

ALTERATION OF BORE-HOLE CORES TO MORDENITE-BEARING ASSEMBLAGES IN ATOSANUPURI ACTIVE GEOTHERMAL AREA, HOKKAIDO, JAPAN

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Introduction

Recently, some interesting papers have described the mineral alteration of cores which came from deep bore-holes at Wairakei, Steamboat Springs, Matsukawa, Odake and Katayama active geothermal areas (STEINER, 1953, 1955; SCHOEN and WHITE 1965; SUMI, 1968; SEKI *et al.* 1969).

During the drilling in these geothermal areas, temperatures at the bore-hole bottoms were usually measured by thermister at intervals of every ten or twenty meters, although it is uncertain whether temperatures thus measured can be equated exactly with the temperatures which previously existed in the undrilled field.

The depth of the rocks from which the described cores came is known from the drilling record. The prevailing rock-pressures at these depths can then be calculated from density data of bore-hole cores.

Steam pressures prevailing at the depths can be roughly estimated from measured well-head pressures.

The chemical characters of the fluid which participated in rock alteration is known from analytical data of gas and water separated from steam which gushed out through drilled holes after the cessation of drilling.

Chemical characters of the original rocks and chemical variation of rocks during the hydrothermal alteration by geothermal fluids can also be determined from study of the chemistry of unaltered and altered rocks.

Petrochemical and mineralogical studies of bore-hole cores in combination with geochemical study of hot-steam and geophysical measurements of rock-pressures and temperatures prevailing at depth in geothermal areas should be called the analysis of "natural syntheses" of polycomponent systems. These studies should provide important quantitative or semi-quantitative information on

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rock-metamorphism.

In this paper, hydrothermal alteration of bore-hole cores at Atosanupuri geothermal area in Hokkaido, Japan, will be described in some detail.

Geological outline of the Atosanupuri district

The geology and petrochemistry of Atosanupuri volcano of Quaternary age have been studied by KATSUI (1958, 1961). Electric Development Co. Ltd. has also carried out some detailed geological investigation of Atosanupuri active geothermal area and its surrounding area. Fig. 1 is a geological map compiled from papers by KATSUI (1958) and HIROSUGI (1967).

The oldest rocks exposed in this area constitute a thick pile of andesitic lava (Column A in Table 1) which is covered by a well-stratified pumice fall of dacitic composition (Column B in Table 1) in the western part of this area.

After the deposition of the dacitic pumice fall, a subsidence of the center of the volcano occurred to form a caldera, the diameter of which is almost 5 km. This was followed by the formation of six lava domes of dacitic composition (Column C in Table 1) inside and outside the caldera.

The above-noted Atosanupuri volcanic rocks are covered in the eastern part of this area by an andesitic pumice fall deposit from nearby Mashu volcano.

Rock alteration

There is a high heat flow area inside of the caldera of Atosanupuri volcano (Fig. 2). The highest temperature attained at a depth of 1.5 m from the land-surface is over 60°C.

Volcanic rocks exposed in this geothermal area have generally been altered to soft milky white or gray siliceous rocks by fumarolic activity. Opaline silica, saponite, pyrite and a small amount of sulphur are the constituent minerals of these altered volcanic rocks. The distribution of the

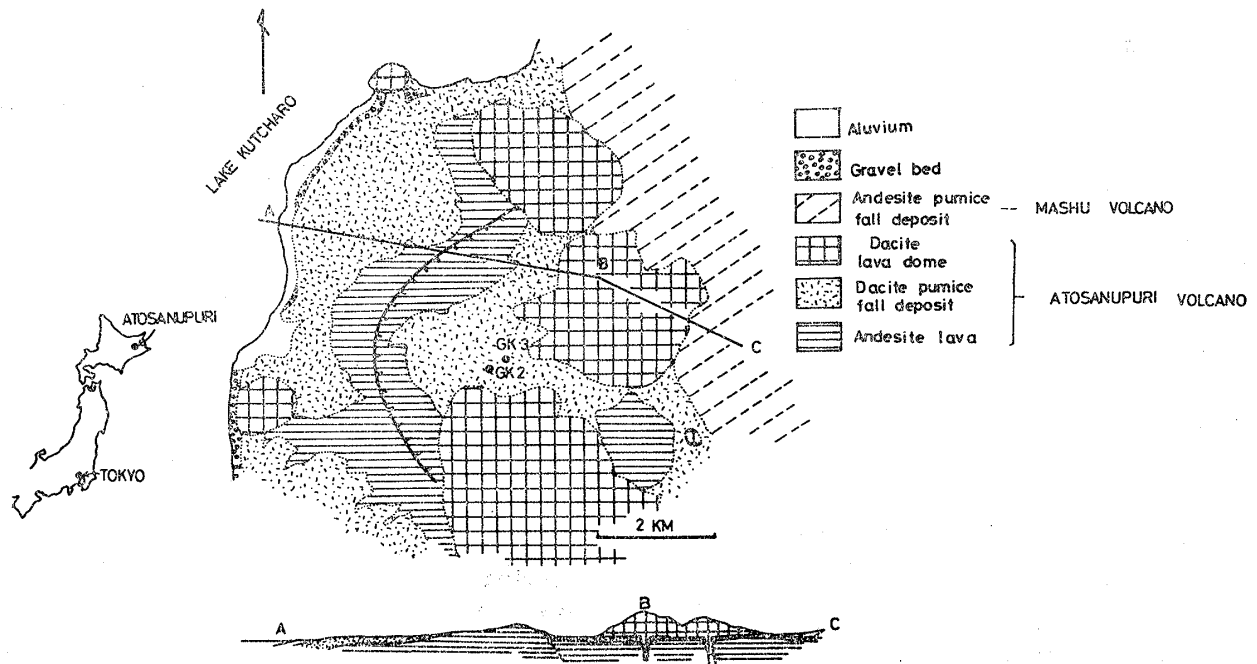


Fig. 1. Geological map of the Atosanupuri volcano (KATSUI, 1958 and HIROSUGI, 1967).

Table 1. Chemical compositions of volcanic rocks of Atosanupuri volcano (KATSUI, 1958, 1961).

	A Augite- hypersthene andesite lava	B Augite- hypersthene dacite pumice	C Augite- hypersthene dacite lava
SiO ₂	64.26	69.81	72.64
TiO ₂	0.91	0.58	0.68
Al ₂ O ₃	14.87	13.23	12.92
Fe ₂ O ₃	2.18	2.07	1.52
FeO	5.03	1.79	1.93
MnO	0.14	0.07	0.07
MgO	1.76	0.94	1.14
CaO	5.49	3.31	2.53
Na ₂ O	3.70	3.79	4.03
K ₂ O	0.83	1.49	1.62
P ₂ O ₅	0.20	0.09	0.04
H ₂ O+	0.25	2.73	0.61
H ₂ O-	0.36	0.33	0.15
Total	99.98	100.23	99.88

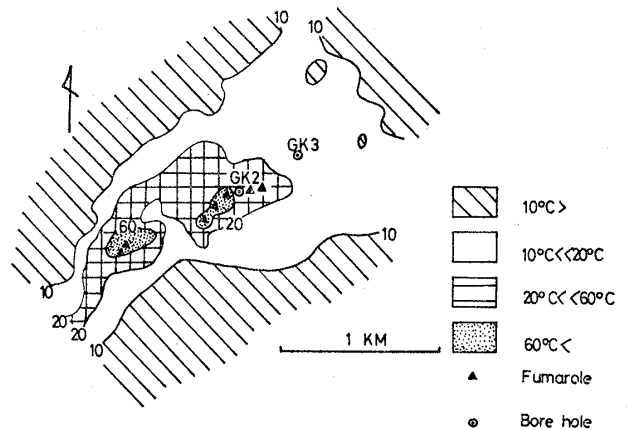


Fig. 2. Thermal map at the depth of 1.5 m below the surface central part of Atosanupuri volcano (see Fig. 1).

fumarolic surface alteration is confined to the area in which the temperature at a depth of 1.5 m is higher than 20°C (Fig. 3).

Recently Electric Development Co. Ltd. has drilled two deep holes GK-2 and GK-3 at the Atosanupuri geothermal area. The pressure and amount of steam issuing from the GK-2 hole are 2.3—2.5 kg/cm and 1.0 ton/hour respectively, but there was no emission of steam from the drill-hole GK-3. The present writer examined the hydrothermal alteration of cores from these two boreholes by thin section-petrographic and by X-ray

powder diffraction techniques.

Cores examined by the present writer are mostly augite-hypersthene andesite lava and agglomerate.

Phenocrysts of augite and hypersthene are generally fresh but are partly replaced by green or brownish green clay minerals (saponite) along their crystal margins or cleavage planes. Plagioclase phenocrysts which usually show distinct zonal structure suffer only slight alteration to mordenite or to sodic plagioclase along their crystal margins.

The groundmass of core volcanic rocks were initially composed chiefly of glass and micro-

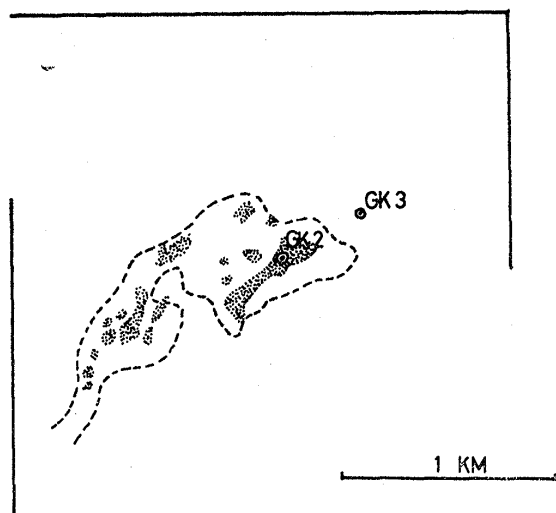


Fig. 3. Distribution of surface alteration (dotted area) in central part of Atosanupuri volcano. A broken line shows the isotherm-line of 20°C at 1.5 m meters depth (see Fig. 2).

crystals of augite, hypersthene, plagioclase and magnetite. The groundmass generally suffered much stronger hydrothermal alteration than phenocrystic minerals. Augite and hypersthene in the groundmass have been replaced almost completely by green or brownish green clay minerals. Glass and plagioclase laths in the groundmass have also altered into mordenite associated with minor amounts of calcite, hematite and clay minerals.

All cores studied by thin sections were also crushed by iron-mortar into powder under 100 mesh (0.18 mm in diameter). The powders were dried after the washing away of fine-particles in water. Then zeolite specimens associated with some amounts of saponite and minor amount of quartz were separated by means of heavy liquid of density = 2.50. Zeolite identified in this study is exclusively mordenite, the most characteristic X-ray diffraction peaks of which are as follows:

$$2\theta = 9.7, 13.4, 19.6, 22.2, 25.5, 26.2 \text{ and } 27.6$$

(in degree $\text{CuK}\alpha$)

Clay minerals generally show dark green or brownish green pleochroism under the microscope and have moderate or high double-refraction. X-ray diffraction data of four samples of clay minerals separated from core specimens (GK-2, 236.5 m, 601.0 m, 735.0 m and GK-3, 208.0 m) exhibit an especially clear shift of the 15 Å diffraction peak to 16–17 Å by the treatment with ethylene glycol. This and the above-noted optical

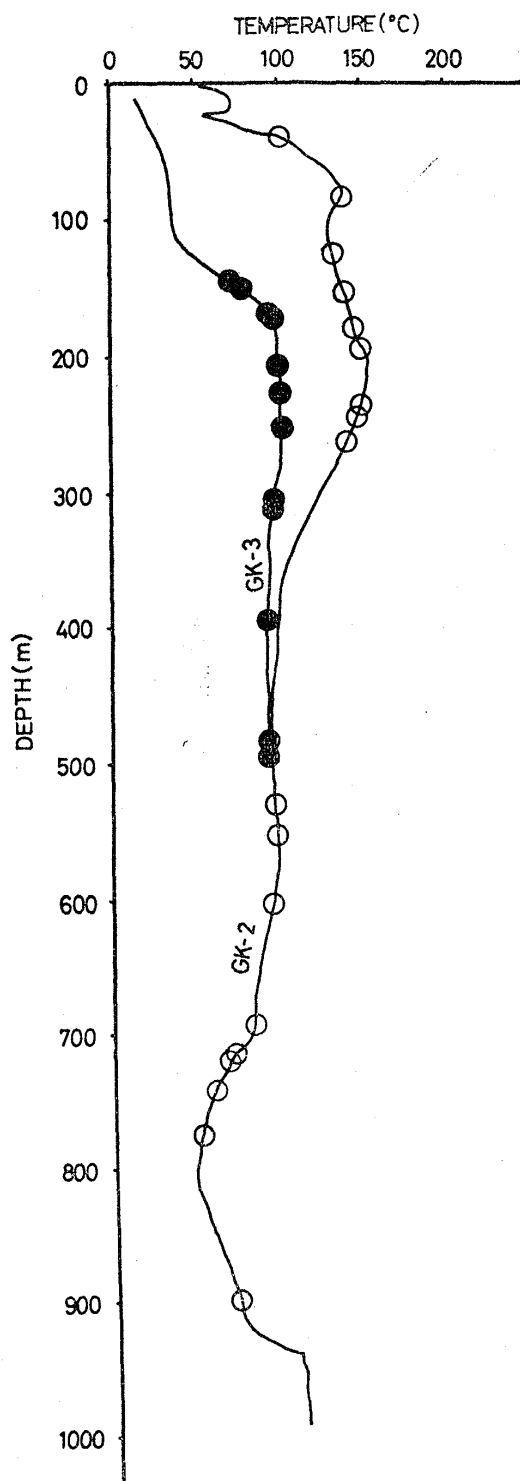


Fig. 4. Geothermal gradients and the distribution of mordenite in deep bore-holes GK-2 and GK-3 drilled in Atosanupuri volcano. Open circles and solid circles show the distributions of mordenite-bearing bore-hole cores in GK-2 and GK-3 respectively.

Table 2. Depths and alteration minerals of cores came from deep-drill holes GK-2 and GK-3 in the Atosanupuri geothermal area.

Depth(m)	Alteration minerals					
	Quartz	Calcite	Clay mineral	Mordenite	Pyrite	Others
GK-2						
39.5	+		+	+		
83.0	+		+	+	+	
125.0	+		+	+	+	
152.5	+		+	+	+	
178.5	+		+	+		
197.0	+		+	+		
236.5	+		+	+	+	Hematite {Epidote Albite
238.0	+	+	+			
249.0	+	+	+	+		Hematite
269.0	+	+	+	+		
305.0	+	+	+	+		
371.0	+		+			
443.0	+	+	+	+		
495.0	+	+	+			
529.0	+		+	+		
552.0	+	+	+	+		
584.0	+	+	+	+		
596.0	+		+			
601.0	+	+	+	+	+	
654.0	+	+	+	+		
691.0	+		+	+		
692.0	+		+	+		
714.0	+	+	+	+		
719.0	+	+	+	+		
735.0	+	+	+	+		
774.0	+		+			
809.0	+	+	+			
822.0	+	+	+			
830.0	+	+	+			{Hematite Albite
840.0	+	+	+			Albite
851.0	+	+	+			Albite
864.0	+	+	+			
895.2	+	+	+	+		Albite
951.2	+	+	+			Anhydrite
GK-3						
105.0	+	+	+			Hematite
146.0	+		+	+		
150.0	+	+	+	+	+	
170.0	+		+	+	+	
172.0	+	+	+	+		
195.0	+		+			
208.0	+		+	+		
226.0	+		+	+		
250.0	+	+	+	+		
305.0	+	+	+	+		
311.0	+	+	+	+		
399.0	+	+	+	+		Albite
486.0	+	+	+	+		Albite
496.0	+	+	+	+		Albite

properties indicate that these clay minerals are so-called saponite, that is mixed-layer minerals of montmorillonite and vermiculite type.

Table 2 summarizes the assemblages of hydrothermal minerals identified in cores from bore-

holes GK-2 and GK-3 by thin section and X-ray diffraction techniques. Fig. 4 shows the relation between the geothermal gradient and zeolite distribution in these two holes.

No gypsum, anhydrite or alunite has been formed

Table 3. Chemical characters of gas and water separated from steam emitted through drill-hole GK-2 of Atosanupuri geothermal area (HIROSUGI, 1967).

Gas		Water	
Volume %	H ₂ S	0.010—0.005	mg/l
	SO ₂	none	
	CO ₂	95.1—97.5	
	CO ₃ ^{''}	6.2—8.6	
	HCO ₃ [']	6.1—7.5	
	Cl [']	0.0—0.8	
	SO ₄ ^{''}	0.0—8.1	
	H ₂ S	trace	
	SiO ₂	0.0—3.8	
	Ca ⁺⁺	none	
	Mg ⁺⁺	0.0—0.1	
	Na ⁺	0.0—28.0	
	K ⁺	0.0—1.4	

in bore-hole cores examined in this area. These three minerals, however, have been reported as commonly found accessory or major minerals of cores from deep holes drilled in other geothermal areas such as Matsukawa (SUMI, 1968) and Katayama (SEKI, *et al.*, 1969). Low concentration of SO₄^{''} in hot-solutions or steam by which the deeper part of Atosanupuri geothermal area was altered is a most probable reason to explain the absence of alunite, gypsum and anhydrite in GK-2 and GK-3 cores (Table 3 and Table 4). SEKI *et al.*, (1969) showed that the high concentration of SO₄^{''} in steam erupted from holes drilled in the Matsukawa geothermal area must be related to the rare occurrence of calcium-zeolites such as laumontite and wairakite and the common occurrence of anhydrite and alunite in bore-hole cores of this geothermal area.

In Atosanupuri geothermal area where steam of low concentration of SO₄^{''} was emitted through bore-hole GK-2, not only sulphate minerals but also calcium zeolites such as laumontite and wairakite can not be found within bore-hole cores. Instead of these calcium-zeolites, a sodic zeolite, mordenite occurs commonly in these cores in as-

sociation with quartz, saponite, calcite and other minerals.

Why does mordenite so commonly occur and why do neither laumontite nor wairakite occur in this Atosanupuri geothermal area?

There is a significant difference in chemical composition of volcanic rocks between the Atosanupuri geothermal area and the Katayama geothermal area from where the common occurrence of wairakite and laumontite has been reported (SEKI *et al.*, 1969). Na₂O/CaO ratios of volcanic rocks of the Atosanupuri area are higher

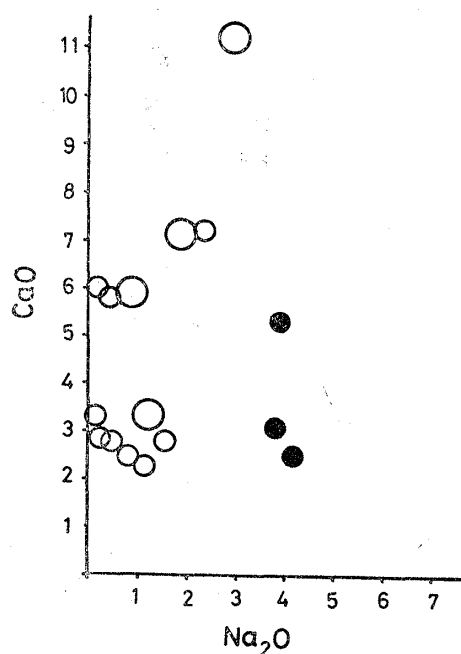


Fig. 5. CaO and Na₂O contents of volcanic rocks in Atosanupuri (solid circles), Katayama (large open circles) and Matsukawa (small open circles). Data came from SUMI (1968), SEKI and others (1969) and KATSUI (1958, 1961).

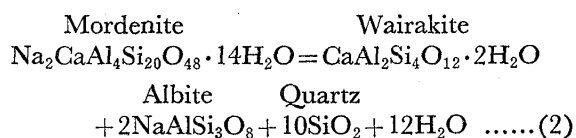
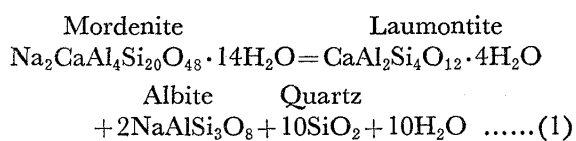
Table 4. Comparison of chemical characters of gas and water forming steams in Atosanupuri, Katayama and Matsukawa geothermal areas.

		Atosanupuri (HIROSUGI, 1967)	Katayama (HIROSUGI, 1969; SEKI and others, 1969)	Matsukawa (SUMI, 1968; MIYAMORI 1968)
H ₂ S+SO ₂ /CO ₂ ratio(vol.) in gas		0.00—0.04	0.17—0.22 (average, 0.19)	0.07—0.51 (average, 0.22)
Water (mg/l)	SO ₄ ^{''}	0.0—8.1	4.9—69.0 (average, 37.1)	95.6—1346.4 (average, 480.7)
	Cl [']	0.0—0.8	0.9—6.2 (average, 2.1)	1.4—25.5 (average, 5.0)
	Na ⁺	0.0—28.0 (average, 24.0)	1.0—131.2 (average, 70.0)	14.0—266.4 (average, 121.7)

than those in the Katayama and Matsukawa areas (Fig. 5).

Mordenite is a kind of Na-zeolite in which Na/Ca varies from 1.1 to 2.3. Laumontite and wairakite, however, are calcium zeolites in which Na/Ca ratio ranges only from 0.0 to 0.2. It is probable that the common occurrence of mordenite and the absence of laumontite and wairakite in bore-hole cores of the Atosanupuri area is at least partly due to the high Na/Ca ratio of original volcanic rocks of this geothermal area.

Chemical relations between mordenite and laumontite and between mordenite and wairakite are as follows:



To form mordenite from the laumontite + albite assemblage or from the wairakite + albite assemblage with excess silica under constant temperature and solid pressures, H₂O pressure or chemical potential of H₂O must increase. Consequently, perhaps the Atosanupuri geothermal area which is represented by the mordenite side of the above equations has been subjected to higher values of P_{H₂O}/P_{total} than those prevailing in the katayama geothermal area in which laumontite and/or wairakite-bearing mineral assemblages are most widely developed as hydrothermal alteration products.

It has been already stated, however, that the pressure and amount of steam, almost 99% or more of which is occupied by water issuing from bore-holes of Katayama geothermal area, attain to 10.5 kg/cm² and 30 ton/hour respectively (SEKI, *et al.*, 1969), but from GK-2 of Atosanupuri geothermal area there can be measured only 2.5-kg/cm² steam pressure of the order of 1.0 ton/hour.

Therefore the difference of steam pressure or water pressure prevailing at depth in the Katayama and Atosanupuri areas may not be critical for the different kinds of zeolites formed as alteration products of volcanic rocks in these two geothermal areas.

It is a noticeable fact that water condensed from the steam of the Atosanupuri geothermal area has much lower contents of Cl' and SO₄'' than those of Katayama and Matsukawa geothermal

areas (Table 4). In the Katayama geothermal area, NaCl and KCl occur as major scale deposit inside steel pipes through which steam issued (HIROSUGI, 1969). Scale deposited on the inside of pipes transporting steam and hot-water in the Matsukawa geothermal area are mostly composed of Na₂SO₄, K₂SO₄, SiO₂ and FeSO₄ with minor amounts of NaCl (FUJII, 1969). The common occurrence of a Na-zeolite, mordenite, in rocks of deeper parts of the Atosanupuri geothermal field may have been partly due to low dissolution of sodium from rocks into permeating alkaline steam or hot-water of low concentration of SO₄'' and Cl'. On the other hand, at Katayama geothermal area most of the Na₂O in the original volcanic rocks may have been dissolved by acid steam and the CaO/Na₂O ratio in these rocks has increased sufficiently to stably form calcium zeolites such as laumontite and wairakite instead of mordenite.

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北海道アトサヌプリ地熱地帯のボーリングコアの変質

関 陽 太 郎

(要 旨)

アトサヌプリ地熱地帯にほられた 500m, 1,000m の深度までのボーリングのコアを吟味した結果, この地熱地帯の深部を構成する火山岩はモルデナイトを含む鉱物組合せに変質していることがわかった. 火山岩の化学成分上の特徴 ($\text{Na}_2\text{O}/\text{CaO}$ 比が高い) と, 変質にあずかっ

た熱水または蒸気の SO_4^{2-} と Cl^- がすくないということが, この地熱地帯にローモンタイトやワイラカイトができないでモルデナイトが晶出している主な原因であろう.