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HYDROTHERMAL ALTERATION IN THE SUNAGOHARA FORMATION, OKUAIZU GEOTHERMAL SYSTEM, JAPAN

Yoji Seki

Geological Survey of Japan, Higashi 1-1-3, Tsukuba, Ibaraki, 305-8567 Japan

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ABSTRACT

Hydrothermal alteration of the Quaternary Sunagohara Formation was studied using bulk XRD techniques and thin sections. The Sunagohara Formation, which is composed of rhyolite lava domes and tuffaceous lacustrine sediments, is present at shallow depths in the Okuaizu geothermal system. The maximum depth of the base of the lake sediments is about 350 m and the maximum measured temperature in the Sunagohara Formation is about 120 ^{0}C. Five alteration zones can be recognized based on the distribution of clays and zeolites: the least altered (LA) zone is characterized by fresh volcanic glass and is found at the surface outside the Nishiyama spa and geothermal area. The smectite-mordenite (SM) zone is found at the surface around the Nishiyama spa and at shallow depths in the geothermal area. The interstratified clay mineral (IS) zone underlies the SM zone and is also found at the surface of the Nishiyama spa. These alteration zones are horizontaly zoned around the center of the geothermal system, with the IS zone in the center, followed outward by the SM and LA zones. The illite-chlorite (IC) zone is only found in drill hole samples from the geothermal area. The distribution of the SM, IS and IC zones at depth can be correlated with increasing temperature. The kaolinite (K) zone is present at the surface around the Nishiyama spa and geothermal area, and is thought to have been formed by interactions with near surface acid sulfate type water.

1. INTRODUCTION

In the Okuaizu geothermal system, the basement rocks at reservoir depths have been altered not only by the present geothermal activity but also through Miocene submarine hydrothermal activity (Seki, 1991). Because many alteration minerals were produced by both events, it is difficult to distinguish alteration minerals related to the present activity from those related to Miocene hydrothermal activity. However the Quaternary Sunagohara Formation, which is found in the shallow portions (<350 m depth) of the geothermal system, has only undergone hydrothermal alteration related to the present geothermal activity. Thus, reliable information on the alteration related to the present geothermal activity can be obtained through studies of the Sunagohara Formation.

2. OVERVIEW OF THE SYSTEM

2.1 Geological setting

The Okuaizu geothermal area is located about 50 km inland of the present volcanic arc, which is parallel to the Japan trench. The regional geology and stratigraphy are summarized in Figs. 1 and 2. The basement in the Okuaizu and surrounding area is thought to be composed of a pre-Tertiary granodiorite and/or metamorphosed sedimentary rocks (Suzuki et al., 1986). Early to middle Miocene formations (Oh-hizawa, Takizawagawa, Ogino and Urushikubo Formations) consist mainly of rhyolitic to dacitic lavas and volcanoclastic rocks, and minor clastic rocks that unconformably overlie the basement (Hayakawa et al., 1974; NEDO, 1985; Nitta et al., 1987). The late Miocene Iriyamazawa Formation was deposited in a large caldera, 20 x 15 km in diameter, and consists of dacitic ash-flow tuffs, debris avalanche deposits and lake sediments. It unconformably overlies the early to middle Miocene formations (Yamamoto, 1992). The Pleistocene Sunagohara Formation, which is composed of lacustrine sediments and rhyolitic lava domes, formed in a caldera environment and unconformably covers the Miocene formations (Komuro, 1978; Mizugaki, 1993). The uppermost portion of the geothermal system, which is developed within the Sunagohara Formation, formed at about 0.5 Ma. The Sunagohara caldera has a funnel-shaped profile with a relatively small central vent (Mizugaki, 1993). The lower portion of the system—to depths of about 2000 m (-1600 m ASL)—is hosted by the Miocene formations. The nearest recent volcano, Numazawa Kazan, is located 10 km west of the geothermal system and was last active about 5,000 years ago.

2.2 Surface features

More than 15 hot springs that discharge near-neutral pH dilute NaCl-type water with total flow of >270 l/min. are found in the northern part of the geothermal system (Nishiyama spa; Fig. 5). Temperatures range from 60^0 to 93^{0}C (Hirukawa et al., 1981). Relatively weak surficial discharges of CO_2 and H_2S occur mainly along the Chinoikezawa fault zone where the highest subsurface temperatures have been measured. There are some other weak gas discharges around the Nishiyama spa and along the Sarukurazawa fault zone (Figs. 3 and 4).

2.3 Hydrology

Fluid flow and the thermal structure of the Okuaizu geothermal system are strongly controlled by fractures (Saeki, 1993). The productive portion of the system is composed of two zones of open-space fracture swarms called the Chinoikezawa (CFZ) and the Sarukurazawa fault zones (SFZ); both dip steeply NE and strike NW (Figs. 3, 4 and 5). The major fluid entries in the production wells are at 1000 to 2600 m depth (-2000 to -600 m above sea level), where the wells intersect the two of fault zones. At these depths, formation temperatures range from 200^0 to 340 ^{0}C (Seki and Adachi, 1997).

The geothermal fluid is characterized by moderate salinities (about 2 wt% TDS) and high non - condensable gas contents (1 wt% CO_2 and 200 mg/kg H_2S). The ratios of B/Cl and Br/Cl show no evidence of a present-day sea water component in the geothermal fluids. The relative He, Ar and N_2 contents of gases from geothermal well discharges are close to the composition of volcanic arc magmatic gas, indicating that the Okuaizu system has a relatively large contribution of magmatic gas (Seki, 1996).

3. HYDROTHERMAL ALTERATION OF THE SUNAGOHARA FORMATION

3.1 Original rock type

The distribution of rock types within the Sunagohara Formation and a geologic cross section across the Okuaizu geothermal system are shown in Figs. 3 and 4, respectively. Lake sediments of the Sunagohara Formation have been divided into lower, middle and upper members (Mizugaki, 1993). The lower member consists of fine tuff interlayered with gravel, sand and pumice. The middle member consists mainly of sandstone and mudstone with well developed bedding. This member often contains large amounts of biotite and volcanic glass. The upper member is composed of mudstone and alternating layers of sandstone and conglomerate with little volcanic-derived material. Dome-forming rhyolite is glassy with a perlitic texture and phenocrysts of quartz, plagioclase, K-feldspar, hornblende, muscovite and biotite.

3.2 Zoning and spatial distribution of the alteration minerals

Hydrothermal minerals seen in the Sunagohara Formation include: quartz, cristobalite, adularia, kaolinite, smectite, interstratified illite-smectite, interstratified chlorite-smectite, illite, chlorite, jarosite, clinoptilolite, mordenite, laumontite, smectite, calcite, dolomite, siderite, rhodochrosite, gypsum, sulfur, orpiment, sphalerite, marcasite and pyrite.

Hydrothermal quartz is commonly found in all but the least altered rocks occuring in the peripheral parts of the Sunagohara Formation. Around the Nishiyama spa, silicified ryholitic tuff with K-feldspar and interstratified clay minerals are found near hot spring vents. Cristobalite is rare but abundant in several places near the Nishiyama spa. Adularia is common in permeable tuffaceous rocks exposed at the surface and at depth. Kaolinite is not common but is found sporadically at the surface around the Nishiyama spa and in drill hole cuttings from well 84N-2t, which is close to the center of the present geothermal activity. Smectite is widespread at the surface except in the area adjacent to the Nishiyama spa., where interstratified illite-smectite is predominant. Hydrothermal illite and chlorite are rare and limited in deeper underground samples such as in well 84N-2t. Pyrite is common in all rock types around the Nishiyama spa and geothermal area. Jarosite derived from pyrite, although less commonly, has the same distribution. Orpiment and sulfur are locally found in permeable tuffaceous rocks around hot springs.

The alteration zonation based on the distribution on clays and zeolites is summarized in Fig. 6. The surfacial distribution of the key minerals and the distribution of hydrothermal minerals at depth are shown in Figs. 7 and 8, respectively. The least altered (LA) zone is characterized by the presence of fresh volcanic glass. This zone is found peripheral to the Nishiyama spa and geothermal area, outside the area with pyrite. Rocks in the LA zone are grayish-white to white in color. The smectite-mordenite (SM) zone is found at the surface around the Nishiyama spa and at shallow depths within the geothermal area. Rocks in this zone are bluish-gray in color due to the presence of fine-grained pyrite. The interstratified clay (IS) zone underlies the SM zone and is also found at the surface adjacent to the Nishiyama spa. In the SM and IS zones, pyrite is commonly found at the surface and in drill cuttings. These alteration zones are distributed around the center of the present geothermal system with the IS zone centrally located, the SM zone in an intermediate position and with the LA zone on the periphery. The illite-chlorite (IC) zone is only recognized at depth in the geothermal area. At depth there is a progression from the SM, IS and IC alteration zones. This progression correlates with increasing temperature. The kaolinite zone is sporadically distributed at the surface around the Nishiyama spa and in the geothermal area. It is rarely seen in drillhole samples of the Sunagohara Formation.

3.3. Comparison with other geothermal systems

Compared with the temperature ranges typically observed for hydrothermal minerals in geothermal systems, temperatures in the Okuaizu system appear to be relatively low. For example, the present maximum temperature in the IS zone is 120 ^{0}C and in the SM zone is 50 ^{0}C (Fig. 8). Commonly observed temperature ranges for minerals in those alteration zones are 100 to 170 ^{0}C for smectite, 100 to 160 ^{0}C for mordenite, and 140 to 220 ^{0}C for interstratified illite-smectite (Henley and Ellis, 1983). Therefore the present temperature in the Okuaizu system is at least 50 ^{0}C lower than in other active geothermal systems. This may indicate that the shallow portion of the Okuaizu geothermal system had higher (>50 ^{0}C) temperatures in the past time.

4. CONCLUSIONS

Five alteration zones are recognized in the lake sediments of the Sunagohara Formation, which occupies the uppermost portion of the Okuaizu geothermal system. The least altered (LA) zone is characterized by fresh volcanic glass and is at the surface outside the geothermal area. The smectite-mordenite (SM) zone is present at the surface in the geothermal area and at shallow depth in the geothermal system. The interstratified clay mineral (IS) zone underlies the SM zone and is found at the surface in the center of the geothermal area. These alteration zones show horizontal distribution from the present geothermal center with IS zone through SM zone to the periphery with LA zone. The illite-chlorite (IC) zone is only found at depth in the geothermal area. At depth the SM, IS and IC alteration zones can be correlated with increasing temperature. The kaolinite (K) zone is locally developed at the surface in the geothermal area, and is thought to have been formed by interaction with near surface acid sulfate waters. Temperatures at depth in the Okuaizu system based on mineral distributions are at least 50 ºC lower than the generally observed temperature ranges for these hydrothermal minerals in other geothermal systems. This may indicate that the shallow portion of the Okuaizu geothermal system was hotter in the past.

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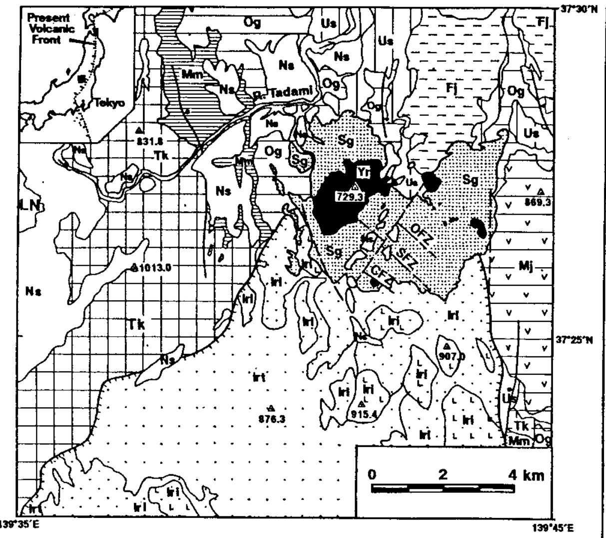

Figure 1. Location and regional geology.
CFZ: Chinoikezawa fracture zone, SFZ: Sarukurazawa fracture zone, OFZ: Oizawa fracture zone, LN: Lake Numasawa (crater lake of Quaternary Numasawa volcano). The other abbreviations are shown in Fig. 2. Compiled from NEDO (1985), Yamamoto (1992) and Mizugaki (1993).

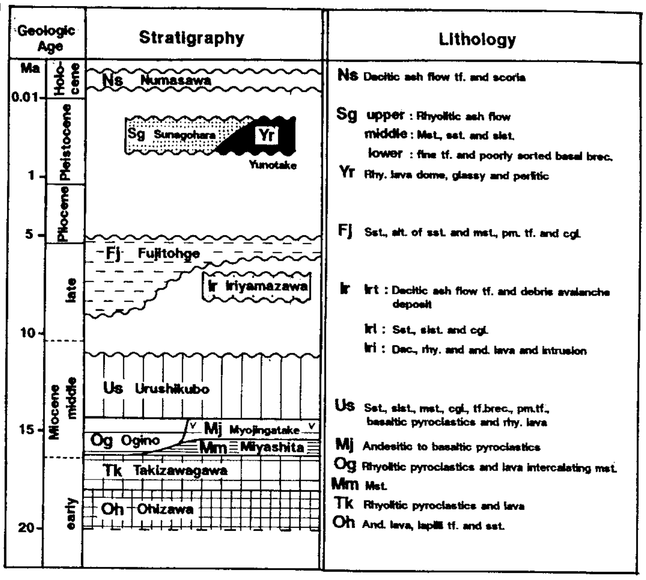

Figure 2. Stratigraphy in the Okuaizu district. Sunagohara Formation has started to deposit at about 0.5 Ma in the depression formed by the Sunagohara caldera volcano. Compiled from NEDO (1985), Yamamoto (1992) and Mizugaki (1993).

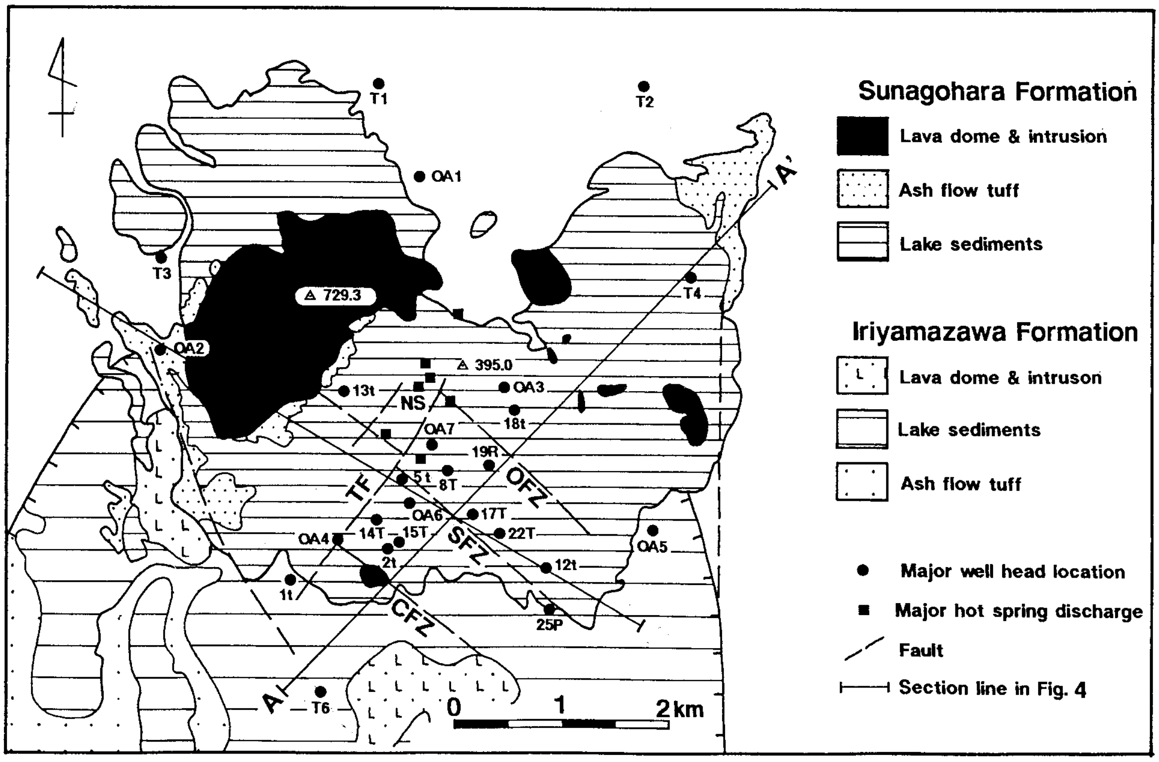

Figure 3. Map showing surface geology of the Sunagohara Formation, major fractures and location of several exploration and production wells. A-A' is cross section line shown in Fig. 4. TF: Takiyagawa Fault, NS: Nishiyama spa. The other abbreviations are as in Fig. 2. 340 °C high temperature center is located in the deeper portion along the CFZ, while higher temperature area near surface is around NS and OFZ. Compiled from Yamamoto (1992) and Mizugaki (1993).

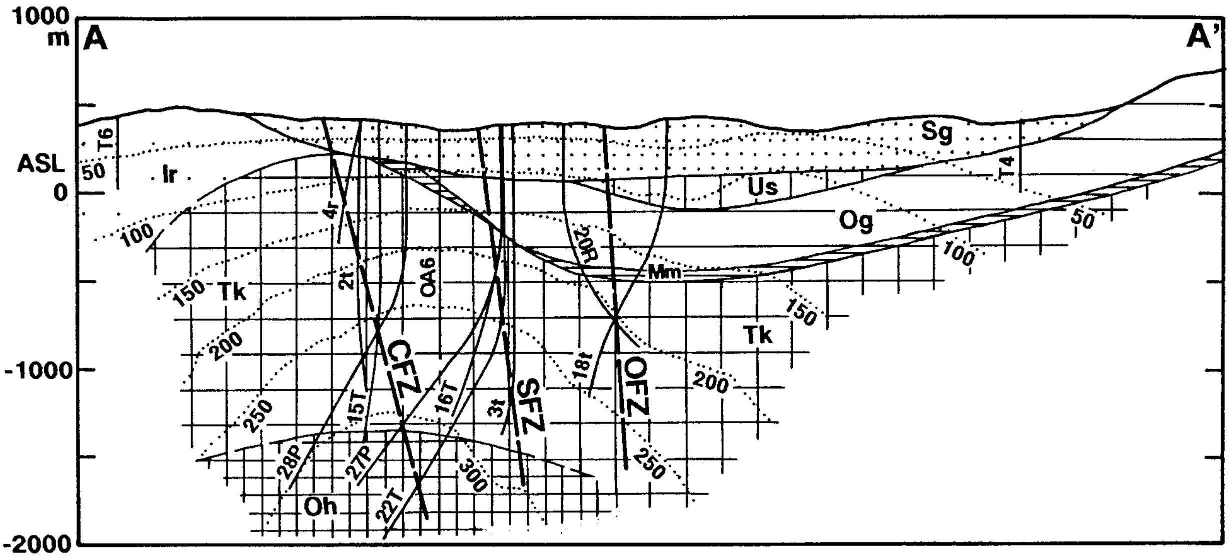

Figure 4. Geologic section of A-A' in Fig. 3 with isotherm, major fractures and geothermal well traces. The other abbreviations are as in Fig. 2. High temperature deeper fluid ascends along the CFZ and the SFZ. Compiled from Seki and Adachi (1997).

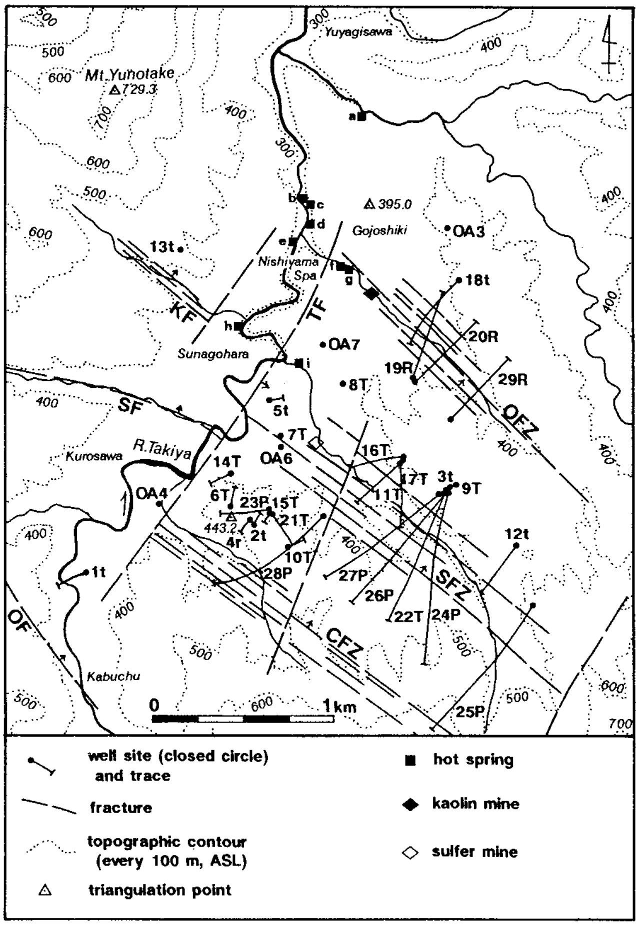

Figure 5. Map showing surface features, fractures and well head locations and traces. Compiled from Seki (1991) and Nitta et al. (1995)

Hydrothermal mineral	Increasing depth ---> LA	SM	IS	IC	Sporadic K
Quartz		- - -			
Cristobalite	- -	- -	- -		
K-feldspar		- - -	- - -	- - - -	- -
Kaolinite					
Smectite	- -		- -		- - -
Chl./Smec.			- - -		
Ill./Smec.					
Illite			- -		- -
Chlorite			- -		
Mordenite			- -		
Clinoptilolite	- -	- - -			
Laumontite			- -		
Gypsum		- -	- -	- -	
Calcite		- -	- -	- -	- - - -
Dolomite			- - -	- -	
Siderite			- - -	- -	
Sulfur		- -			
Orpiment		- -			
Pyrite		- - -	- - -	- - -	- - - -

Figure 6. Mineral zoning in the Sunagohara Formation. LA: least altered zone, SM: smectite-mordenite zone, IS: interstratified clay minerals zone, IC: illite-chlorite zone and K: kaolinite zone. Solid line and broken line mean common and rare, respectively.

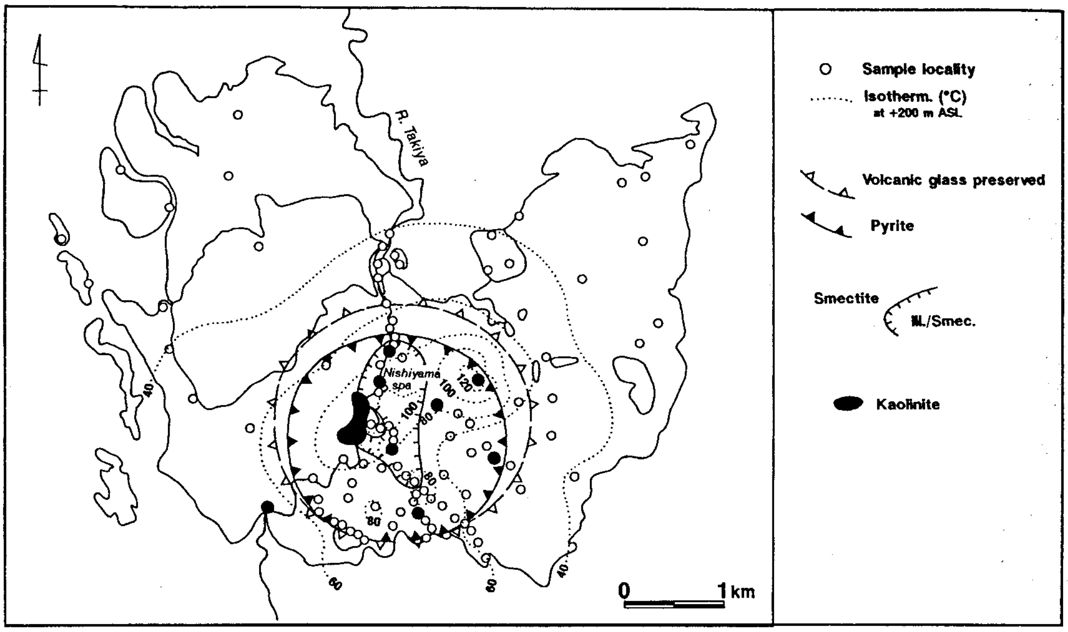

Figure 7. Mineral distributions at the surface.
Area of interstratified illite-smectite corresponds to the IS zone. LA (least altered) zone corresponds area of preserved volcanic glass, which is on the periphery of the geothermal system. SM zone is found between LA and IS zones. Distribution of these alteration zones are basically concordant with near surface isotherm. Present surface elevation ranges 300 to 700 m ASL.

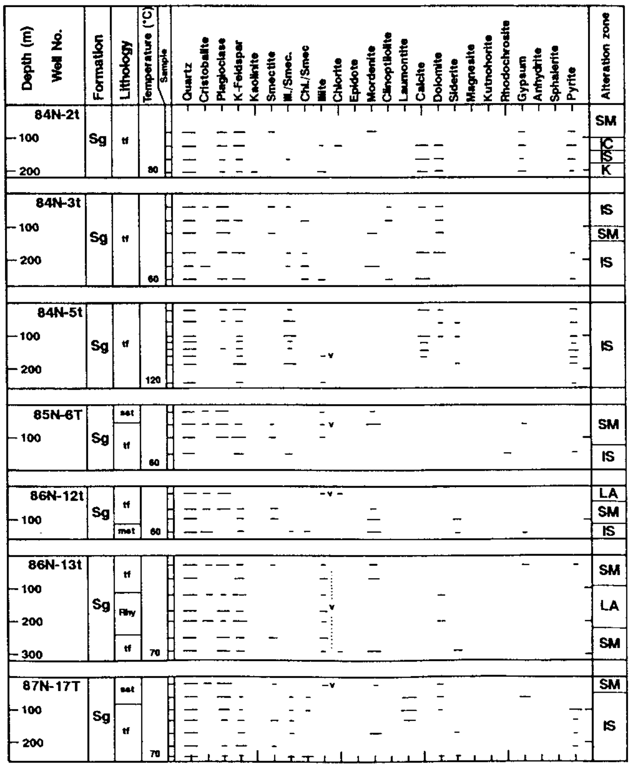

Figure 8. Mineral distributions in drill cuttings.
Rhy: rhyolite, tf: rhyolitic tuff, sst: tuffaceous sandstone, mst: tuffaceous mudstone and v: volcanic-derived muscovite. The other abbreviations are as in Figs 2 and 6.