	3.245	100	110
2.489	34	2.489	41	101
2.297	16	2.297	7	200
2.188	19	2.188	22	111
2.054	11	2.054	9	210
1.688	38	1.687	50	211
1.625	32	1.624	16	220
.....	...	1.480	8	002
1.453	14	1.453	6	310
1.360	18	1.360	16	301

1 : Rutile separated from the rutile-kaolin-quartz
rock (T 3-199 m).

2 : Synthetic rutile (A. S. T. M. card 4-0551).

V. Microscopic and X-ray Characteristics of Altered Rocks

The petrography of rocks in each zone is given in this chapter. The data on X-ray measurement are summarized in Table 10.

V. 1 Rocks of saponite zone

Weakly altered andesite (HF8)

The rock is deep green.

Phenocrysts are plagioclase, hypersthene, augite, quartz and ore mineral. Matrix is composed of plagioclase, clinopyroxene, rhombic pyroxene, felsic minerals and ore mineral. As secondary minerals saponite and opal (?) are found.

Plagioclase of phenocryst is 0.1~1.5 mm in length, and strongly zoned. Most crystals are water clear but some contain dusty substances. Crystals are partly saponitized along cracks, while they are free from albitization.

Pyroxene of phenocryst, 0.1~1.2 mm in length, is abundant, and includes saponite along some cleavage planes.

Quartz of phenocryst shows corroded form and is scanty in quantity.

In some parts of groundmass or interstices of plagioclase and pyroxene, minute saponite and opal (?), etc. are crystallized, as secondary products from volcanic glass. Saponite occurs not only as the secondary mineral as mentioned above but also as veinlets. This mineral forms aggregate of minute greenish brown crystals, and larger crystals show distinct pleochroism, from pale yellow to greenish brown. Elongation is negative and refractive indices are slightly higher than Canada balsam. Judging from its interference color, birefringence may be nearly 0.02.

Opal (?) is anhedral and colorless. Refractive indices are lower than Canada balsam, and birefringence is faintly recognized.

V. 2 Rocks of chlorite zone

a) Chlorite-laumontite rock (BR2-470 m)

The rock was collected at the depth of 470 m. It is light gray and hard.

Phenocryst is quartz and plagioclase.

Quartz is 0.1~1mm in size and is corroded form.

Plagioclase is mostly laumontitized. Fresh plagioclase exhibits distinct zonal structure. Laumontite is mostly fresh but partly clouded with dusty materials. Each of dusty materials is elongated in shape, and have birefringence of 0.02~0.025 estimated from its interference color. Judging from the X-ray diffraction pattern, it is mixed-layer mineral of sericite-montmorillonite. Laumontite comprises numerous dusty materials and is associated with a small amount of anhydrite and/or calcite. The mixed-layer mineral and anhydrite may have been formed by the destruction of laumontite.

In matrix, quartz, laumontite, clay mineral, leucoxene and pyrite are recrystallized.

b) Chlorite-montmorillonite-calcite (BR2-435 m)

The rock was collected at the depth of 435 m. It is pale green.

Phenocryst is abundant, and is composed of quartz and the pseudomorph after plagioclase.

Table 10. X-ray diffraction data for rocks.—Continued.

HF 89		T3-313m		BR2-530m		Cl-9		T3-204m		BR2-521m		HF133 a	
d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	I	d(Å)	I
15	M	15	41	15	50	7.2	82	9.4	4	7.2	28	4.9	4
8.9	7	7.2	5	4.45	13	5.7	6	7.1	25	4.37	7	4.25	32
4.47	M	5.1	7	4.25	36	4.9	7	4.46	13	4.25	24	3.48	5
4.25	Q	4.47	15	3.34	100	4.44	33	4.35	16	4.13	20	3.34	100
3.53	22	4.25	33	3.18	18	4.36	32	4.25	31	3.59	21	2.97	11
3.34	100	3.34	100	3.03	11	4.25	42	4.15	11	3.50	33	2.46	15
2.55	9	3.12	7	2.71	5	4.13	32	3.84	6	3.34	100	2.28	13
2.46	Q	3.03	15	2.55	8	4.00	14	3.71	25	2.71	7	2.24	9
2.28	Q	2.71	9	2.46	11	3.79	22	3.58	100	2.46	9	2.13	10
2.24	Q	2.57	8	2.28	9	3.59	68	3.12	8	2.32	4	1.98	7
2.13	Q	2.46	15	2.13	9	3.48	10	2.71	8	2.28	7	1.89	2
1.98	Q	2.28	12	1.98	5	3.45	14	2.56	8	2.13	5	1.82	18
1.82	Q	2.24	7	1.82	13	3.34	100	2.50	8	1.98	5	1.74	2
1.68	M	2.22	6	1.67	5	3.25	10	2.46	14	1.82	12	1.67	6
1.67	Q	2.13	9	1.54	9	2.98	11	2.42	11	1.67	5	1.54	15
1.54	Q	1.98	6	1.54	Q	2.79	5	2.38	6	1.54	8	1.45	4
1.50	M	1.91	8	1.87	4	2.59	18	2.34	11	1.49	4		
		1.87	4	1.82	13	2.50	22	2.28	11				
		1.82	15	1.67	5	2.46	12	2.24	7				
		1.67	8	1.64	9	2.38	11	2.22	6				
		1.64	12	1.54	14	2.32	41	2.13	8				
		1.54	14	1.50	6	2.28	10	1.98	8				
		1.50	6			2.24	7	1.91	5				
						2.22	8	1.82	18				
						2.13	8	1.67	8				
						1.98	16	1.66	7				
						1.90	6	1.63	12				
						1.82	16	1.54	13				
						1.74	4	1.49	3				
						1.68	6						
						1.67	8						
						1.65	15						
						1.55	6						
						1.54	12						
						1.49	15						

A: Alunite, Ad: Andalusite, Ab: Anhydrite, C: Calcite, Ch: Chlorite, C/M: Mixed-layer mineral of montmorillonite-chlorite, Cr: α -Cristobalite, D: Diaspore, G: Gypsum, H: Hydromica, H: Laumontite(Leonhardtite), M: Montmorillonite, L: Laumontite(Leonhardtite), Pt: Montmorillonite,

The pseudomorph is composed of aggregate of laumontite, calcite and clay mineral. Calcite is euhedral. Laumontite shows honey-combed structure with the inclusions of numerous, fine-grained clay minerals. It is clear under the microscope that laumontite is changed into calcite and clay mineral (montmorillonite).

Matrix is composed of quartz, calcite, clay mineral, leucoxene, pyrite and others.

c) Anhydrite-calcite-chlorite rock (BR 2-500 m)

The rock was collected at the depth of 500 m. It is gray and rather soft. The impregnation of pyrite is distinct.

Under the microscope, the phenocrystic quartz, 0.2~2 mm in size, is common. Feldspar or its pseudomorph is rarely recognized.

In matrix, quartz, clay mineral, anhydrite, leucoxene and pyrite are recrystallized, and there are found some pools in which calcite (0.1~0.3 mm in length), anhydrite (0.1~0.8 mm in length) and clay mineral are predominated. It is possible that the pool is the pseudomorph after plagioclase, because it shows the outline of plagioclase.

Clay mineral is fibrous, and its crystallinity is rather high. The length of crystal is up to 0.1 mm in some cases. Judging from X-ray diffraction data (Table 7), it is 1:1 regular mixed-layer mineral of sericite-montmorillonite.

Quartz shows often mosaic texture with undulated extinction. It attains 0.5 mm in maximum size.

V. 3 Rocks of montmorillonite zone

a) Calcite-montmorillonite-quartz rock (T3-313 m)

The rock was collected at the depth of 313 m. It is originated from andesite, and is gray, rather soft.

Under the microscope, original porphyritic texture is still preserved.

Plagioclase of phenocryst is completely recrystallized to montmorillonite and calcite.

Quartz of phenocryst is rarely present, and is water clear, euhedral or semi-euhedral.

In matrix, montmorillonite, calcite, quartz and pyrite are recrystallized.

Montmorillonite is fibrous, less than 0.03 mm in length, and its elongation is negative. Birefringence is smaller than 0.01, and refractive indices are higher than Canada balsam. The X-ray reflection of 15.4 Å changes into 16.5 Å by treatment with ethylene glycol.

Quartz, 0.4 mm in maximum size, is clouded with dusty materials, and shows undulated extinction.

b) Montmorillonite clay (HF89)

The clay was collected at the earth's surface.

The clay is yellowish white. The X-ray reflection of 15.4 Å is changed into 17.3 Å by treatment with ethylene glycol.

V. 4 Rocks of kaolin zone

a) Kaolin-quartz rock (T3-204 m)

The rock was collected at the depth of 204 m. It is gray and soft. This rock consists of kaolin, quartz, rutile, leucoxene, pyrite and sericite-like mineral. It comprises kaolin-rich part and quartz-rich part.

Quartz forms mosaic aggregate of small crystals of 0.02 mm in size. It is clouded with dusty materials. Sericite-like mineral forms spherulitic aggregate, about 0.2 mm in diameter, of the fibrous crystals. Birefringence is 0.01~0.02 and elongation is negative. The 9.36Å reflection of X-ray (Table 10) is characteristic.

b) Kaolin-quartz clay (CI-9)

The clay was collected at the earth's surface. It is milky white.

V. 5 Rocks of alunite zone

a) Quartz-alunite rock (T7-167 m)

The rock was collected at the depth of 167 m. It consists of quartz and alunite accompanied with a small amount of rutile, and it comprises alunite-rich part and mosaic quartz-rich part.

Alunite is less than 0.12 mm in length. It shows parallel extinction and negative elongation. Birefringence is 0.015~0.020, and refractive indices are lower than Canada balsam.

Some crystals of quartz are coarse-grained (less than 0.4 mm in size) and clouded with dusty materials, but others are fine-grained (less than 0.05 mm in size) and water clear. Primary quartz showing corroded form is rarely found. It is 0.6 mm in size and water clear.

Rutile is smaller than 0.2 mm in length.

b) Compact siliceous rock (HF 133 a)

The rock was collected at the earth's surface. It is white with brownish stains.

Under the microscope, most part of the rock is composed of mosaic aggregate of quartz, in which minute alunite flakes (0.01~0.03 mm in length) are uniformly scattered.

c) Porous siliceous rock (HF 133 f)

The rock was collected at the earth's surface. It is white, hard and porous.

Under the microscope, most part of the rock is composed of mosaic aggregate of quartz and small pools of alunite.

V. 6 Rocks of pyrophyllite zone

a) Andalusite-pyrophyllite-quartz rock (T7-24 m)

The rock was collected at the depth of 24 m. It is white to gray and soft. Porphyritic texture of original andesite is still preserved.

Under the microscope, phenocrystic plagioclase is replaced by pyrophyllite which is associated with a small amount of pyrite and dusty materials.

In matrix, pyrophyllite, quartz, andalusite, pyrite, leucoxene are recrystallized. It comprises two parts, pyrophyllite part and quartz-andalusite part.

Pyrophyllite is smaller than 0.01 mm is size, and slightly elongated in shape. Birefringence is nearly 0.02 and refractive indices are nearly equal to Canada balsam. Mosaic aggregate of quartz (0.01~0.03 mm in size) are found in the quartz-andalusite part.

Andalusite is needle- or lath-shaped, fresh and 0.05~0.10 mm in length. Elongation is negative.

Alunite was detected by X-ray diffraction pattern of the whole rock, but not by the microscopic observation.

b) Diaspore-zunyite-pyrophyllite rock (CI-13)

The rock was collected at the earth's surface. It is pinkish white and massive.

Under the microscope, it consists mainly of pyrophyllite, and is associated with leucoxene, diaspore and zunyite. The last two minerals often form small spots of 0.1~0.2mm in diameter.

Diaspore is smaller than 0.05mm in length, colorless and prismatic. Cleavage is distinct. It shows parallel extinction and negative elongation.

Zunyite is smaller than 0.01 mm in length. It is colorless, tetrahedral and is nearly isotropic.

VI. Chemical Compositions of Altered Rocks

Chemical compositions of eighteen rock samples are listed in Table 11. Recalculated compositions excluding H_2O^+ , H_2O^- , CO_2 , SO_3 and S are shown in Table 12.

VII. Temperature Measured in Bore Holes

In four bore holes, T1, T2, T3 and BR1, temperature was repeatedly measured at the bottom of holes. The depth-temperature curves and the temperature section obtained from the above data are shown in Figs. 14 and 15, respectively.

The section shows that the thermal gradient at about 160 m in depth is steeper than in the shallower and deeper parts. The depth, about 160 m, corresponds exactly to the boundary between the Matsukawa andesite (relatively compact) and the Tamagawa welded tuff (relatively porous). Probably, the andesite plays a role of "cap rock".

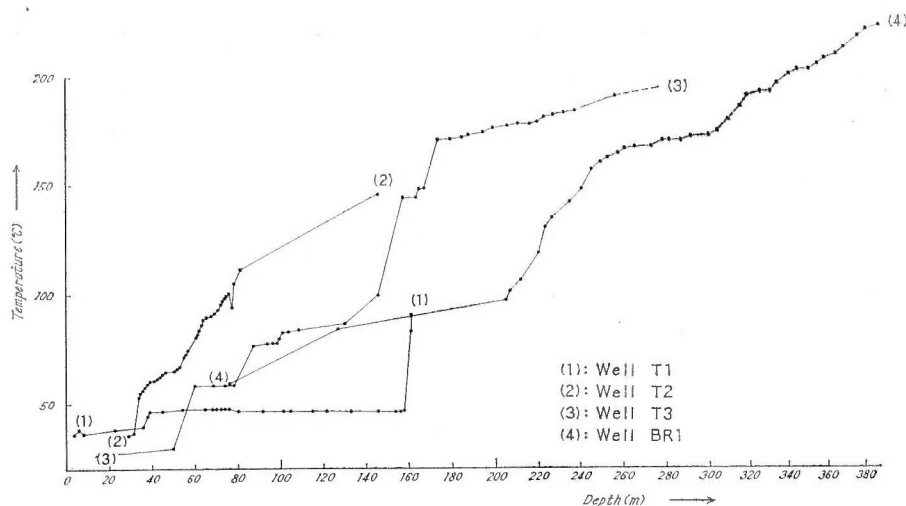


Fig. 14. Depth-temperature curves of the wells T1, T2, T3 and BR1

Table 11. Chemical

	1	2	3	4	5	6	7	8
Sample no.	HF 8	BR2-310m	BR2-470m	BR2-500m	BR2-435m	HF 89	T3-313m	BR2-530m
Wt(%)								
SiO ₂	58.86	58.68	66.56	59.54	63.57	73.56	56.94	66.87
TiO ₂	0.63	0.64	0.30	0.37	0.44	1.15	0.52	0.39
Al ₂ O ₃	15.67	14.62	13.39	11.94	14.00	8.27	14.57	12.69
Fe ₂ O ₃	4.93	0.80	0.63	0.48	0.51	0.82	0.47	0.21
FeO	2.75	2.76	0.45	0.31	1.53	0.11	0.36	0.11
Fe	—	1.93	2.30	3.33	1.35	—	3.88	2.27
MnO	0.12	0.17	0.09	0.04	0.11	0.02	0.31	0.13
MgO	3.95	3.80	2.70	2.02	3.15	1.16	2.97	2.95
CaO	7.38	3.42	2.87	5.81	2.87	0.01	2.92	2.37
Na ₂ O	2.24	1.18	1.32	0.36	0.43	0.00	0.20	1.19
K ₂ O	0.79	1.20	0.57	0.62	1.21	0.03	0.72	0.58
P ₂ O ₅	0.01	0.10	0.06	0.05	0.06	0.00	0.07	0.06
S	—	2.22	2.64	3.82	1.55	—	4.46	2.61
SO ₃	0.02	0.02	0.60	5.47	0.02	0.29	tr.	1.54
CO ₂	—	1.04	0.15	0.87	0.78	—	1.30	0.66
H ₂ O ⁺	1.24	4.79	4.06	4.06	4.80	2.79	5.94	3.76
H ₂ O ⁻	1.10	2.60	0.97	1.36	2.66	11.68	4.28	1.60
Total	99.69	99.97	99.66	100.45	99.14	99.89	99.91	99.99
Ap. G. * ₂		2.45	2.53	2.36			2.50	2.37
Tr. G. * ₃		2.59	2.65	2.72	2.55			2.65

*1: Total of (S+SO₃) as S.

*2: Apparent specific gravity.

*3: True specific gravity.

Note: Eight analyses, nos. 1, 6, 7, 9, 10, 12, 13 and 14, are taken from SUMI's (1966) paper.

Samples prefixed with "HF" or "CI" (within parenthesis) were collected at the earth's surface. The localities of these samples are shown in Fig. 5 (a and b). Other samples are collected from drilling cores. The first marks (before hyphen) of these sample nos. mean the symbols of bore holes, and the second numerals (after hyphen) mean the depths where the samples were collected. The localities of bore holes are shown in Fig. 7.

No. 1: Weakly altered andesite (HF8) from the saponite zone. Analyzed by M. KAWANO.

No. 2: Weakly altered andesite (BR 2-310m) from the saponite zone. Analyzed by K. MAEDA.

No. 3: Chlorite-laumontite rock (BR 2-470m) from the chlorite zone. Analyzed by K. MAEDA.

No. 4: Anhydrite-calcite-chlorite rock (BR 2-500m) from the chlorite zone. Analyzed by K. MAEDA.

No. 5: Chlorite-montmorillonite-calcite rock (BR 2-435m) from the chlorite zone. Analyzed by K. MAEDA.

No. 6: Montmorillonite clay (HF89) from the montmorillonite zone. Analyzed by M. KAWANO.

compositions of rocks.

9	10	11	12	13	14	15	16	17	18
Cl-9	T3-204m	BR2-521m	HF133a	HF133f	T7-167m	MR1-596m	Cl-13	T7-24m	MR1-760m
55.28	60.22	63.79	90.84	81.16	52.12	60.71	59.28	67.78	68.40
1.33	0.64	0.34	0.35	0.50	0.42	0.06	0.48	0.49	0.38
29.47	20.94	11.67	3.30	6.96	18.32	10.81	31.81	12.90	12.78
0.53	0.82	0.39	0.21	0.08	0.03	2.49	tr.	tr.	0.70
0.11	0.18	0.11	0.11	0.07	0.04	0.14	0.48	0.39	0.23
—	3.14	2.12	—	—	0.09	—	0.53	5.38	1.38
0.00	0.01	tr.	0.00	0.00	0.01	0.00	0.00	tr.	tr.
0.01	0.07	tr.	0.03	0.03	0.07	tr.	tr.	tr.	0.44
0.01	0.08	6.03	0.04	0.47	0.06	2.65	tr.	tr.	3.36
0.01	0.17	0.08	0.15	0.31	1.16	0.89	0.14	0.42	0.13
0.01	0.09	0.03	0.14	0.46	2.95	1.90	0.08	0.13	2.28
0.07	0.11	0.06	0.00	0.04	0.04	0.04	0.05	0.06	0.02
—	3.60	2.44	—	—	0.11	7.24 ^{*1}	0.61	6.18	1.58
1.58	1.07	8.34	2.87	6.71	17.42	—	0.03	0.66	4.73
—	tr.	0.04	—	—	tr.	0.03	0.07	0.04	0.11
10.78	7.58	4.67	1.59	2.74	6.70	4.81	5.46	3.36	2.64
0.52	1.10	0.23	0.10	0.14	0.08	0.09	0.09	0.35	0.35
99.80	99.82	100.34	99.73	99.67	99.62	91.86	99.11	98.14	99.51
	2.68	2.35			2.55	2.17	2.56	2.56	2.59
		2.75				2.77	2.85	2.83	2.76

No. 7: Calcite-montmorillonite-quartz rock (T 3-313m) from the montmorillonite zone. Analyzed by K. MAEDA.

No. 8: Anhydrite-montmorillonite-quartz rock (BR 2-530m) from the montmorillonite zone. Analyzed by K. MAEDA.

No. 9: Kaolin-quartz clay (Cl-9) from the kaolin zone. Analyzed by M. KAWANO.

No.10: Kaolin-quartz rock (T 3-204m) from the kaolin zone. Analyzed by K. MAEDA.

No.11: Anhydrite-kaolin-quartz rock (BR 2-521m) from the kaolin zone. Analyzed by K. MAEDA.

No.12: Compact siliceous rock (HF 133a) from the alunite zone. Analyzed by M. KAWANO.

No.13: Porous siliceous rock (HF 133f) from the alunite zone. Analyzed by M. KAWANO.

No.14: Quartz-alunite rock (T 7-167m) from the alunite zone. Analyzed by K. MAEDA.

No.15: Quartz-alunite rock (MR 1-596m) from the alunite zone. Analyzed by K. MAEDA.

No.16: Diaspore-zunyite-pyrophyllite rock (Cl-13) from the pyrophyllite zone. Analyzed by K. MAEDA.

No.17: Andalusite-pyrophyllite rock (T7-24m) from the pyrophyllite zone. Analyzed by K. MAEDA.

No.18: Anhydrite-pyrophyllite-quartz rock (MR 1-760m) from the pyrophyllite zone. Analyzed by K. MAEDA.

Table 12. Recalculated chemical compositions of rocks.

Salt, le no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Wt(%)	HF 8	BR2-310 m	BR2-470 m	BR2-500 m	BR2-455 m	HF 89	T3-313 m	BR2-530 m	Cl-9	T3-204 m	BR2-571 m	HF 133a	HF133f	T7-167 m	MR1-506 m	Cl-13	T7-24m	MR1-700 m
Si	28.38	30.84	34.24	32.93	33.44	40.55	31.84	34.94	29.88	32.68	35.38	44.79	42.28	32.48	35.75	30.00	36.33	35.63
Ti	0.39	0.43	0.20	0.26	0.29	0.88	0.37	0.26	0.92	0.44	0.24	0.22	0.34	0.34	0.05	0.31	0.34	0.25
Al	8.54	8.68	7.78	7.46	8.32	5.15	9.21	7.49	18.00	12.84	7.31	1.84	4.10	12.90	7.20	18.17	7.81	7.52
Fe ³⁺	3.55	0.63	0.48	0.40	0.40	0.67	0.40	0.16	0.43	0.66	0.32	0.15	0.06	0.03	2.18	tr.	tr.	0.55
Fe ²⁺	2.20	2.40	0.38	0.28	1.34	0.10	0.33	0.95	0.10	0.16	0.10	0.09	0.06	0.04	0.14	0.04	0.35	0.20
Fe	—	2.16	2.52	3.92	1.51	—	4.62	2.53	—	3.63	2.51	—	—	0.12	—	0.56	6.15	1.53
Mn	0.09	0.15	0.08	0.04	0.09	0.02	0.29	0.12	0.00	0.00	tr.	0.00	0.00	0.00	0.00	0.00	tr.	tr.
Mg	2.45	2.57	1.79	1.44	2.13	0.82	2.14	1.98	0.01	0.05	tr.	0.02	0.02	0.05	tr.	tr.	tr.	0.30
Ca	5.42	2.74	2.25	4.90	2.30	0.01	2.49	1.89	0.01	0.06	5.10	0.03	0.37	0.06	2.37	tr.	tr.	2.67
Na	1.71	0.98	1.08	0.31	0.36	0.00	0.18	0.99	0.01	0.15	0.07	0.12	0.25	1.14	0.83	0.10	0.36	0.10
K	0.67	1.11	0.52	0.61	1.13	0.03	0.71	0.54	0.01	0.08	0.03	0.12	0.42	3.25	1.98	0.07	0.12	2.10
P	0.00	0.05	0.03	0.03	0.03	0.00	0.03	0.03	0.03	0.06	0.03	0.00	0.04	0.02	0.05	0.02	0.03	0.01
O	46.60	47.26	48.65	47.42	48.66	51.84	47.39	48.12	50.60	49.19	48.91	52.62	52.06	49.57	49.45	50.73	48.51	49.14
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Note : Excluding H₂O⁺, H₂O⁻, CO₂, SO₃ and S.

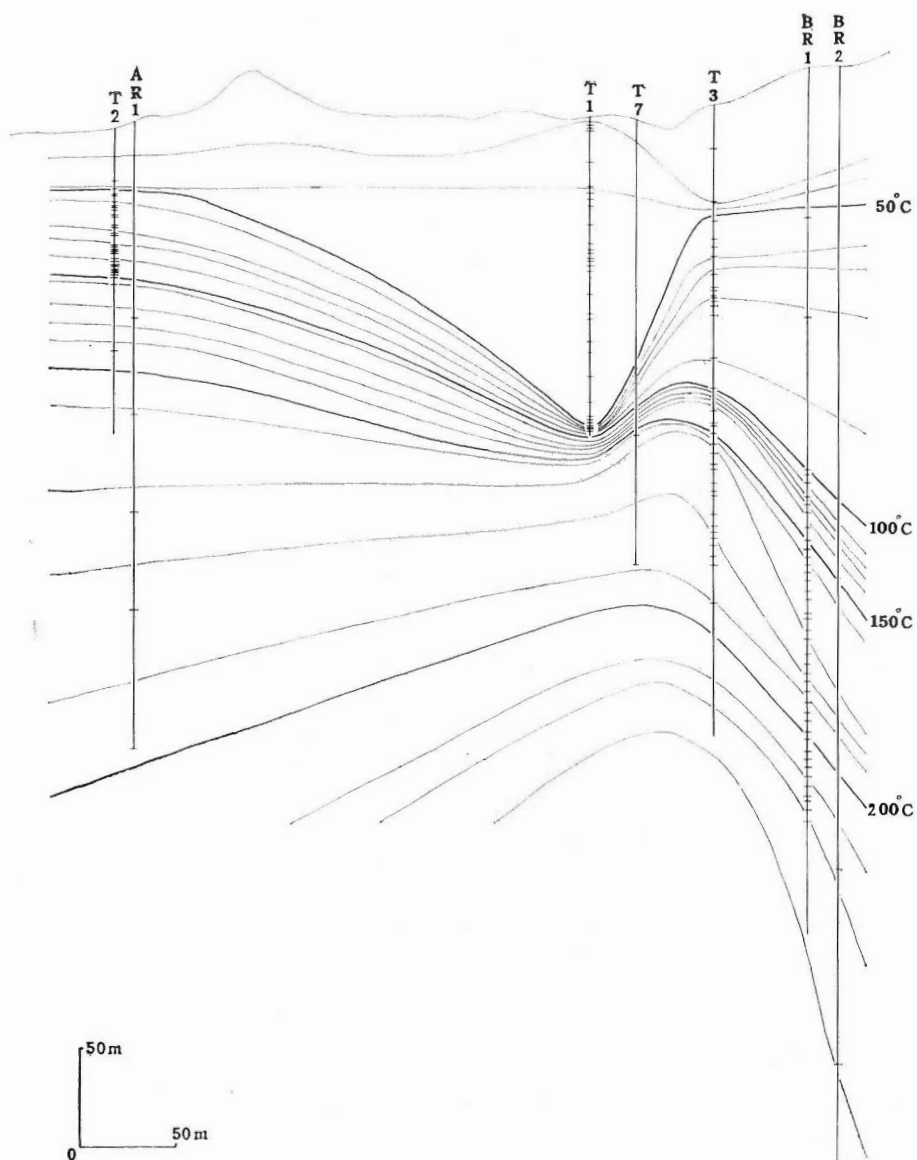


Fig. 15. Temperature section in the Matsukawa geothermal area.

VIII. Chemical Compositions of Hot Water

Table 13 shows the chemical compositions of hot water.

The pH values of the water in this table are 2.5~6.3. It is noticed that they contain high contents of sulphite ion and low contents of chlorine ion.

Table 13. Chemical compositions of hot water.

	1	2	3	4	5	6	7	8	9	10	11	12	13
pH	2.5	3.2	2.7	3.1	3.3	2.8	3.2	3.8	5.4	4.0	3.8	3.4	6.3
CO ₂ mg/ℓ	—	—	—	—	—	—	—	—	—	—	—	—	—
HCO ₃ ⁻	—	—	—	0.0	—	—	—	0.0	18.3	0.0	0.0	0.0	85.2
SO ₄ ²⁻	319	108	431	315.2	118	176	94.6	1346.4	1316.8	1316.8	900.4	961.3	146.5
H ₂ S	59.5	19.6	20.3	5.2	61.5	45.4	45.9	tr.	tr.	tr.	—	6.1	0.0
Cl ⁻	2.8	4.1	3.4	3.0	1.4	4.1	3.0	3.0	3.0	5.3	49.7	3.5	3.5
Fe ²⁺	tr.	tr.	5.2	8.6	tr.	3.1	0.7	236.7	200.1	—	126.2	86.0	20.1
Al ³⁺	—	—	—	11.5	—	—	5.3	5.1	9.5	—	3.5	10.8	1.5
Mg ²⁺	8.6	3.9	6.4	8.2	1.6	2.1	2.1	35.7	36.5	—	—	26.0	1.3
Ca ²⁺	16.6	12.0	32.4	31.8	11.0	12.0	8.2	31.3	32.3	—	—	30.0	33.9
Na ⁺	—	—	—	40.0	—	—	14.0	266.4	259.2	—	—	—	—
K ⁺	—	—	—	9.6	—	—	7.3	78.4	84.6	—	—	—	—
NH ₄ ⁺	1.52	2.26	2.44	2.5	1.48	1.94	2.0	—	—	—	—	—	—
HBO ₂	—	—	—	13.3	—	—	11.1	11.2	11.0	—	—	—	—
SiO ₂	24	18	74	64.2	38	30	23.0	239	244	—	—	—	—
T. S. M.	378	288	804	670.0	212	274	250.0	2374.0	2332.0	—	—	—	—

T. S. M.: Total solid matter.

- 1 and 2 : Hot water from the hot spring east of well T2. Collected in June, 1955. Analyzed by T. ANDO.
- 3 : Hot water from the hot spring of Shofuso hotel Collected in June, 1955. Analyzed by T. ANDO.
- 4 : Ditto. Collected in Dec., 1959. Analyzed by K. MAEDA.
- 5 : Hot water from well T 4. Collected in June, 1955. Analyzed by T. ANDO.
- 6 : Hot water from well T 1. Collected in June, 1955. Analyzed by T. ANDO.
- 7 : Hot water from well GS-3. Collected in Dec., 1959. Analyzed by K. MAEDA and T. YAMADA.
- 8 : Drainage water from well AR 1. Collected in Aug., 1960. Analyzed by K. MAEDA.
- 9 : Ditto. Collected in Sept., 1960. Analyzed by K. MAEDA.
- 10 : Ditto. Collected in Oct., 1960. Analyzed by K. MAEDA.
- 11 : Ditto. Collected in Jan., 1961. Analyzed by K. MAEDA.
- 12 : Ditto. Collected in Feb., 1961. Analyzed by K. MAEDA.
- 13 : Drainage water from well BR 1. Collected in Feb., 1961. Analyzed by K. MAEDA.

IX. Relative Abundance of Silicon to Aluminium as Referred to Depth

The Matsukawa area is very suitable for studying the difference in features of alteration between shallow part and deep part, because the altered mass is vertically elongated in shape. The similar patterns of zonal arrangement are recognized regardless to the depth as tabulated below.

	Depth at present	Depth from restored surface during main fumarolic activity
"Shallow part"	surface	150 ~ 300 m
"Intermediate part"	170 ~ 210 m	470 ~ 510 m
"Deep part"	440 ~ 500 m	740 ~ 800 m

Fig. 16 (a and b) shows the variation in abundance of elements at the three different depths of each zone. The percentages of elements plotted are recalculated ones excluding H_2O^+ , H_2O^- , CO_2 , SO_3 and S (Table 12).

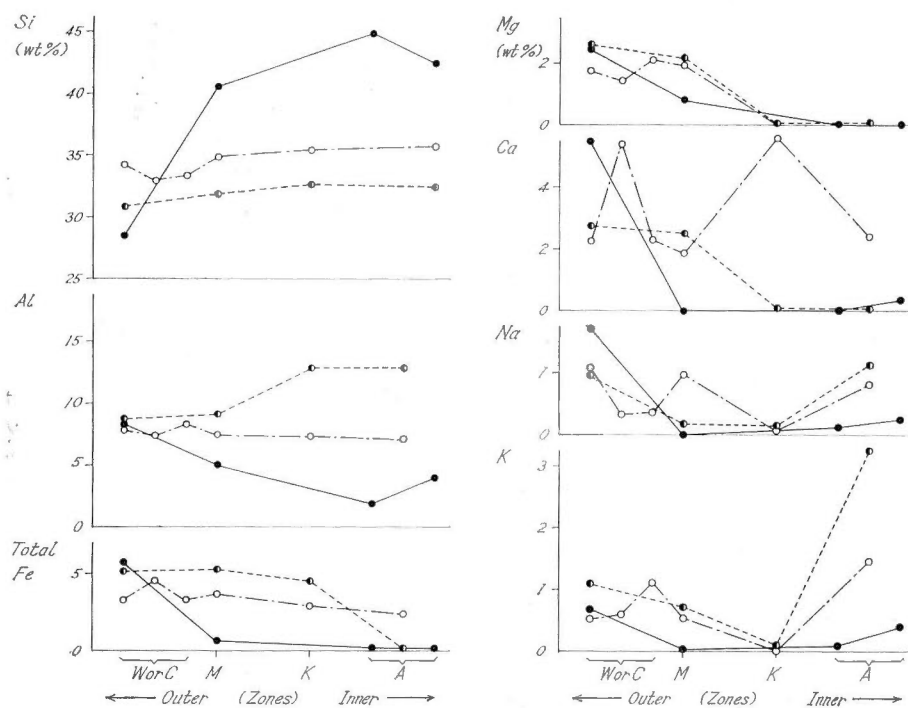


Fig. 16 a. Variation in abundance of elements in alteration zones. Abbreviations of this table correspond to those of Fig. 8. Solid circle: Abundance at "shallow part", Semi-solid circle: "Intermediate part", Open circle: "Deep part" (see Chapter IX).

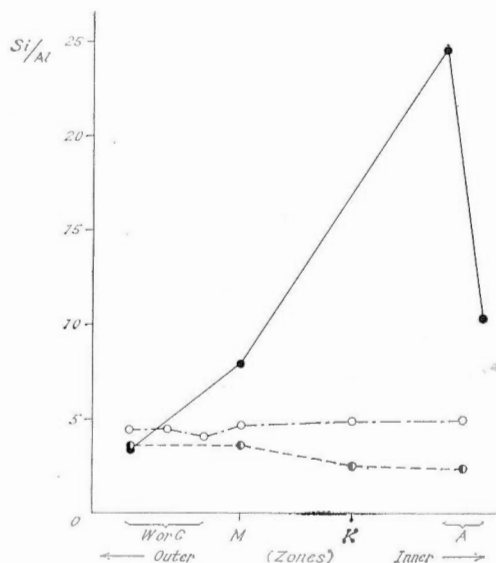


Fig. 16 b. Variation in relative abundance of silicon to aluminium in alteration zones. Abbreviations and symbols of this table correspond to those of Fig. 16 a.

Fig. 16 (a and b) indicates the fact :

- 1) The trend of variation is generally similar to different depths.
- 2) The rate of variation in the shallow part is generally larger than in the deep part.

Among the elements, these two phenomena are exaggerated for silicon and aluminium in the shallow part. The leaching of aluminium and the concentration of silicon increase gradually from saponite zone to alunite zone. At the deep part, the quantities of silicon and aluminium are kept nearly constant throughout different zones.

MASON (1952) reported that, under acid condition, alumina is migrated into solution and silica is left in mother rocks.

As the result of his study in Kosaka mine, IWAO (1954) reported a zonal arrangement of alteration. That is : Fresh rock \rightarrow transitional zone \rightarrow clayey zone \rightarrow weakly silicified zone \rightarrow moderately silicified zone \rightarrow compact silicified zone \rightarrow porous silicified zone, from outer to inner part. He interpreted that the variation of relative abundance of alumina and silica is due to their solubility as a function of pH value.

In the Matsukawa area, the variation of relative abundance of silicon and aluminium is interpreted by MASON's and IWAO's hypotheses in the shallow part at least. In the deep part, however, it cannot be interpreted only by pH condition.

Supposing that the concentration of silicon is affected only by pH condition, the rocks of an altered zone classified by pH condition may show the constant degree of concentration of silicon. This assumption does not correspond with the phenomena of this area described above. Therefore, it must be pointed out that other factors independent of pH value do exist.

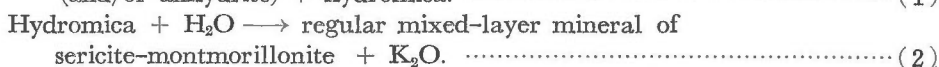
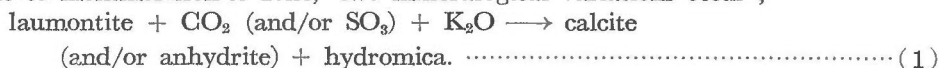
Here, the writer proposes a factor, "discharge of solution" circulating within altered mass, as one of the important factors which affect the leaching and concentration of elements. The discharge of solution affects the quantities of components dissolved and migrated in the solution, e. g. aluminium in acid solution.

The difference in quantities of migrated components between the shallower part and deeper part is probably due to the difference in the discharge of solution between them. The difference of the discharge may be caused by the lateral inflow of solution, as groundwater, from outside into altered mass.

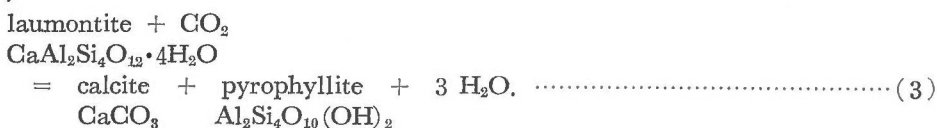
X. Destruction of Zeolite and Formation of Mixed-Layer Minerals

As mentioned in the former sections, III. 2 and V. 2, the assemblage, chlorite—laumontite—hydromica, is characteristic in the chlorite zone (sect. V. 2, sample ; BR2-470 m). On the other hand, in the montmorillonite zone the assemblage, montmorillonite—calcite—regular mixed-layer mineral of sericite-montmorillonite, is commonly found in the sample (BR 2-530 m). Near a boundary between the chlorite zone and montmorillonite zone, some noticeable mineralogical changes are observed. For example, in the handspecimens (BR 2-435 m), laumontite, which has replaced plagioclase, is partly changed into the aggregate of anhydrite and hydromica. Besides, laumontite from the sample (BR 2-500 m) is perfectly changed into calcite with mixed-layer mineral of sericite-montmorillonite.

From these facts, it is presumed that with advance of alteration from chlorite zone to montmorillonite zone, two mineralogical variations occur ;



ZEN (1961 b, p. 402) gives the ideal formula for the destruction of laumontite, thus,



He discusses that the chemical potential of carbon dioxide is most effective on the equilibrium of the equation (3). Therefore, it is suggested that the equation (1) also must be considered from the thermodynamical point of view. The studies from this point is being made.

Sixteen mineral assemblages can be reckoned in the rocks at the transitional part between the chlorite zone and montmorillonite zone. The assemblages and their frequency (in percent) of occurrence are given in Table 14.

Among the assemblages, those on the right hand side of equation (1) combined with those of the left hand side of equation (2), are the most frequent. Meanwhile, those on the left hand side of equation (1) combined with those of the right hand side of equation (2), are scanty. Consequently, it may be concluded that the reaction rate of equation (1) is larger than that of equation (2).

Table 14. Frequency of occurrence for assemblage of calcium-minerals and clay minerals, in the chlorite and montmorillonite zones.

Calcium-minerals in equation (1)	Laumontite	Laumontite + calcite	Laumontite (clouded) + calcite	Calcite
Clay minerals in equation (2)				
Mixed-layer mineral of sericite-mont. (regular type)	0	0	0	8
Mixed-layer mineral of sericite-mont. (random type)	4	4	0	8
Hydromica + mixed-layer mineral of sericite-mont.	0	4	20	4
Hydromica	4	12	25	4

(%)

Note: The frequency (%) is estimated from both microscopic and X-ray observations of twenty four specimens.

XI. Comparison of the Alteration of Matsukawa Area with That of Wairakei

The results of several investigations for alteration in active thermal areas were reported; the works of Yellowstone National Park (FENNER, 1936), Wairakei (STEINER, 1953, 1955), the Geysers (STEINER, 1958) and Sulphur Bank (WHITE and ROBERSON, 1962) are well known.

Above all, for Wairakei of New Zealand, the most detail profile of altered mass is established according to the data of numerous wells.

STEINER demonstrates the following zones of hydrothermal alteration in Wairakei.

- 1) Surface acid leached zone: The characteristic minerals are kaolinite, alunite and opal. This zone is distributed on the earth's surface horizontally over 5 km at least, and reaches vertically the depth of 132 m.
- 2) Zone of argillization: Rhyolite glass is changed to montmorillonitic clays. Plagioclase crystals are sometimes unaltered but are sometimes replaced by calcite. Vertical range of this zone is 30~50 m in thickness.
- 3) Zone of zeolitization: This underlies the zone of argillization and is subdivided into an upper and a lower zones. In the upper zone, the lime soda zeolite "ptilolite" is characteristic and fills vesicles in pumice. In some cases it is associated with minor heulandite. Plagioclase phenocrysts are unaltered. In the lower zeolite zone, wairakite replaces andesine and also fills veins and cavities. Laumontite is found in a zone between ptilolite and wairakite. This zone reaches 450 m in depth.
- 4) Feldspathization zone: An upper subzone is characterized by albitiza-

tion, and a lower one, by aduralia replacing plagioclase. Secondary sphene is scattered. Calcite is locally precipitated, and the alteration of plagioclase to calcite and albite was observed. The bottom of this zone is 550~790 m in depth.

- 5) Zone of hydromica : In this zone which exists below about 700 m, primary plagioclase is replaced by hydromica, as the result of leaching of alkalis by carbon dioxide solution.

The alteration zones of Wairakei and those of the Matsukawa area are correlated as follows, based on their constituent minerals.

(Wairakei)	(Matsukawa)
Surface acid leaching zone	{ Alunite zone Kaolin zone
Zone of argillization	Montmorillonite zone
Zone of zeolitization	Chlorite zone
Feldspathization zone	?
Zone of hydromica	?

The differences in the features of alteration between Wairakei and Matsukawa are noticed.

- 1) The pattern of the distribution of hydrothermal zoning.

The altered mass in Wairakei is horizontally elongated as a whole. According to STEINER, it shows that the hydrothermal fluid spreads evenly, both vertically and laterally through the rocks.

In Matsukawa, on the contrary, it is strikingly vertically elongated, and kaolin zone and alunite zone formed by acid solution penetrate to the depth

Table 15. Size of acid altered mass.

	l(m)	d(m)	d/l
Upper Basin, Yellowstone Park (FENNER, 1936)	?	0	0
Wairakei (STEINER, 1953)	>5,000	90	<0.018
Sulphur Bank (WHITE, 1962)	300	15	0.05
Nishiazuma mine (MUKAIYAMA, 1958)	1,000	200	0.20
Matsukawa	500	>900	>1.80

l : Horizontal size
d : Depth

of 900 m from restored surface at the time of main fumarolic activity (SUMI, 1966). This shows that the pass of hydrothermal fluid was confined to vertical, narrow channels.

- 2) Formation and destruction of zeolite.

According to STEINER, in Wairakei the ascending hydrothermal solution containing excess of soda and lime, deposits zeolite (ptilolite). After the deposition of zeolite, the composition of the ascending solution is changed into the alkaline

solution with excess of magnesia. The solution ascends farther through the fissures, and at higher level it meets the surface water percolating downward. Thus, pore solution resulting from the interaction of the ascending volatiles and the descending surface water effects the argillic alteration.

On the other hand, the formation of zeolite at Matsukawa is older than that of montmorillonite as mentioned in the former chapter. The zeolite is converted at present into aggregates of calcite (and/or anhydrite) and mixed-layer of sericite-montmorillonite. This change may be due to the effect of solution migrated from inside montmorillonite zone to outside chlorite zone.

XII. Summary

The present investigation is summarized as follows :

1) A zeolite and eight clay minerals are identified precisely in hydrothermally altered rocks of the Matsukawa area. They are laumontite, saponite, chlorite, hydromica, montmorillonite, kaolin, pyrophyllite, mixed-layer mineral of montmorillonite-chlorite and mixed-layer mineral of sericite-montmorillonite.

2) Six zones of progressive alteration can be distinguished on the basis of the mineralogical criteria for the zeolite and clay minerals. They are saponite zone, chlorite zone, montmorillonite zone, kaolin zone, alunite zone and pyrophyllite zone. Four zones of them are arranged, from margin to center, as saponite zone (or chlorite zone), montmorillonite zone, kaolin zone, and alunite zone. Such a zonal arrangement is probably formed by the increasing of pH value from center to margin. The pyrophyllite zone only is formed under higher temperature than other five zones.

3) Three dimensional sections of six zones are obtained from the data of core drillings. The sections are characterized by deep-penetrating acid altered zones, compared with that in Wariakei or the other geothermal areas. The pass of solution which formed the hydrothermal aureole in this area might have been confined to vertical narrow channels.

4) Laumontite in chlorite zone is now converted into the aggregate of calcite and mixed-layer minerals with advancing alteration from chlorite zone to montmorillonite zone. The mixed-layer minerals change gradually from hydromica in the chlorite zone to 1 : 1 regular mixed-layer mineral in the montmorillonite zone.

5) Silicon (quartz mineralogically) is concentrated in kaolin and alunite zones as the result of leaching of aluminium under the acid condition. The rate of concentration is generally higher in the shallower part than in the deeper part. Such a difference in quantities of migrated elements is interpreted by difference in discharge of solution circulating within the altered mass.

6) The above features indicate that the hydrothermal alteration of the deeper part in Matsukawa took place with lower discharge of acid solution than that of Wairakei and other areas.

XIII. Acknowledgements

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References

- ALTHAUS, E. (1966) : Der Stabilitätsbereich der Pyrophyllite unter dem Einfluss von Säuren. 1. Mitteilung : Experimentelle Untersuchungen. *Contribution Mineral. Petrol.*, vol. 13, p. 31~50.
- American Society for Testing Materials (1965) : X-ray powder data file (A. S. T. M. card).
- COOMBS, D. S. (1952) : Cell size, optical properties and chemical composition of laumontite and leonhardite. With a note on regional occurrence in New Zealand. *Am. Mineralogist*, vol. 37, p. 812~820.
- COOMBS, D. S. (1954) : The nature and alteration of some Triassic sediments from Southland, New Zealand, *New Zealand Royal Soc. Trans.*, vol. 82, p. 65~109.
- COOMBS, D. S., EILLS, A. J., FYFE, W. S. & TAYLOR, A. M. (1959) : The zeolite facies ; with comments on the interpretation of hydrothermal syntheses, *Geochim. et Cosmochim. Acta*, vol. 17, p. 53~107.
- COOMBS, D. S. (1961) : Some recent work on the lower grades of metamorphism, *Australian Jour. Sci.* vol. 24, p. 203~215.
- EARLEY, J. W., BRINDLEY, G. W., McVEAGH, W. J., & VANDEN HEUVEL, R. C. (1956) : "Montmorillonite-chlorite", *Am. Mineralogist*, vol. 41, p. 258~267.
- FENNER, C. N. (1936) : Bore-hole investigation in Yellowstone Park, *Jour. Geology*, vol. 44, p. 225~315.
- IWAO, S., KISHIMOTO, F. & TAKAHASHI, K. (1954) : Wall rock alteration of the Kosaka mine, Akita prefecture, Japan, *Geol. Survey Japan Rept.*, no. 162, p. 1~31.
- IWAO, S. (1958) : Some aspects on hydrothermal alteration with special reference to the occurrence of clay minerals in Japan, *Tokyo Univ. General Education Sci. Papers*, vol. 8, p. 93~113.
- IWAO, S. (1962) : Silica and alunite deposits of the Ugusu mine ; a geochemical consideration on an extinct geothermal area in Japan, *Japan. Jour. Geol. Geogr.*, vol. 33, p. 131~144.
- KAWANO, Y. & UEMURA, F. (1964) : "Hachimantai" quadrangle in the geological map of Japan (scale 1/50,000). *Geol. Survey Japan (in Japanese)*.
- KITTRICK, J. A. (1960) : Cholesterol as a standard in the X-ray diffraction of clay minerals, *Soil Sci. Soc. America Proc.*, vol. 24, p. 17~20.
- LEONARD, R. J. (1927) : The hydrothermal alteration of certain silicate minerals, *Econ. Geology*, vol. 22, p. 18~43.
- MAG EWAN, D. M. C., RUIZ AMIL, A. & BROWN, G. (1961) : Interstratified minerals, in the X-ray identification and crystal structures of clay mineral (edited by BROWN, G.), *Mineralogical Soc. London*, p. 393~445.
- MASON, B. H. (1952) : *Principles of geochemistry*, John Wiley & Sons, New York.
- MUKAIYAMA, H. (1958) : Problems on the "bottoming" of sulphur deposits, *Mining Geol.*, vol. 8, p. 75~81 (in Japanese).
- NAKAMURA, H. & SUMI, K. (1961) : Geothermal investigations of Matsukawa hot spring area, Iwate prefecture, *Geol. Survey Japan Bull.*, vol. 12, p. 73~84 (in Japanese).
- NOLL, W. (1936) : Synthese von Montmorilloniten, *Chemie der Erde* vol. 10, p. 129~154.

- OINUMA, K. & KOBAYASHI, K. (1960) : Clay mineralogical study on coal-bearing formations of Ishikari coal field, Hokkaido, *Advances in Clay Science* (2), p. 165~177, Clay Research Group of Japan (in Japanese).
- ROY, R. & OSBORN, E. F. (1954) : The system $Al_2O_3-SiO_2-H_2O$, *Am. Mineralogist*, vol. 39, p. 853~885.
- ROY, D. M. & ROY, R. (1955) : Synthesis and stability of minerals in the system $MgO-Al_2O_3-SiO_2-H_2O$, *Am. Mineralogist*, vol. 40, p. 147~178.
- SCHOEN, R. & WHITE, D. E. (1965) : Hydrothermal alteration in GS-3 and GS-4 drill holes, Main Terrace, Steamboat Springs, Nevada *Econ. Geology*, vol. 60, p. 1411~1421.
- SEKI, Y. (1965) : Behavior of carbon-dioxide in low-grade regional metamorphism, *Japan Assoc. Min. Pet. Econ. Jour.*, vol. 54, p. 1~13 (in Japanese).
- SEKI, Y. (1966) : Wairakite in Japan, (I), *Japan, Assoc. Min. Pet. Econ. Jour.*, vol. 55, p. 254~261.
- STEINER, A. (1953) : Hydrothermal rock alteration at Wairakei, New Zealand, *Econ. Geology*, vol. 48, p. 1~13.
- STEINER, A. (1955) : Hydrothermal rock alteration. New Zealand, *Dep. Sci. Industr. Res. Bull.*, 177, p. 21~26.
- SUDO, T. (1958) : "Nendo-Kōbutsu" (Clay minerals), Iwanami-Shoten, Tokyo (in Japanese).
- SUDO, T. (1959) : Mineralogical study on clays of Japan, Maruzen Co., Ltd., Tokyo.
- SUMI, K. (1966) : Hydrothermal rock alteration of Matsukawa geothermal area, Iwate prefecture, *Mining Geol.*, vol. 16, p. 261~271 (in Japanese).
- TAKAHASHI, I. (1959) : Studies on the sulphur and iron-sulphides deposits of the Matsuo mine (3) : On the saponitized andesite, *Mining Geol.*, 9, p. 1~6 (in Japanese).
- TAKEUCHI, T. TAKAHASHI, I. & ABE, H. (1966) : Wall-rock alteration and genesis of sulphur and iron sulphide deposits in northern Japan, *Tohoku Univ. Sci. Repts.*, ser. 3, vol. 9, p. 381~483.
- WHITE, D. E. & ROBERSON, C. E. (1962) : Sulphur Bank, California, a major hot-spring quick-silver deposit. *Geol., Soc. America Bull.*, Buddington vol. p. 397~428.
- YODER, H. S. & EUGSTER, H. P. (1955) : Synthetic and natural muscovites, *Geochim. et Cosmochim. Acta*, vol. 8, p. 225~280.
- YOSHIMURA, S. (1961) : Zeolites in the Miocene pyroclastic rocks in the Oshima-Fukushima district, southwestern Hokkaido, *Geol. Soc. Japan Jour.*, vol. 72, p. 578~583 (in Japanese).
- YOSHIMURA, S. (1964) : Zeolites in the green tuff formation, *Miner. Soc. Japan Jour.*, vol. 7, p. 45~50 (in Japanese).
- ZEN, E-AN (1959) : Clay mineral-carbonate relations in sedimentary rocks, *Am. Jour. Sci.*, vol. 257, p. 29~43.
- ZEN, E-AN (1961_a) : Mineralogy and petrology of the system $Al_2O_3-SiO_2-H_2O$ in some pyrophyllite deposits of North Carolina, *Am. Mineralogist*, vol. 46, p. 52~66.
- ZEN, E-AN (1961_b) : The zeolite facies : An interpretation. *Am. Jour. Sci.*, vol. 259, p. 401~409.

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松川地熱地における岩石の熱水変質

角 清 愛

要 旨

岩手県松川地域において、近年地熱発電の研究・開発のために多くの試錐が行なわれた。筆者は1960年から1966年にわたって、この地域の変質作用の研究に従事し、その際、地表および試錐で得られた試料の変質鉱物を同定し、その組合せに基づいて変質帯の、地表および地下における立体的な分帯を行ない、その累帯配列を明らかにした。研究は地表から深度600mまでの範囲について行なつた。その範囲における変質岩の原岩は、輝石安山岩・安山岩熔結凝灰岩および石英安山岩熔結凝灰岩の3種類である。

松川地域の熱水変質帯は、変質鉱物の種類および組合せに基づいて6帯に分けられる。それらはサポーナイト帯（または緑泥石帯）・モンモリロナイト帯・カオリン帯および明ばん石帯であり、周縁から中心に向つて上記の順に累帯配列している。一方この系列とは別にパイロフィライト帯が上記の累帯配列に重なつて分布している。各帯相互の境界は、帯の名称となつた鉱物が出現、消失する線を基準にして定めた。他の諸鉱物は、帯のちがいでだけでなく、同一帯内でも深さのちがいでよつて、その種類および量が変化するので、分帯の基準とし得ない。すでに報告された多くの合成実験の結果からみて、サポーナイト帯からモンモリロナイト帯・カオリン帯を経て明ばん石帯に至る一連の累帯配列は、pH 値の低下に基づくものであり、またパイロフィライト帯はこれらの帯より高温の条件下で生成したものであることは明らかである。本地域のパイロフィライト帯と緑泥石帯とは、パイロフィライト帯の現在の地温分布が、パイロフィライトの生成に必要な温度に達していないこと、緑泥石帯の構成鉱物が現在は崩壊しつつあることなどの現象から判断して、他の諸帯よりやや古い時期に生成したものとみなされる。

変質鉱物として、1種類の沸石、8種類の粘土鉱物および9種類のその他の鉱物を正確に同定した。沸石は濁沸石である。粘土鉱物は、サポーナイト・緑泥石・加水雲母・モンモリロナイト・カオリン・パイロフィライト・モンモリロナイト-緑泥石混合層鉱物および絹雲母-モンモリロナイト混合層鉱物である。またその他の鉱物は、明ばん石・硬石膏・石膏・方解石・ルチル・黄鉄鉱・ダイアスポア・紅柱石およびズニアイトである。加水雲母はX線回折図において、 10 \AA から低角度側へ強度を漸次低下する帯状反射だけでなく、比較的鋭い 11 \AA 反射をしばしば伴う。この 11 \AA の反射は絹雲母-モンモリロナイト混合層鉱物の不規則なものか、あるいは混合比が1:1でないものが含まれていることに由来するのであろう。絹雲母-モンモリロナイト混合層鉱物のうちには両者1:1の規則的混合層以外に、 25 \AA 反射が現われず、 12.5 \AA 反射がややブロード (broad) な不規則混合層も存在する。

各帯の代表的な岩石18コの化学分析を行なつた。この結果によれば、松川では、浅所ではカオリン帯・明ばん石帯で代表される酸性変質帯に珪素の濃集が起つている。しかし深所では濃集は起つておらず、珪素・アルミニウム相対比は、緑泥石帯・モンモリロナイト帯・カオリン帯および明ばん石帯を通じて、ほとんど一定に保たれている。pH 条件に基づいた変質分帯で、酸性変質帯に珪素が濃集する現象は、酸性条件下でアルミニウムが溶脱され、結果的に珪素が濃集するものであろう。しかし上にのべた松川の現象は単に pH 条件だけでは説明することが出来ない。筆者はそれに対して変質帯

中の循環溶液の流量の大きさを一つの要因として提案した。いわゆる溶脱作用は、元素の、(1) 鉱物から溶液への移動と、(2) 反応系の内側から系外への移動との2つの過程から成り立っており、溶液の流量は(2)の過程に対して大きな役割を果たすにちがいない。深度の差による流量のちがいは地下水の動きなどによつて十分に生じうることである。ここでは代表的な例として、珪素とアルミニウムについて述べたが、元素の移動が深所において少ないという現象は、他のみられるすべての元素についても認めることができる。

緑泥石帯とモンモリロナイト帯との境界部では、濁沸石は、方解石(または硬石膏)と絹雲母-モンモリロナイト混合層鉱物との集合体に変化しつつある。この混合層鉱物は、緑泥石帯に近い所では11Åの反射をもつ加水雲母であるが、モンモリロナイト帯に近づくにしたがつて、12.5Åの反射を持つが25Åの反射を持たない混合層となり、ついに25Åの鋭い反射をもつ1:1の規則的混合層鉱物に移りかわる。言いかえれば、緑泥石帯からモンモリロナイト帯に向つて混合層鉱物の規則性が增大している。また鉱物組合せの現出ひん度から判断すると、加水雲母から規則的混合層鉱物への変化の速度は、濁沸石の崩壊速度より小さい。

活地熱地の中で最もよく研究されたニュージーランドのワイラケイの熱水変質と、松川のそれとを比較してみると、構成鉱物はたがいによく類似し、アルカリ性変質帯から酸性変質帯まで分布している。しかし二つの点で相違がある。第1の相違は変質帯の断面の形状についてである。酸性変質帯についてみれば、ワイラケイでは深さ90m・横5,000m以上、松川では深さ900m・横500mである。また深さと水平巾との比をとれば、松川ではワイラケイの100倍になつていて、両変質帯の形状の差が著しい。第2の相違は、沸石形成の問題である。ワイラケイでは現在でも沸石が生成しつつある(ただし浅部では上昇熱水液の化学的性質の変化によつてモンモリロナイトが生成しつつある)。一方松川では沸石形成の時期は過ぎ去り、それは現在は方解石(または硬石膏)と混合層鉱物とに分解しつつある。

PLATES
AND
EXPLANATIONS

(with 6 plates)

Figs. 1~4 : Electron micrographs, $\times 12,000$

Fig. 5 : Microphotograph, crossed nicols, $\times 20$

Figs. 6~9 : Microphotograph, crossed nicols, $\times 50$

Figs. 10~12 : Microphotograph, open nicols, $\times 50$

A : Alunite Ad : Andalusite Ag : Augite

Ah : Anhydrite C : Calcite D : Diaspore

Hp : Hypersthene L : Laumontite M : Montmorillonite

Mx : Mixed-layer mineral of sericite-montmorillonite

P : Pyrophyllite Pl : Plagioclase Pt : Pyrite

Q : Quartz Sp : Saponite Z : Zunyite

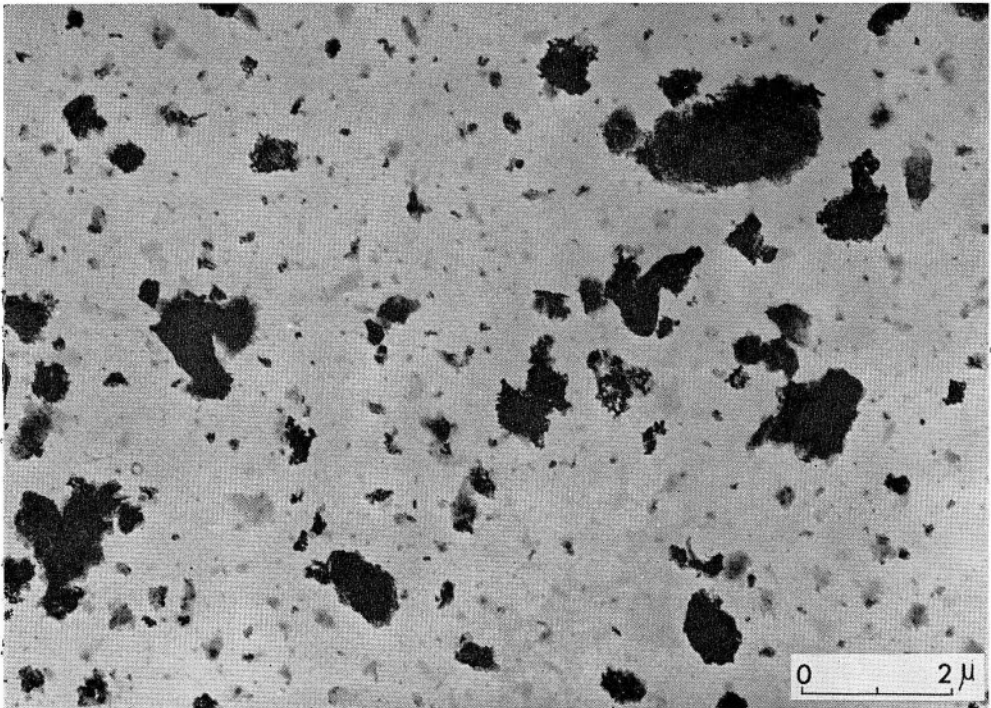


Fig. 1. Montmorillonite separated from montmorillonite-quartz clay (HF89).

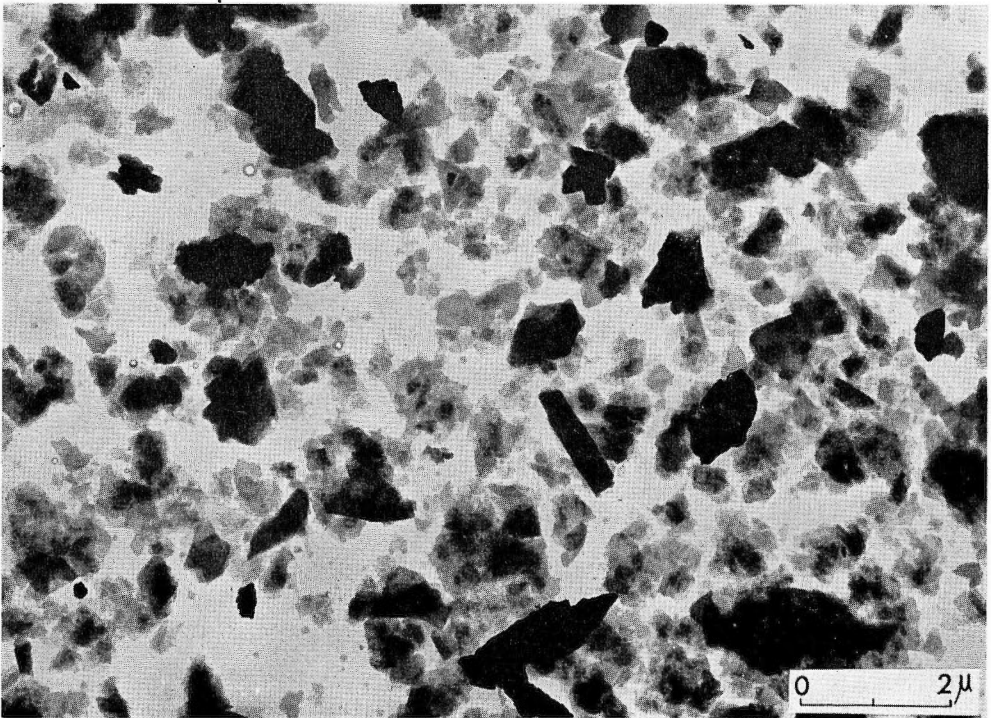


Fig. 2. Mixed-layer mineral of sericite-montmorillonite separated from anhydrite-calcite-chlorite rock (BR2-500m).

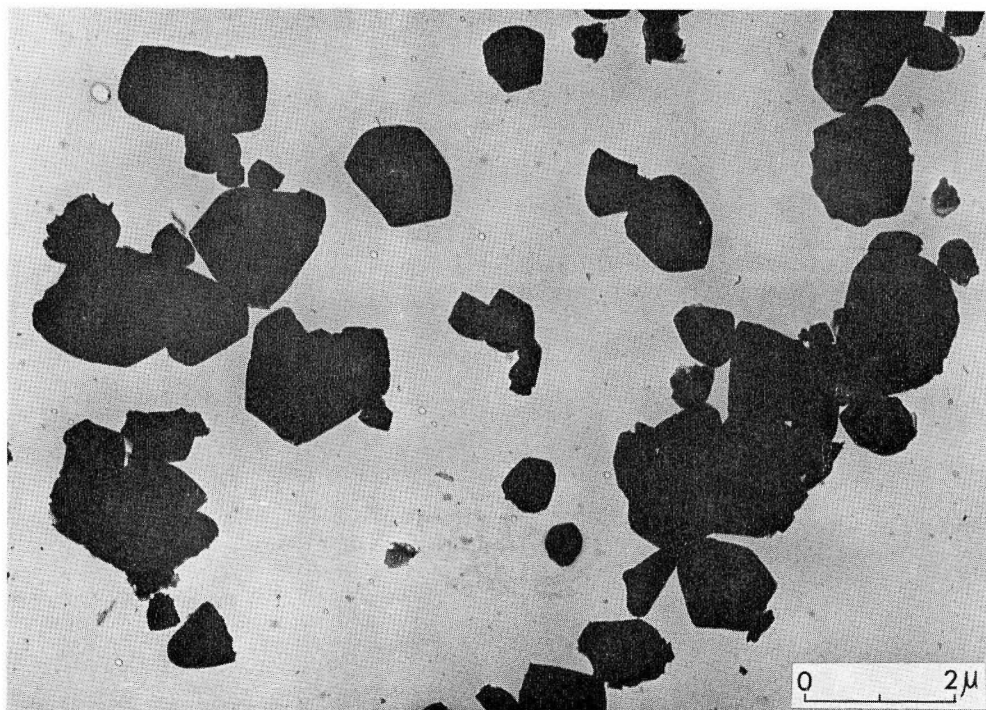


Fig. 3. Kaolin separated from kaolin-quartz clay (Cl-9).

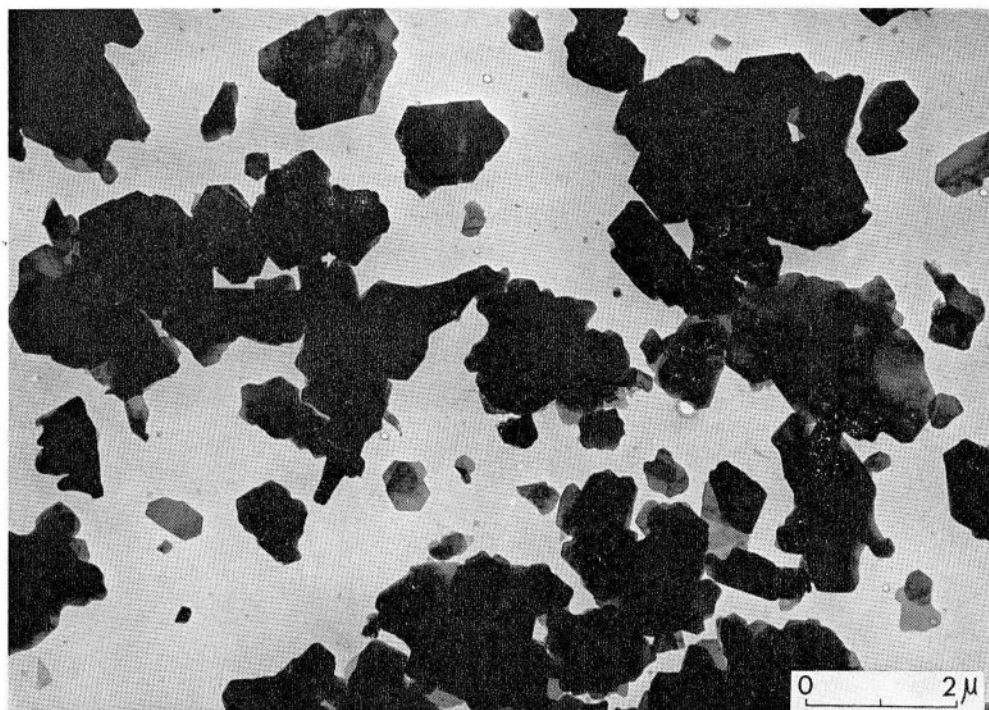


Fig. 4. Pyrophyllite separated from diaspore-zunyite-pyrophyllite rock (Cl-13).

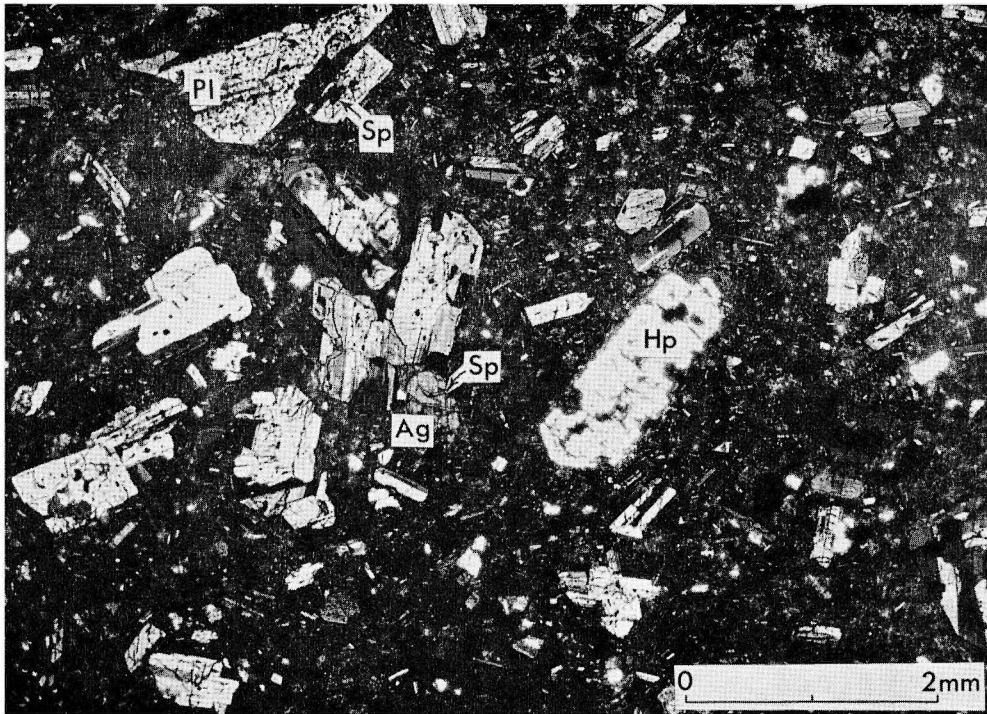


Fig. 5. Weakly altered andesite (HF 8).

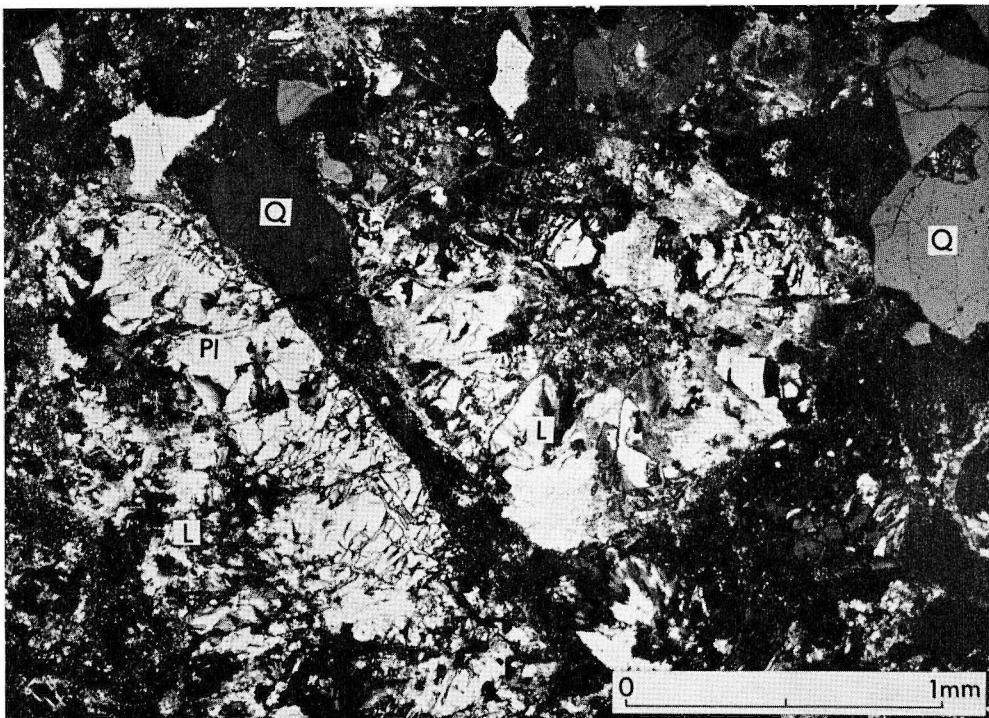


Fig. 6. Chlorite-laumontite rock (BR2-470m).

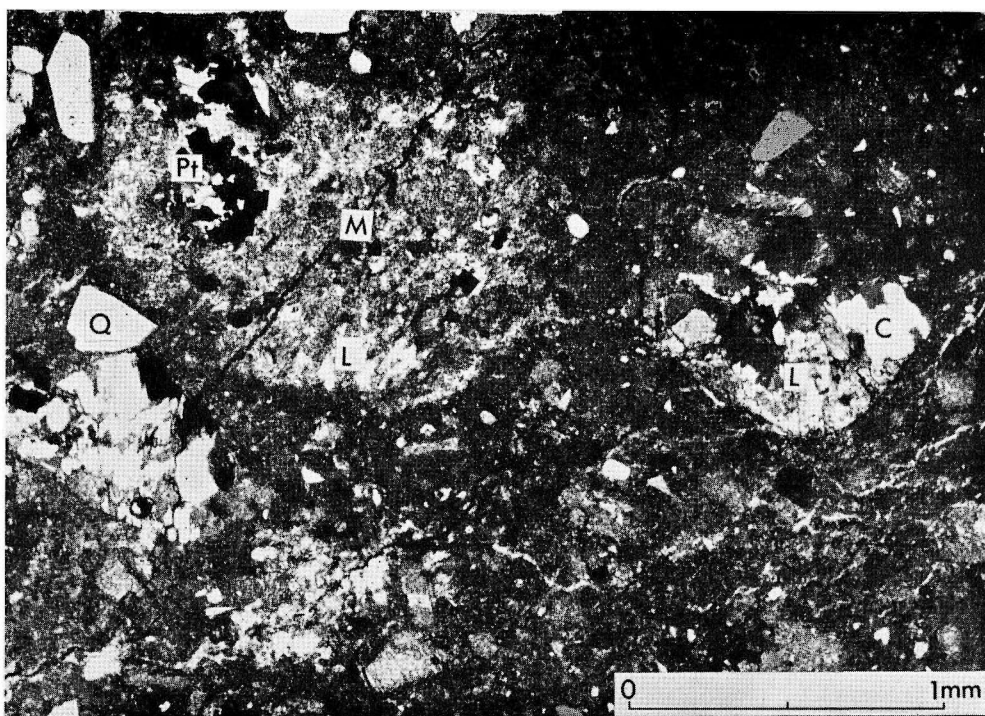


Fig. 7. Chlorite-montmorillonite-calcite rock (BR2-425m).

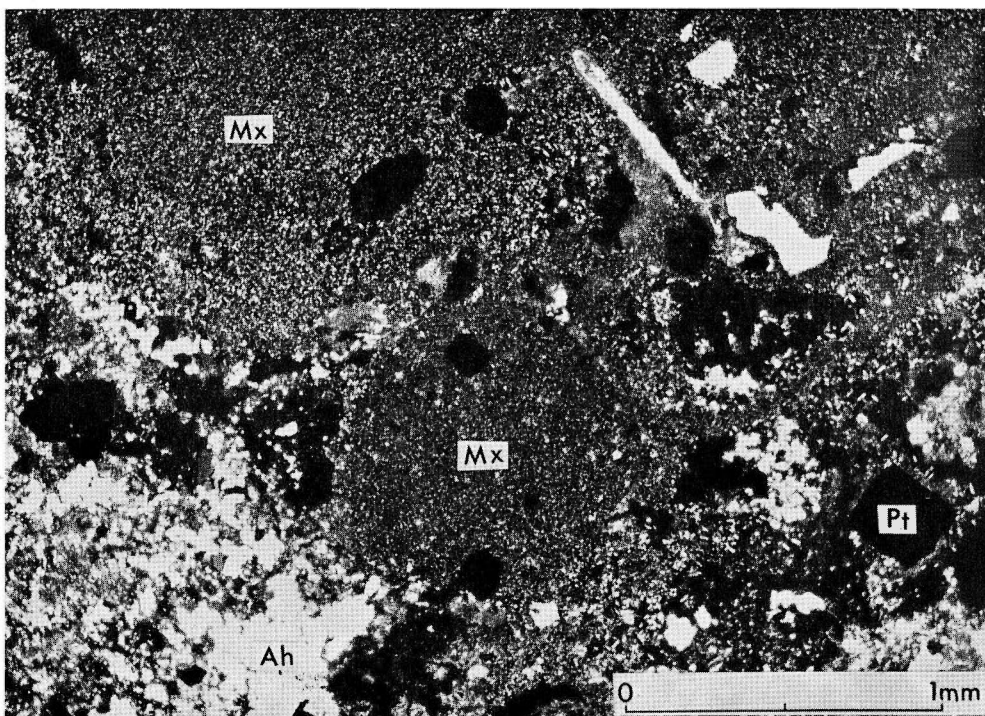


Fig. 8. Anhydrite-calcite-chlorite rock (BR2-500m).

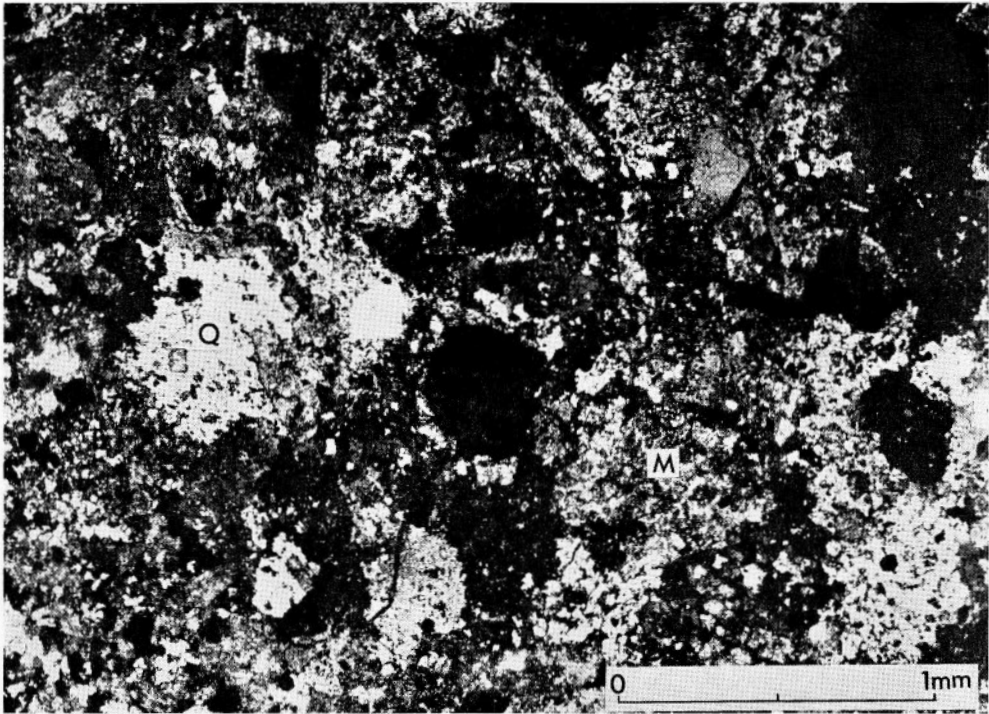


Fig. 9. Calcite-quartz-montmorillonite rock (T3-313m.)

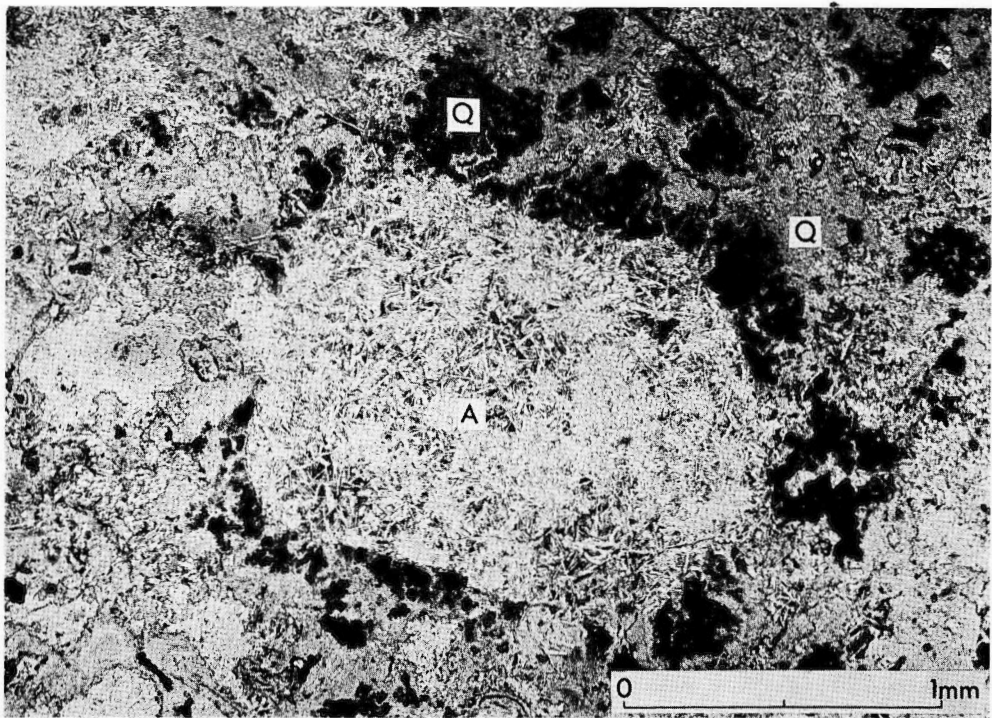


Fig. 10. Quartz-alunite rock (T7-167m).

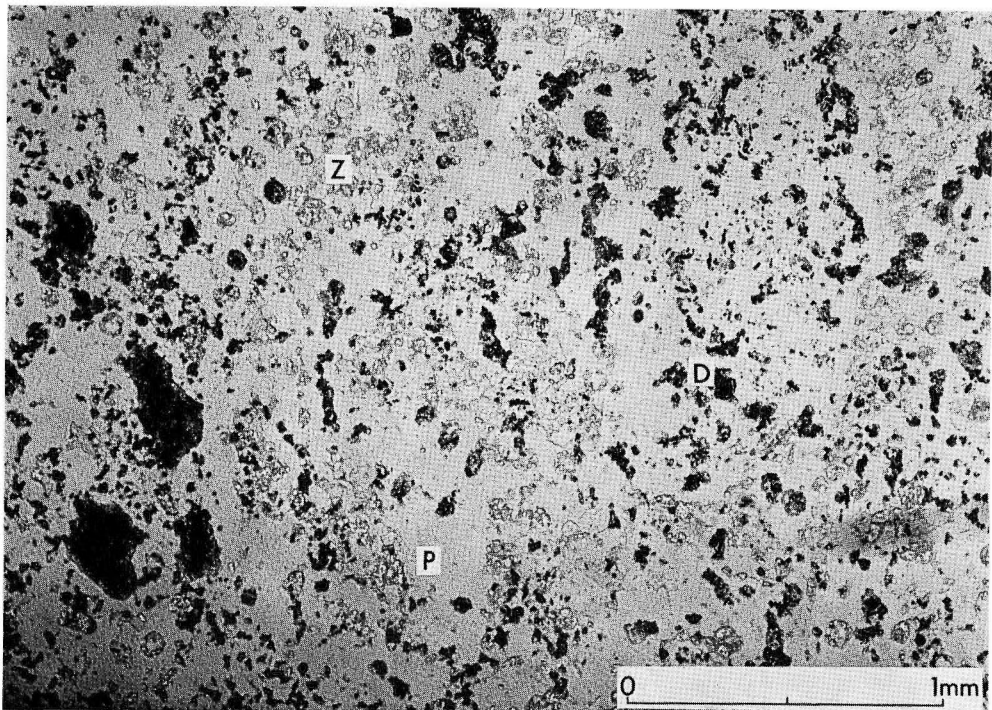


Fig. 11. Diaspore-zunyite-pyrophyllite rock (Cl-13).

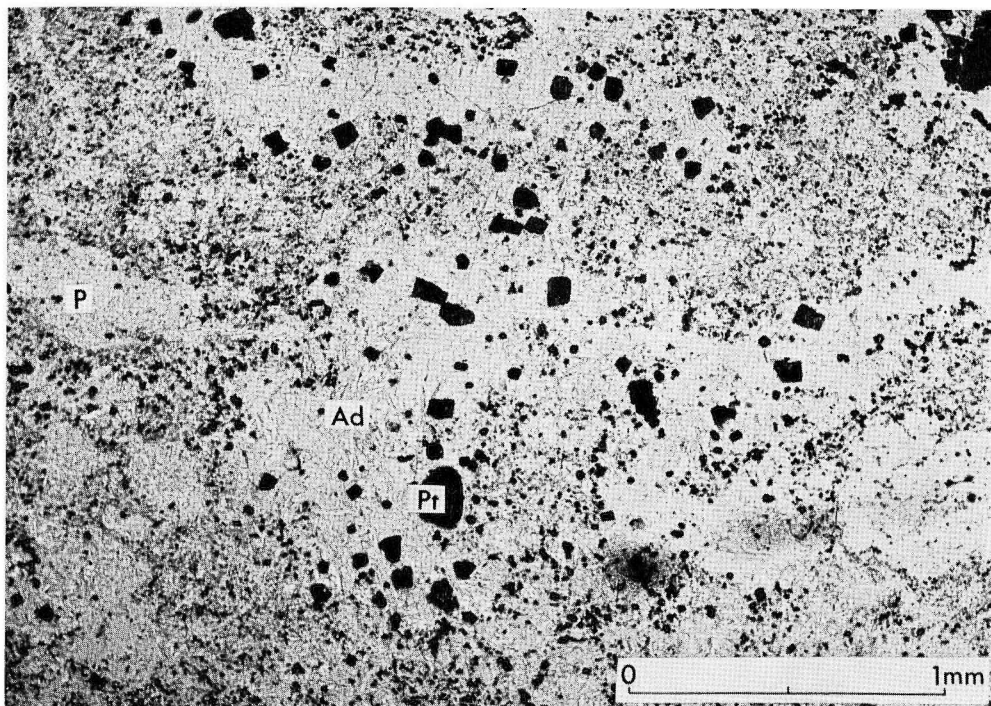


Fig. 12. Andalusite-pyrophyllite-quartz rock (T7-24m).

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 - a. 地質
 - b. 岩石・鉱物
 - c. 古生物
 - d. 火山・温泉
 - e. 地球物理
 - f. 地球化学
- B. 応用地質に関するもの
 - a. 鉱床
 - b. 石炭
 - c. 石油・天然ガス
 - d. 地下水
 - e. 農林地質・土木地質
 - f. 物理探鉱・化学探鉱および試錐
- C. その他
- D. 事業報告

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 - f. Geochemistry
- B. Applied geology
 - a. Ore deposits
 - b. Coal
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地質調査所報告

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SUMI, K.

**Hydrothermal Rock Alteration of the Matsukawa Geothermal
Area, Northeast Japan**

Kiyoshi SUMI

地質調査所報告, No. 225, p. 1~44, 1968

19 illus., 6 pl., 17 tab.

In the Matsukawa area, where hydrothermally altered rocks are extensively distributed, three-dimensional sections of the altered aureole were obtained by several core drillings. The altered aureole can be divided into six zones based upon the stability range of minerals. Four zones of them are aligned, from margin to center, as saponite zone (or chlorite zone), montmorillonite zone, kaolin zone and alunite zone. Besides them, pyrophyllite zone is distinguished. The formation of such a zonal arrangement is considered to be controlled by the increasing of pH value from center to margin. The pyrophyllite zone only is formed under higher temperature than other five zones.

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