The physical and chemical structure of the Oku-aizu geothermal system, Japan

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The physical and chemical characteristics of the Oku-aizu geothermal system, northeast Japan, are reviewed, with these data used to construct a geochemical model of the system. The exploration of this area started in 1974, with a total of 39 wells being drilled through fiscal year 1990. A total of 509 t/h of dry steam (165°C) was confirmed during the simultaneous production test, equivalent to about 55 MW of electric power.

The bedrock of the production zones are Miocene formations composed mainly of rhyolitic lavas and pyroclastics. Pre-Tertiary basement unconformably underlie these formations. The uppermost portion of the system is comprised of a Quaternary lacustrine deposit which was penetrated by shallow rhyolite intrusions at 0.2 to 0.5 Ma. This lacustrine deposit is thought to be related to a subsidence structure.

Two different types of hydrothermal alteration are recognized. One is related to submarine volcanic activity in the Miocene, and is composed of chlorite and sericite. The other is a product of the present geothermal system, and has advanced argillic alteration zones at the surface and an argillic zone at depth. Alteration minerals observed in the advanced argillic zone are smectite and mordenite with a minor amount of sericite, alunite and kaolinite. Those in the argillic zone are smectite, interlayered illite-smectite, kaolinite, zeolite and K-feldspar. Anhydrite is common in the deeper portion of the system at higher temperature.

The highest measured temperature is 341°C, and temperatures higher than 300°C are quite common in production zones. Isotherms at -1200 m ASL open to the SE, which may indicate the direction of the heat source. From the deepest drilled levels to about -200 m ASL, the thermal gradient is small, indicating the existence of non-boiling convection over this depth range. The uppermost part of the convection cell is limited by a sealed zone caused by argillic alteration and a Miocene mudstone formation. The system is considered to have had little boiling in its natural state before exploration. However, it is presently boiling around geothermal wells due to the pressure drop caused by reservoir fluid discharge.

The composition of the reservoir fluid is characterized by high salinity (about 2 wt%) and a large amount of non-condensable gas (about 1 wt% CO₂ and 250 mg/kg H₂S). This, as well as its very high underground temperature, is consistent with isotopic indications of a magmatic component to the discharge of the system. This idea is also concordant with the B/Cl and Br/Cl ratios.

Small amounts of base metal sulfide mineralization (pyrite, sphalerite, galena, chalcopyrite etc.) are present at the level of the production zone. This is considered to be a product of the present geothermal system, judging from its mode of occurrence. Significant concentrations of precious metals (Au ≤ 116 mg/kg, Ag ≤ 3.49 wt%) were found in sulfide scales collected from surface two-phase lines.

INTRODUCTION

Thirty nine wells have been drilled up to early 1991 in and adjacent to the Oku-aizu geothermal system, located in Yanaizu town, Fukushima prefecture, northeast Japan (Fig. 1 and Table 1).

The system is now in the final stage of assessment prior to development by the Oku-aizu Geothermal Co., Ltd. (OAG) as an energy source.

The system is known for its highly productive geothermal wells, and also for base metal

Fig. 1. Location of the Oku-aizu geothermal system.

mineralization and precious metal-rich sulfide scaling. The salinity (NaCl equiv. up to about 2 wt%) and reservoir temperature (often $> 300^{\circ}\text{C}$, maximum 341°C measured) are the second highest in Japan (after Fushime, a sea-water dominated system). The extensive drilling and discharge testing of wells by OAG to date has provided sufficient detail to make a basic interpretation of the physical and chemical structure of the system prior to exploitation. However, further study is necessary to establish the evolution of the geothermal system. The purpose of this paper is to provide an update on earlier published reports, largely by OAG, and to integrate the

Table 1. Specifications of geothermal wells (OAG, pamphlet)

Well	Purpose	Target	W.H.E. (m ASL)	B.H.D. (m)	B.H.S. (mm)
OA-1	structural survey		320	1005	78
OA-2	ditto		472	1004	78
OA-3	ditto		392	1500	100
OA-4	ditto		345	1305	100
OA-5	ditto		392	1006	75
OA-6	environment. assess.		376	1500	80
OA-7	ditto		363	1004	102
84N-1t	exploration	OF	376	2003	79
84N-2t	ditto	CFZ	424	1507	101
84N-3t	ditto	SFZ	449	1845	79
84N-4r	reinject. evaluation	CFZ	424	712	76.2
84N-5t	exploration	TF	357	1707	81
85N-6T	product. evaluation	CFZ	428	1655	215.9
85N-7T	reservoir evaluation		377	659	215.9
85N-8T	ditto		370	659	215.9
85N-9T	ditto		460	701	215.9
86N-10T	product. evaluation	CFZ	426	1660	215.9
86N-11T	ditto	SFZ	415	1655	215.9
86N-12t	exploration	SFZ	490	1574	101.0
86N-13t	ditto	KF	418	1406	101.0
87N-14T	product. evaluation	CFZ	392	1560	215.9
87N-15T	ditto	CFZ	400	1860	215.9
87N-16T	ditto	SFZ	415	1758	215.9
87N-17T	ditto	SFZ	415	1661	215.9
87N-18t	exploration	OFZ	413	1654	76.2
88N-19R	reinject. evaluation	OFZ	401	1505	311.2
88N-20R	ditto	OFZ	401	1459	311.2
89N-21T	product. evaluation	CFZ	400	2010	215.9
89N-22T	ditto	CFZ(SE)	443	2609	215.9
90N-23P	product. evaluation	CFZ	400	1909	215.9
90N-24P	ditto	CFZ(SE)	443	2610	215.9
90N-25P	ditto	CFZ(SE)	508	2699	215.9

Abbreviations: W.H.E., well head elevation; B.H.D., bottom hole depth; B.H.S., bottom hole diameter; CFZ, Chinoikezawa fault zone; SFZ, Sarukurazawa fault zone; OFZ, Oizawa fault zone; TF, Takiyagawa fault; KF, Kitanosawa fault; OF, Onogawara fault.

physical and chemical characteristics of the system into an internally consistent model of the pre-exploitation system.

DEVELOPMENT HISTORY

Exploration of the Oku-aizu geothermal system commenced with a reconnaissance survey by Mitsui Mining and Smelting Co., Ltd. (MMSC) in 1974. Subsequently, the first-phase geological, geophysical and geochemical survey was conducted by the New Energy Development Organization (NEDO) from 1976 to 1977. After a geophysical and geochemical survey by MMSC in 1981, the second-phase geological, geochemical and geophysical survey by NEDO was conducted from 1982 to 1983. During this period, 13 core holes (290 to 1500 m depth) were drilled to determine the geological structure and heat flow. Some of these holes were the first to encounter a productive reservoir. In 1983, the Okuaizu Geothermal Co., Ltd (OAG) was established to carry out further exploration and assessment, and to undertake development. From 1984 to 1985, OAG carried out geological, geophysical and geochemical surveys, and drilled five cored wells and four other wells (cuttings only). Production tests of 18 to 119 days for each productive well were also conducted. From 1986 to 1989, 13 more wells (all with cuttings) were drilled, with 30 to 109 day production tests conducted for each production well (Nitta *et al.*, 1987; Ishihara, 1988 and recent company pamphlet). Table 1 lists targets and characteristics of 33 wells.

A total of 509 t/h of dry steam at about 165°C from nine wells was confirmed during a three month simultaneous production test, from December, 1989, to February, 1990 (Nitta *et al.*, 1990). Three additional production wells were drilled during fiscal year 1990.

The Okuaizu Geothermal Co., Ltd. originally planned to develop 55 MW from the system (OAG, explanation pamphlet). As a result of an independent feasibility study from 1986 to 1988, 55 MW of power production for 30 years was predicted, without reservoir pressure support by

reinjection. Further production wells have been added after that reservoir evaluation. The target of power capacity has now been increased to 65 MW based on the results of steam discharge from new production wells, confirmed by the latest production tests held in 1990 (Nitta *et al.*, 1990).

GEOLOGICAL SETTING AND SURFICIAL FEATURES

Geology, stratigraphy and structure

The Oku-aizu area is located in the "Green Tuff region", characterized by Neogene submarine volcanic activity, and is about 50 km west of the present volcanic front. Numazawa-kazan is the nearest Quaternary volcano (10 km west), and was active about 5000 years ago (Kato *et al.*, 1984).

The basement is thought to be pre-Tertiary granodiorite and/or sedimentary rocks, although it has not been reached by drilling in this area (Nitta *et al.*, 1987). Miocene formations (Oh-hizawa, Takizawagawa, Ogino and Urushikubo Formation) consist of rhyolitic lavas and pyroclastic rocks intercalated with clastic rocks, plus minor basaltic rocks, and probably unconformably overlie the basement. Pliocene dacitic pumice tuff intercalated with clastic rocks (Fujitoge Formation) rest unconformably on the Miocene formations. Pleistocene lacustrine sediments (Sunagohara Formation) unconformably covers the Pliocene formation in a limited ring-shaped area about 3 km in diameter surrounding rhyolite lava domes (Yunotake rhyolite; Fig. 2). These rhyolite lava domes are shallow level intrusives into the lacustrine sediments (NEDO, 1985; Nitta *et al.*, 1987). The unconformity between the Quaternary and underlying formations is generally steep and in some places has an associated poorly-sorted basal breccia from the adjacent underlying strata (Komuro, 1978). The distribution of the lacustrine sediments is concordant with the large depth to basement (below -2500 m ASL) inferred from gravity survey (Fig. 3; Nitta *et al.*, 1987). The surficial distribution of these forma-

Fig. 2. Regional geology of the Oku-aizu geothermal system (Nitta *et al.*, 1987). Area in the box is shown in Fig. 4.

Table 2. A regional stratigraphic column of the Oku-aizu district (Nitta *et al.*, 1987)

Geologic Age	Formation	Lithology	Thick. (m)	Absolute Age (Ma)
Quat.	Numazawa Pyroclastics	Dacitic pyroclastic flow, tuff and scoria		0.005
	Sunagohara	Glassy and perlitic rhyolite, tuffaceous sandstone, siltstone and conglomerate	> 150	0.2–0.9 (Rhy.)
Plioc.	Fujitoge	Sandstone, rhythmic alternation of tuffaceous and stone and mudstone, pumice tuff and conglomerate	300	3.2±0.3 (Rhy.)
Mioc.	Urushikubo	Sandstone, siltstone, mudstone, conglomerate, tuff breccia, pumice tuff, basaltic pyroclastics, and rhyolite lava	200–600	5.3±0.4 (Rhy.)
	Ogino	Rhyolitic pyroclastics and lava, andesitic-basaltic pyroclastics, and mudstone (Miyashita mudstone member)	200–300	8.8±0.4 (And.)
	Takizawagawa	Rhyolitic pyroclastics and lava	1000–1300	
	Oh-hizawa	Conglomerate, sandstone and rhyolite	500–600	

tions is shown in Fig. 2 and the detailed stratigraphy is described in Table 2.

The area of the lacustrine sediments is considered to coincide with a collapse basin (Hayakawa *et al.*, 1977, Komuro, 1978 and Suzuki *et al.*, 1986). Competing ideas have been presented as to the cause of the collapse. The first is a local tectonic subsidence (Hayakawa *et*

al., 1977; Suzuki, 1986). The second is a magmatic intrusion-related collapse (not a caldera collapse but rather a keystone graben structure; Komuro, 1978; MITI, GSJ, 1978). The third is a caldera collapse (Yamamoto, in press). Further detailed lithologic and volcanologic study is necessary to resolve this question.

Fig. 3. Depth below surface (in m) of the pre-Tertiary basement inferred from gravity anomalies (Nitta *et al.*, 1987).

The hydrological system is strongly controlled by a tectonic fracture system (Fig. 4). The production area is composed of two major fault zones called the Chinoikezawa and Sarukurazawa fault zones. Both strike NW, and dip 76° and 83° NE, respectively, with swarms of associated open-space fractures (Nitta *et al.*, 1987). There is another major fracture zone called Oizawa fault zone, located about 1 km NE of the Sarukurazawa fault zone. It strikes nearly

Fig. 4. Distribution of major fracture systems, hot springs and area of surficial alteration, and geothermal wells (compiled from Nitta *et al.*, 1987 and OAG, unpublished data). Abbreviations: C.F.Z., Chinoikezawa fault zone; S.F.Z., Sarukurazawa fault zone; O.F.Z., Oizawa fault zone; T.F., Takiyagawa fault; N.S., Nishiyama spa; R.T., River Takiyagawa. Symbols: —, fault and dip; —, inferred fault; ■, geothermal well (production); ◆, geothermal well (reinjection); ●, geothermal well (others); ×, hot spring; —, border of surficial alteration area.

Table 3. Analytical results of hot spring waters in the Nishiyama spa (Hirukawa *et al.*, 1981)

No.	NYC-6	NYC-7	NYC-8	NYC-9	NYC-10	NYC-11	NYC-12	NYC-13
Date of analysis	1955/01/20	51/01/16	61/11/22	51/01/12	51/01/16	51/01/20	51/01/12	56/11/15
Temperature (°C)	93.0	68.0	79.0	71.0	61.0	65.0	77.0	67.0
pH	8.1	8.1	7.0	8.0	7.8	8.2	8.3	6.6
Component (mg/kg)								
Na ⁺	1292	1562	1640	1635	1679	1449	1472	966
K ⁺	169	340	165	185	433	118	167	117
Mg ²⁺	2.3	30.7	4.8	5.7	29.7	5.3	10.2	1.2
Ca ²⁺	50.4	51.8	31.9	42.8	58.1	57.5	65.9	26.5
NH ₄ ⁺	—	0.2	0.51	0.4	0.2	6.2	0.5	—
Fe ²⁺	0.2	8.0	0.04	—	4.7	1.4	1.2	18.8
Al ³⁺	2.3	—	1.45	0.3	—	1.4	0.7	2.7
Mn ²⁺	—	—	0.39	0.8	—	—	—	0.56
Cl ⁻	1630	2215	2438	2226	2297	1886	2139	1492
Br ⁻	—	—	0.36	—	—	—	—	—
I ⁻	—	—	0.68	—	—	—	—	—
F ⁻	0.08	—	0.90	—	—	—	—	—
SO ₄ ²⁻	263	302	290	314	338	276	313	187
HCO ₃ ⁻	732	798	78.3	417	1085	578	302	80.1
CO ₃ ²⁻	—	5.8	0.03	68.2	—	42.7	20.0	—
SiO ₂	130	149	134	132	173	134	101	179
H ₂ S	—	—	2.9	—	—	—	—	5.1

parallel to the productive fault zones and dips 87° NE. The temperature in the deeper part of this zone is much lower (about 100°C) than that of the productive zones, leading to the decision to use this fault zone for reinjection.

Thermal manifestations

Several hot springs are located within the area (Fig. 4), some of which have temperatures close to boiling. Some weak gas discharges composed of CO_2 and/or H_2S are also present.

Of the 15 total hot springs, three have temperatures above 90°C ; they constitute the Nishiyama spa. Although the confirmed flow is 267 l/min., the total flow is thought to be much more, as considerable leakage into the local river occurs (Nitta *et al.*, 1987). The hot springs discharge dilute NaCl-type waters (Na^+ : 966 to 1679 mg/kg, Cl^- : 1492 to 2438 mg/kg) with low CO_2 (total CO_2 : several 100 mg/kg) and H_2S (several mg/kg) (Hirukawa *et al.*, 1981, Table 3). Most hot springs are located where the Oizawa fault zone intersects the Takiyagawa fault zone, about 1 km north of the productive zone.

Several discharges of CO_2 with H_2S occur mainly along the Chinoikezawa fault zone where the highest subsurface temperatures are recorded. There are also a few gas discharges along the Takiyagawa fault and the Sarukurazawa fault zone (Nitta *et al.*, 1987).

HYDROTHERMAL ALTERATION

Regional alteration in the Miocene

The Oku-aizu geothermal system is largely hosted by rocks affected by regional alteration during the Miocene (the "Green-Tuff"). In the Aizu district, which surrounds the Oku-aizu geothermal system, the following succession of regional alteration has been recognized from surface downwards; fresh glass, clinoptilolite-mordenite, analcime, laumontite, and albite-chlorite-sericite zones (Hayakawa *et al.*, 1977). In the Oku-aizu system itself, chlorite-sericite alteration has affected the greater part of the Miocene formations, mostly composed of rhyolitic lava, tuff and tuff breccia (for example,

OA-2 (Fig. 5a), OA-5 (Fig. 5b) and OA-6, compiled from NEDO, 1985). A significant portion of this chlorite-sericite zone is considered to be a product of the early regional alteration, though distinguishing this from similar alteration related to the present system is quite difficult (Nitta *et al.*, 1987).

Present system-related alteration

Argillic to advanced argillic alteration occurs at shallow levels and anhydrite at deeper, higher temperature levels, and are considered to be related to the present geothermal system. In addition, carbonate minerals are commonly observed in most wells in the system, also related to present hydrothermal activity.

Argillic alteration occurs mainly in the Sunagohara Formation, a Quaternary lacustrine deposit composed of tuffaceous sandstone and siltstone, and in the Urushikubo Formation, composed of tuffaceous sandstone, siltstone, mudstone, rhyolitic glassy tuff, pumiceous tuff, and lava. In some wells (86N-12t, 87N-17T (Fig. 5d), 89N-22T (Fig. 5e) and 90N-24P), this alteration is also seen in the Ogino and Takizawagawa Formations, composed mainly of rhyolitic lava, tuff and tuff breccia, with some Miocene mudstone.

The alteration minerals of the argillic zone comprise smectite, interlayered illite-smectite, kaolinite, zeolite and K-feldspar. Smectite-zeolite +/– interlayered illite-smectite +/– K-feldspar form a sub-zone in the relatively shallow part (typically observed in wells 87N-17T (Fig. 5d), 89N-22T (Fig. 5e) and 90N-23P), while kaolinite +/– K-feldspar occurs at deeper levels (OAG, unpublished data). Advanced argillic alteration, composed mainly of smectite and mordenite, with minor sericite, kaolinite and alunite (Nitta *et al.*, 1987 and Imai *et al.*, 1988) is found locally near the Sarukurazawa fault zone. The surface extent of this argillic to advanced argillic alteration is about 4.4 km^2 (Fig. 4; Nitta *et al.*, 1987).

Anhydrite is widespread in the deeper part of the system, where temperatures are greater than 100 to 200°C . Anhydrite occurs as open-space

Fig. 5a. Lithology and alteration mineralogy including major circulation-loss points of well OA-2 (compiled from NEDO, 1985). Abbreviations: Sg, Sunagohara formation; Us, Urushikubo formation; Og, Ogino formation; My, Miyashita mudstone member; Tk, Takizawagawa formation; Oh, Oh-hizawa formation; smec, smectite; ill/sm, interlayered illite-smectite; morden, mordenite; kaol, kaolinite; crist, cristobalite; ser, sericite; chl, chlorite; anh, anhydrite; cc, calcite and ksp, K-feldspar. These abbreviations are the same for the rest of Fig. 5.

Fig. 5b. Lithology and alteration mineralogy including major circulation-loss points of well OA-5 (compiled from NEDO, 1985).

Fig. 5c. Lithology and alteration mineralogy including major circulation-loss points of well 87N-16T (compiled from OAG, unpublished data).

Fig. 5d. Lithology and alteration mineralogy including major circulation-loss points of well 87N-17T (compiled from OAG, unpublished data).

Fig. 5e. Lithology and alteration mineralogy including major circulation-loss points of well 89N-22T (compiled from OAG, unpublished data).

fracture fillings, as well as alteration of host rock minerals (NEDO, 1985; OAG, unpublished data).

Carbonate minerals observed in the geothermal system include calcite, dolomite, siderite, rhodochrosite, kutnahorite, ankerite and magnesite. The calcite distribution is discontinuous in most wells or even absent (84N-1t, 86N-13t and 87N-16T (Fig. 5c)). Rhodochrosite appears over a wide range of depth in some wells (85N-9T, 87N-14T, 87N-15T, 89N-21T and 89N-22T (Fig. 5e); OAG, unpublished data).

THERMAL STRUCTURE

Direct measurement

The thermal structure of the geothermal system may be constructed from thermal profiles based on temperatures measured 120 hours after drilling, the time allowed for thermal conditions to stabilize (Fig. 6). The thermal structure is primarily controlled by the fracture system. A zone of argillic alteration at shallow levels appears to act as a barrier to upflow (at depth of

Fig. 6. Initial thermal profiles of several representative wells (after post-drilling stabilization for 120 hours (except 89N-22T, which was 48 h)) (compiled from NEDO, 1985 and OAG, unpublished data). Abbreviations: A, OA-2; B, OA-5; C, 84N-1t; D, 86N-11T; E, 87N-15T; F, 87N-16T; G, 87N-17T; H, 87N-18t; I, 88N-19R; J, 89N-22T. The lower levels of wells 11T, 16T, 17T, 18t, 19R and 22T are inclined. No depth correction for the inclination was made. Maximum difference from the true depth is about 200 m (89N-22T). Well head elevations are mainly 400 ± 50 m ASL.

about -200 m to $+200$ m ASL).

In the deeper part of the system (deeper than -1000 m ASL), the zone of thermal updoming is located along the Chinoikezawa fault zone, and isotherms open towards the SE. At shallower levels (about -300 m to -1000 m ASL), the highest temperature isotherms are located between the Chinoikezawa and the Sarukurazawa fault zone. Still closer to the surface (shallower than -300 m ASL), an axis of thermal maxima changes direction to parallel the Takiyagawa fault zone, trending NE-SW. At a level of $+200$ m ASL, the highest temperature isotherm closes towards the NE, about 2.5 km from the Chinoikezawa fault zone (Fig. 7; OAG,

Fig. 7. Temperature distribution at -1200 , -400 and $+200$ m ASL, with distribution of major fractures at each level (OAG, unpublished data). Abbreviations: C.F.Z., Chinoikezawa fault zone; S.F.Z., Sarukurazawa fault zone; O.F.Z., Oizawa fault zone. Symbols: —, fracture system; —300, isotherm with temperature ($^{\circ}\text{C}$).

unpublished data).

The depth where the high temperature axis changes direction corresponds approximately to the base of the zone of argillic alteration. The temperature gradient increases at that depth (Fig. 8; OAG, unpublished data), which may relate to a convection cell beneath the zone sealed by argillization.

Judging from the thermal profiles, the present system does not appear to be boiling in its natural state, though local zones of boiling in low pressure fractures may exist.

Fig. 8. Temperature cross-section along A-A' (Fig. 4), with geology (OAG, unpublished data). Abbreviations are the same as in Figs. 4 and 5. Symbols: —, formation boundary; —, fault; —, isotherm with temperature ($^{\circ}\text{C}$).

Some wells have thermal inversions at depth (N57-OA-3 and 87N-18t (Fig. 6H)), which probably indicate cool inflows, as in N57-OA-3, where the isotherms pinch with an axis concordant to the Oizawa fault zone (Fig. 7; OAG, unpublished data).

Fluid inclusion thermometry

Homogenization temperatures of fluid inclusions hosted mainly by anhydrite and calcite have been measured for several wells. All fluid inclusions are two-phase gas and liquid inclusions. No liquid CO_2 or halite have been observed. Both primary and secondary inclusions are recognized. The former possess regular shapes and often form clusters (Takenouchi, 1988a).

The degree of filling of the inclusions in the same cluster commonly varies which may indicate boiling during the formation of the mineral (Takenouchi, 1988a).

Homogenization temperatures of most inclusions in anhydrite in OA-7, located between the Sarukurazawa and Oizawa fault zones, appear to agree with the measured down hole temperatures, though some are several tens of degree ($^{\circ}\text{C}$) higher. Concordance of homogenization

Fig. 9. Distribution of homogenization temperatures of fluid inclusions in anhydrite and calcite including down hole temperature profiles for wells OA-6 and OA-7 (Nitta *et al.*, 1987, based on Takenouchi, 1986). Abbreviations: anh, anhydrite; cc, calcite; ST, stabilization time after drilling (hours); D.H.T., measured down hole temperature. Boiling-point versus depth curve (1 wt% CO_2 at 350°C) is also shown for OA-7.

temperature with the measured down hole temperature can be observed at levels shallower than 1000 m depth in OA-6, penetrating the Sarukurazawa fault zone (Fig. 9; Takenouchi, 1985).

Fluid inclusions in sphalerite at GL-1329.5 m of 84N-2t have homogenization temperature ranging from 196 to 222°C (Imai *et al.*, 1988), which is about 50°C lower than the present temperature.

RESERVOIR CONDITIONS BEFORE AND AFTER EXPLOITATION

Reservoir condition in initial stage

The reservoir condition at the initial stage of exploration is considered to be very close to that of the natural state. Judging from the following observations made during the initial stage of exploration, the overall Oku-aizu geothermal

Fig. 10. Total discharge enthalpy versus well head pressure for 85N-6T (Nitta *et al.*, 1987).

system appears to have been sub-boiling, though there may have been minor local zones of boiling.

Some wells drilled in the beginning stage of the exploration (e.g. OA-4, 84N-2t and 85N-6T)

Table 4. Temperature and enthalpy data of geothermal wells

Well	Date	W.H.P. (b.g.)	T.dh (°C)	H.td (kJ/kg)	H.l (kJ/kg)	H.ex (kJ/kg)
OA-4	84/02/07	17.5	267	1140	1169	—
OA-6	83/12/22	0.7	286	1603	1268	335
84N-1t	85/06/14	1.1	254	908	1105	—
84N-2t	85/11/08	6.2	311	1365	1407	—
84N-3t	86/01/16	0.6	277	1415	1220	195
84N-5t	84/12/08	0.0	265	1220	1159	61

Original data from Nitta *et al.* (1987) and NEDO (1985). Abbreviations: W.H.P., well head pressure; T.dh, maximum measured down hole temperature; H.td, total discharge enthalpy; H.l, enthalpy of steam saturated water at T.dh; H.ex, excess enthalpy (H.td-H.l).

had normal enthalpy, while only one (OA-6) showed an excess enthalpy of discharge (Table 4). Most down hole temperature profiles do not reach boiling point for depth temperatures, calculated on the basis of estimated dissolved gas concentrations (Fig. 6). The total discharge enthalpy versus well head pressure for 85N-6T (Nitta *et al.*, 1987; Fig. 10) indicates that aquifer boiling takes place around the well due to the pressure drop induced by discharge of the well. The same situation is recognized in other wells.

Although local, gas-rich reservoirs were

Fig. 11. Total discharge enthalpy changes with time during production tests for several wells (OAG, unpublished data).

reported (based on drilling records, e.g., -831 m in 84N-1t; Nitta *et al.*, 1987), these phenomena are considered to be rather exceptional.

Reservoir condition after discharge

After wells OA-4 and OA-6 discharged geothermal fluid during the first stage of exploration in 1982 and 1983, nine more production wells were drilled up to 1989 and several production tests were carried out. As a result of these discharge tests, the reservoir pressure decreased slightly and discharge-induced reservoir boiling around the geothermal wells subsequently occurred. Most wells showed an excess enthalpy of discharge (Table 4) during their individual production tests.

During the first simultaneous production test of five production wells (84N-2t, 85N-6T, 86N-10T, 87N-14T and 87N-15T, from December, 1987, to March, 1988), all five wells showed a significant amount of excess enthalpy, up to 600 kJ/kg. The only exception was well 87N-14T, which showed normal enthalpy to slight excess enthalpy conditions in the beginning stage of the test. This development of excess enthalpy is considered to be derived from excess steam inflow produced from reservoir boiling caused by the discharge-induced pressure drop. The total discharge enthalpy of each well gradually increased with time during the test (Fig. 11), which indicates extension of boiling around the wells into the reservoir.

Due to the steam generated in an aquifer subjected to extensive amounts of discharge-induced boiling, the composition of the total discharge is seldom representative of the composition of reservoir liquid in the formation, prior to boiling (Seki, 1990b).

FLUID CHEMISTRY

Chemical characteristics of well discharges

One characteristic phenomenon of this system is the high gas content in well discharges. The concentrations of non-condensable gases (NCG) in steam separated at about 6.5 kg/cm²

range from 2 to 10 vol%. Most of the NCG is CO₂ (95 to 99%) with the balance being H₂S (0.1 to 4%) and residual gases. Among the residual gases, N₂ dominates (78 to 98%) (Table 5; NEDO, 1985; Nitta *et al.*, 1987; OAG, unpublished data).

The separated liquid has the highest salinity of geothermal systems in Japan (except for Fushime, which is sea water dominant; Akaku and Yagi, 1988; Akaku, 1990). The dominant anion is Cl⁻ (5300 to 22000 mg/kg) and major cations are Na⁺ (2700 to 10600 mg/kg) with lesser amounts of K⁺ (180 to 2550 mg/kg) and Ca²⁺ (26 to 1750 mg/kg). The silica concentration is also high (440 to 1010 mg/kg), reflecting the relatively high reservoir temperature. Remarkably high concentrations of Mn²⁺ (up to 420 mg/kg) is another peculiar characteristic of this system (Table 5; NEDO, 1985; Nitta *et al.*, 1987; OAG, unpublished data).

Estimated reservoir fluid composition prior to boiling

The composition of the reservoir fluid is necessary in order to calculate mineral-fluid equilibria and to estimate such development-related factors as the potential for scaling. However, as previously mentioned, the reservoir fluid composition cannot be directly determined from total discharge composition for wells with excess enthalpy. This is because the excess steam will have a higher and probably variable gas concentration compared with the original aquifer fluid prior to boiling, due to fractionation under different conditions of boiling (Henley, 1984). Therefore, to estimate the reservoir fluid composition prior to boiling, the steam fraction and concentration of each component in steam at the feed point(s) has to be estimated.

Based on this concept and integrated with an aquifer boiling model, the reservoir fluid composition prior to boiling for wells 85N-6T, 87N-14T and 87N-15T was estimated (Seki, 1990b). The calculated concentrations of non-volatile components for the three wells producing from the same fracture zone (Chinoikezawa fault zone), agreed well with each other. The esti-

Table 5. Analytical results and discharge data of geothermal wells

Well	OA-4	OA-6	84N-11	84N-21	84N-31	84N-51	85N-6T	85N-10T	86N-11T	87N-14T	87N-15T	87N-16T	87N-17T	89N-21T	89N-22T
Sampling date	84/2/3	83/12/26	85/6/14	85/11/8	86/1/16	84/12/8	86/12/20	87/9/26	89/1/8	87/10/30	87/12/7	89/1/8	89/1/8	89/12/26	89/12/25
W.H.P. (b.g.)	0.2	0.2	1.1	6.2	0.6	0.0	21.0	10.0	8.3	9.6	62.7	8.6	8.0	8.5	15.3
P sep (b.g.)	0.04	0.0	0.04	0.14	0.20	0.01	4.53	6.50	6.42	6.57	6.50	6.46	6.45	6.42	6.42
F.stm (t/h)	5.8	0.6	5.9	24.1	2.8	1.9	59.4	49.9	42.6	48.9	87.7	35.8	41.7	51.8	63.3
F.wat (t/h)	4.7	1.1	20.9	33.4	3.5	3.4	135.2	34.5	55.7	67.2	134.0	63.2	38.6	25.2	28.9
H.id (kJ/kg)	1660	1210	908	1365	1415	1220	1295	1920	1596	1565	1519	1447	1773	2092	2121
Steam sample (vol%)															
H ₂ O	96.60	—	90.12	96.37	95.85	96.79	90.67	96.68	92.88	97.16	96.62	97.37	89.94	97.82	95.21
Gas	3.40	—	9.88	3.63	4.15	3.21	9.33	3.32	7.12	2.84	3.38	2.63	10.06	2.18	4.79
Gas CO ₂	96.5	—	99.0	96.3	99.1	98.1	96.6	97.0	97.6	96.5	96.6	97.8	97.4	96.3	95.6
H ₂ S	2.7	—	0.1	3.0	0.3	1.3	2.6	2.3	1.9	2.8	2.7	1.6	2.0	3.1	3.8
R.gas	0.8	—	0.9	0.7	0.6	0.6	0.8	0.7	0.5	0.7	0.7	0.6	0.6	0.6	0.6
R.gas H ₂	—	—	0.4	7.10	2.0	6.0	3.10	9.50	4.70	3.80	10.30	3.40	18.5	11.7	21.4
N ₂	—	—	98.4	92.3	97.0	92.0	96.1	89.5	94.6	95.2	89.0	95.7	77.9	87.4	77.9
CH ₄	—	—	1.2	0.3	0.6	2.0	0.50	0.67	0.54	0.66	0.42	0.58	3.28	0.515	0.448
He	—	—	—	0.05	0.03	—	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.047	0.047
Ar	—	—	—	0.27	0.41	—	0.31	0.21	0.11	0.32	0.20	0.24	0.26	0.254	0.196
Water sample (mg/kg)															
pH (at 25°C)	7.05	5.50	7.98	6.44	6.30	6.89	6.37	7.03	6.90	6.70	6.56	6.67	7.68	6.38	5.64
Li ⁺	—	—	—	9.8	16.9	—	5.3	—	7.33	—	—	12.0	3.9	10.5	10.7
Na ⁺	5300	2700	5560	7120	10600	6990	3600	3770	5170	6210	7170	8020	3010	7770	5310
K ⁺	1400	180	644	2050	2550	1350	1030	940	1060	1640	2000	1940	547	1950	1780
Mg ²⁺	1.10	0.10	3.22	8.05	20.8	15.4	8.9	5.16	8.11	3.63	9.81	20.4	3.84	9.63	6.55
Ca ²⁺	230	42	26.0	1160	1750	788	609	385	586	1030	1060	1330	81.2	1220	647
Al ³⁺	0.43	0.10	0.87	0.19	0.40	0.09	0.12	0.28	0.29	0.02	0.64	0.14	0.21	0.55	1.47
Mn ²⁺	—	—	—	419	185	—	129	17.0	46.9	125	290	311	0.9	266	356
Fe ²⁺	0.92	70.0	0.69	0.31	1.47	0.2	0.93	0.42	0.49	0.02	1.69	0.61	0.11	1.07	50.1
Cu	—	—	—	—	—	—	—	—	—	—	—	—	—	0.25	0.18
Pb	—	—	—	—	—	—	—	—	—	—	—	—	—	1.8	1.5
Zn	—	—	—	—	—	—	—	—	—	—	—	—	—	1.01	1.28
NH ₄ ⁺	—	—	—	—	—	—	—	—	—	—	—	—	—	2.9	2.7
Cl ⁻	—	—	—	2.90	4.40	—	1.93	—	2.69	—	—	2.55	1.53	4.84	5.86
SO ₄ ²⁻	8800	6900	7780	15000	21800	13400	7930	7360	10000	13300	15300	17000	5300	16500	11700
HCO ₃ ⁻	36.0	191	771	4.0	6.2	50.2	61.7	102	48.1	62.7	7.1	65.4	34.5	22.4	34.3
F ⁻	83.0	4.3	956	41.1	5.2	122	27.0	53.2	23.5	44.3	35.9	<5	145	20	11
Br ⁻	—	—	—	2.70	1.94	—	1.45	—	1.78	—	—	1.90	1.81	2.64	3.25
I ⁻	—	—	—	29.1	43.0	—	11.2	—	17.3	—	—	34.0	10.8	31.4	22.6
SiO ₂	—	—	—	4.1	5.9	—	2.0	—	2.8	—	—	4.3	1.5	2.8	2.9
HBO ₂	680	439	450	990	866	662	605	642	771	787	1010	821	632	887	952
As	568	—	304	628	846	—	337	—	462	—	—	624	370	693	693
Hg	8.00	2.20	8.2	12.4	14.6	6.4	6.52	6.70	7.73	11.7	17.2	12.6	2.20	17.4	0.87
H ₂ S	<0.001	<0.001	—	—	—	—	—	—	<0.0005	—	—	<0.0005	0.0006	<0.0005	<0.0005
data source	A	A	B	B	B	B	C	C	C	C	C	C	C	C	C

Data sources are A, NEDO (1985); B, Nitta et al. (1987) and C, OAG (unpublished). Steam samples were collected at steam lines under the separation pressure. Water samples were collected at two-phase lines under the atmospheric pressure. Abbreviations: W.H.P., well head pressure; b.g., bars gauge; P.sep, separation pressure; F.stm, flow rate of separated steam; F.wat, flow rate of separated water; H.id, total discharge enthalpy.

Table 6. Total discharge composition and estimated reservoir fluid composition prior to boiling (other than gas)

Well	0A-4	84N-1t	84N-2t	84N-3t	84N-5t	85N-6T	86N-10T	86N-11T	87N-14T	87N-15T	87N-16T	87N-17T	89N-21T	89N-22T
Date	84/02/03	85/06/14	85/11/08	86/01/16	84/12/08	86/12/20	87/09/26	89/01/08	87/10/30	87/12/07	89/01/08	89/01/08	89/12/26	89/12/25
H.t.d	1660	908	1365	1415	1220	1295	1290	1596	1565	1519	1447	1773	2092	2121
T.aq	249	221	285	272	250	242	242	261	262	286	267	242	266	272
Hvap.ta	2802	2802	2773	2788	2802	2804	2804	2796	2796	2772	2792	2804	2793	2788
Hliq.ta	1081	948	1262	1195	1085	1047	1047	1139	1144	1268	1169	1047	1164	1195
SFDh	0.336	0	0.068	0.138	0.079	0.141	0.497	0.276	0.255	0.167	0.171	0.413	0.570	0.581
factor	1.057	1	1.073	1.160	1.085	1.164	1.988	1.381	1.342	1.200	1.207	1.704	2.324	2.388
T.D.C.														
(mg/kg)														
Na	2372	4336	4136	5889	4484	2501	1541	2930	3594	4334	5120	1447	2543	1664
K	623	502	1191	1417	866	716	384	601	949	1209	1238	263	638	558
Mg	0.49	2.50	4.68	11.6	9.88	6.18	2.11	4.60	2.10	5.93	13.0	1.85	3.15	2.05
Ca	103	20.3	674	972	506	423	157	332	596	641	849	39.0	399	203
Fe	0.41	0.54	0.18	0.82	0.14	0.65	0.17	0.28	—	1.02	0.39	0.05	0.35	15.7
Al	0.19	0.68	0.11	0.22	0.06	0.08	0.11	0.16	—	0.39	0.09	0.10	0.18	0.46
Mn	—	—	243	103	—	89.6	6.95	26.6	72.4	175	199	0.43	87.1	112
Cl	3939	6067	8713	12110	8596	5509	3009	5666	7698	9248	10850	2548	5400	3667
SO ₄	16.1	601	2.32	3.44	32.2	42.9	41.7	27.3	36.3	4.29	41.8	16.6	7.33	10.8
SiO ₂	304	351	575	481	425	420	263	437	456	611	524	304	290	298
HBO ₂	254	237	362	470	—	234	—	262	—	—	398	178	227	218
E.A.C.														
(mg/kg)														
Na	3775	4336	4439	6833	4867	2912	3063	4046	4823	5202	6178	2466	5909	3974
K	939	502	1278	1644	940	834	763	830	1274	1451	1494	448	1483	1333
Mg	0.74	2.50	5.02	13.5	10.7	7.20	4.19	6.35	2.82	7.12	15.7	3.15	7.32	4.90
Ca	155	20.3	723	1128	549	493	312	458	800	769	1024	66.5	927	485
Fe	0.62	0.54	0.19	0.95	0.15	0.76	0.34	0.39	—	1.22	0.47	0.09	0.81	37.5
Al	0.29	0.68	0.12	0.26	0.07	0.09	0.22	0.22	—	0.47	0.11	0.17	0.42	1.10
Mn	—	—	261	120	—	104	13.8	36.7	97.2	210	240	0.73	202	267
Cl	5936	6067	9350	14050	9330	6414	5981	7824	10310	11100	13100	4342	12550	8758
SO ₄	24.3	601	2.49	3.99	35.0	50.0	82.9	37.79	48.79	5.15	50.4	28.3	17.09	25.8
SiO ₂	458	351	617	558	461	489	523	603	612	733	632	518	674	712
HBO ₂	383	237	388	545	—	272	—	362	—	—	480	303	528	521

Abbreviations: T.D.C., total discharge composition; E.A.C., estimated aquifer composition prior to boiling. Original data were provided by OAG. Estimation followed Seki (1990b). T.aq, temperature of aquifer from silica geothermometer; Hvp.ta, enthalpy of vapor at T.aq; Hliq.ta, enthalpy of liquid at T.aq; SFDh, steam fraction at down hole conditions; factor, correction made to T.D.C. to get E.A.C.

Fig. 12. Chloride-enthalpy diagram for calculated reservoir fluids. Original data provided by OAG. Calculation of reservoir compositions based on results by Seki (1990b).

mated ranges of gas concentrations in the reservoir liquid prior to boiling are 0.3 to 1.0 wt% for CO_2 and 150 to 250 mg/kg for H_2S , with the upper values most likely (Seki, 1990b).

The estimated concentrations of non-volatile components in the reservoir liquid prior to boiling, based on the analytical results listed in Table 5 and corrected for steam loss, are listed in Table 6.

The fluid pH at reservoir temperature is calculated from the estimated reservoir fluid composition using the chemical speciation code "PECS" (Takeno, 1988), and ranges from 4.1 to 5.5 (Seki, unpublished). These values are somewhat higher than the pH of 3.79 calculated assuming no excess steam and consequently no excess CO_2 in the total discharge (Ichikuni and Tsurumi, 1988).

Probable fluid types and mixing trends

A chloride-enthalpy plot of initial discharge compositions of each production well, corrected to reservoir values, is shown in Fig. 12. Well 87N-15T appears to be closest in composition to a "parent fluid", given its high chloride concentration and the highest temperature indicated by the silica geothermometer (Fournier and Potter, 1982).

It is difficult to confidently determine the

degree of boiling, and dilution trends, because of the large excess enthalpies, though some possibilities may be considered. The first is a recognition of a mixing trend between the deep fluid (of high salinity and higher enthalpy, represented by 87N-15T) and a shallower, possibly conductively (or steam) heated ground water of zero salinity and a temperature less than 200°C. This cannot be proven because down hole samples of marginal monitor and exploration wells are not available.

The second probable trend is that of mixing of deeper fluid or mixed fluid of the first trend with cold ground water at relatively shallow depths. This mixing is responsible for the waters discharging from hot springs along the Takiyagawa fault zone, which have approximately 1500 to 2500 mg/kg chloride and temperatures of 61 to 93°C (Table 3).

Isotopic characteristics and component ratios

An oxygen and hydrogen isotopic study of geothermal waters was conducted by Dr. O. Matsubaya and presented in Nitta *et al.* (1987) (Fig. 13). Isotopic values of meteoric waters collected in this area lie on the local meteoric water line ($\delta^{18}\text{O}$: -10 to -12 per mil, δD : -66 to -72 per mil), described by Sakai and Matsubaya (1974). Geothermal fluids discharging from wells have

Fig. 13. (a) $\delta^{18}\text{O}$ -chloride diagram for geothermal well discharges, hot spring waters and local meteoric waters (modified from Nitta *et al.*, 1987). (b) $\delta^{18}\text{O}$ - δD diagram for geothermal well discharges, hot spring waters and local meteoric waters. The compositional range of Japanese high temperature volcanic gas (J-HTVG) is also shown (modified from Nitta *et al.*, 1987). Symbols: ■, geothermal well discharge; ●, hot spring water; ▲, local meteoric water. Line (1) ($\delta\text{D} = 8\delta^{18}\text{O} + 26$) and (2) ($\delta\text{D} = 8\delta^{18}\text{O} + 10$) are local meteoric water lines according to Sakai and Matsubaya (1974).

Fig. 14. Reservoir temperature versus saturation indices ($\log Q/K$) for calcite, anhydrite, K-feldspar and K-mica based on the estimated composition of reservoir fluid (Seki, unpublished data). Original data provided by OAG. Estimation based on gas results of Seki (1990b), with saturation calculations carried out by PECS (Takeno, 1988). Reservoir temperatures were determined by Fournier and Potter (1982). Gas concentrations were assumed to be 1 wt% for CO_2 and 250 mg/kg for H_2S for all wells. Symbols: ■, muscovite; ●, K-feldspar; △, anhydrite; ◇, calcite.

much heavier values of oxygen $\delta^{18}\text{O}$: +2 to +3 per mil) and hydrogen (δD : -32 to -35 per mil). The isotopic values of hot spring waters lie on a line connecting these two endmembers, indicating that the hot springs are produced by mixing of deep geothermal fluid and local ground water, as suggested from chloride-enthalpy relations (Fig. 12). This mixing trend is also clear on the chloride- $\delta^{18}\text{O}$ diagram. According to Nitta *et al.* (1987), Matsubaya believes that the geothermal fluids are formation waters related to Miocene sea water trapped in formations, since the geothermal fluids lie on a line connecting local ground waters and sea water on the chloride- $\delta^{18}\text{O}$ diagram (Fig. 13).

However, the isotopic composition of geothermal fluids are consistent with local meteoric water dilution of a fluid with composition similar to typical Japanese high temperature volcanic gases, the latter having values of +6 to +10 per mil for $\delta^{18}\text{O}$ and of -15 to -35 per mil for δD (Matsuo *et al.*, 1974; Mizutani *et al.*, 1986). This correlation suggests a significant contribution of magmatic fluids to this geothermal system, with acidity neutralized at depth. The same relationship for chloride- δD and $\delta^{18}\text{O}$ - δD

is noted for the Nigorikawa geothermal system (Yoshida, 1991), who argues for a sea water component.

The uncertainty of the fossil sea water hypothesis is indicated by the B/Cl and Br/Cl ratios. The B/Cl weight ratio of separated water from geothermal wells ranges from 0.006 to 0.021 (Nitta *et al.*, 1987; OAG, unpublished data, Table 5), much higher than that of sea water (0.00024). Also, the Br/Cl weight ratio is 0.0014 to 0.0020, versus 0.0034 of sea water.

Mineral-fluid saturation conditions

Saturation conditions of several minerals for the estimated reservoir fluid have been calculated. The estimated reservoir fluids (corrected for excess enthalpy sampling) of both 87N-14T and 87N-15T are undersaturated with respect to calcite ($\log Q/K$: -1.55 and -0.80), are saturated to oversaturated with anhydrite (+0.03 and +0.58), and are oversaturated with pyrite (+1.98 and +2.92) (Seki, 1990a), based on calculation using the chemical speciation code "PECS" (Takeno, 1988). Similar results were also obtained for other wells in the system (Fig. 14). Undersaturation of calcite is also indicated by the fact that all wells except 86N-10T

are free of calcite scaling (Nitta *et al.*, 1987).

The saturation index for K-feldspar varies from -1.7 to +1.6, and that for K-mica ranges widely from -2.8 to +5.4 (Fig. 14).

Fluid inclusion chemistry

The gas composition of fluid inclusions in anhydrite from 84N-2t, 86N-13t and 87N-18t were determined by crushing and chromatographic analysis (Takenouchi, 1988a and 1988b). The ranges of mole fractions of gases analyzed were CO₂: 0.87–0.95, N₂: 0.01–0.11 and CH₄: 0.01–0.04 (mole fraction), which basically agrees with the composition of the present fluids. The net CO₂ concentration in the inclusion liquid varies from 5.2 to 6.8 wt%, somewhat higher than that estimated here (about 1.0 wt%).

BASE METAL MINERALIZATION

Sulfide mineralization occurs as mainly veinlets in drill core, and consists of pyrite + / - sphalerite + / - galena + / - chalcopyrite from wells such as OA-4, OA-6, 84N-2t and 87N-15T (Table 7; NEDO, 1985; Nitta *et al.*, 1987; OAG, unpublished data). From drill cuttings of produc-

Table 7. Distribution of base metal sulfides in drilling cores and cuttings of geothermal wells (compiled from NEDO, 1985 and OAG, unpublished data). All data are elevations in m ASL.

Well	Sphalerite	Galena	Chalcopyrite
N57-OA-2	-41		-41, -120, -412
N57-OA-3		-944	
N57-OA-4	+65, -7, -21 -83 to -260	-21 -83 to -260	+65 -83 to -260
N58-OA-5		-381	
N58-OA-6	-656, -678, -1098		
N58-OA-7	-563, -570, -589	-570	-570
84N-2t	-687 to -764 -807, -873	-687 to -764 -873	-807
84N-4r	+239	+239	+275 to +239
84N-5t	-744, -981	-744	
85N-6T	+288 to +268		
87N-14T	+252 to +132 -88 to -108 -386 to -504		
87N-15T	+280 to +200 +140 to +100 -1457	-1457	

tion wells 87N-14T and 87N-15T, sphalerite and pyrite have been recognized by XRD (OAG, unpublished data). These sulfide minerals often have euhedral crystals coexisting with euhedral quartz $\pm$ anhydrite $\pm$ rhodochrosite, and are on the surface of the open-space fractures in production zones (Nitta *et al.*, 1987). In addition, the base metals in solution were found to be relatively high in separated waters from well discharges (e.g., 89N-21T and 89N-22T; Table 5). Therefore, this sulfide mineralization is considered to be the product of the current geothermal system (Imai *et al.*, 1988).

PRECIOUS METAL-BEARING SULFIDE SCALING

Sulfide scales are found on the inside casing wall of well 84N-2t, and inside the two-phase line of surface facilities at 87N-15T. The latter includes a significant amount of precious metals.

Minerals found in scale taken from the casing wall, from the 980 m depth to the well head of 84N-2t, are pyrrhotite, pyrite, alabandite, wurtzite (Mn-bearing), sphalerite (Mn-bearing), galena, cubanite, chalcopryrite, tetrahedrite, pyrargyrite, stibarsen, calcite and rhodochrosite (Imai *et al.*, 1987 and 1988). This well cuts the Chinoikezawa fault zone below about 1000 m depth. Measured temperature and pressure ranges for this section of well were 165 to 305°C and 7 to 117 kg/cm², respectively (Imai *et al.*, 1987 and 1988).

Sulfide scales precipitated in the two-phase line down stream of the well head pressure control valve of 87N-15T during a 141 day discharge test from November, 1987, to March, 1988. Total weight of the sulfide scales precipitated in the section was about 433 kg (Nitta *et al.*, 1991). Sulfide minerals of Au, Ag, Cu, Pb and Zn are concentrated just after the well head control valve, where a large pressure and temperature drop rapidly occurs (about 100°C and 50 kg/cm² decrease). The major mineral is tetrahedrite with fine grained galena. Sphalerite is also present, with a vesicular to compact texture (Abe *et al.*, 1990). The gold and silver con-

Fig. 15. Structural and fluid flow model of the Oku-aizu geothermal system. Abbreviations are the same as in Fig. 4.

centration ranges from 1.2 to 116 mg/kg and 0.04 to 3.49 wt%, respectively (Nitta *et al.*, 1991). The scales also have Cu, Pb and Zn maxima of 16.0 wt%, 15.0 wt% and 15.4 wt%, respectively (Nitta *et al.*, 1991; Aoki, 1989).

FLOW MODEL OF THE SYSTEM

By integrating the geological, thermal, structural, hydrological and geochemical information described above, the following model has been deduced for the overall structure of the pre-exploited geothermal system at Oku-aizu (Fig. 15).

The heat source probably exists under the SE extension of the Chinoikezawa fault zone, judging from the isotherm distribution at deeper levels (for example, -1200 m ASL; Fig. 7). This heat source is most likely a cooling silicic igneous body, perhaps related to the Yunotake rhyolites (0.2 to 0.5 Ma; Table 2) or the Numazawa volcano which is located about 10 km west of the

system and was active about 5000 years ago.

Underground fluid flow in the Oku-aizu system is strongly controlled by the fracture system accompanying the fault zones. The permeability of the bedrock (Takizawagawa Formation) in the production zone is generally quite low. Geothermal fluid rises along the deeper portion of the Chinoikezawa and probably Sarukurazawa fault zones, both of which are steeply dipping NE and striking NW. The zone of argillic alteration and the Miyashita mudstone member from about -800 m to +200 m ASL act as aquitards where open-space fractures are not connected. Consequently, the high temperature geothermal fluid which is ascending below the sealed zone does not easily discharge to shallow levels.

A portion of the convecting geothermal fluid discharges along the Takiyagawa fault, which strikes NE and dips steeply SE. This fault intersects the Chinoikezawa and Sarukurazawa fault zones at their NW ends. The outflow rises to the NE along the Takiyagawa fault, and is finally mixed with cold ground water near the surface. Some of the flow encounters a cold influx along the Oizawa fault zone near the intersection of the two fault systems. The Nishiyama hot springs (elevation: 290 m ASL) are discharges of these mixed fluids.

Underground fluid generally flows from south to north. Therefore, the expected recharge of the system may be to the south, an area of topographic high extending from Mt. Sarukuragatake (peak elevation: 907 m ASL; Fig. 2).

The reservoir was not boiling in its natural state, except for local upflow in some fractures. However, the fluid is presently boiling around the geothermal wells due to the discharge-induced pressure decrease.

The most conspicuous chemical characteristics of the geothermal system is the high salinity and large concentration of gases (dominantly CO_2). These characteristics, in conjunction with the trends in isotopic composition, suggest a significant contribution of magmatic fluid to the system. This may also account for the very high

temperatures (maximum measured temperature of 341°C at -2610 m of 89N-22T; OAG, unpublished data) in the deeper portion of the system. If true, then the acidic magmatic component has been neutralized before ascending to the drilled portion of the system.

CONCLUSIONS

The physical and chemical characteristics and a model of the Oku-aizu geothermal system are summarized as follows.

Geothermal fluid flow in the Oku-aizu geothermal system is strongly controlled by a fracture system. There are three major fracture zones called the Chinoikezawa, the Sarukurazawa and the Oizawa fault zones, striking NW and dipping steeply NE. The former two produce high enthalpy geothermal discharges.

A high temperature fluid convects upward until it is limited by a sealed zone composed of argillic alteration products such as smectite, interlayered illite-smectite and kaolinite. The Miyashita mudstone member, located approximately at the same elevation as the argillic alteration, also acts as an aquitard.

The system had little boiling in its natural state, judging from well discharges and measured temperature profiles during the initial stage of exploration. However, the reservoir is now boiling around geothermal wells due to the pressure drop caused by discharging of geothermal fluid. Consequently, all producing geothermal wells presently have excess enthalpy.

The deeper reservoir fluid has a high temperature (greater than 300°C), and is estimated to have a salinity of about 2 wt% and a large gas component (about 1 wt% CO_2 and 250 mg/kg H_2S).

The chemical characteristics of high salinity and gas contents are considered to be related to a magmatic component in the discharge. Isotopic characteristics and very high measured temperature (341°C), much higher than most geothermal systems in Japan, also support this idea.

Sulfide mineralization, such as pyrite, sphalerite, chalcopyrite and galena observed in

drill cores, appear to be related to the present geothermal fluid, judging from their mode of occurrence, high concentrations of base metals in solution, and the fact that similar sulfide is depositing in several geothermal wells in this system. Recently reported Au- and Ag-bearing sulfide scaling in two-phase lines in surface facilities indicates that the system is also transporting Au and Ag.

To improve our understanding of the evolution of the system, a detailed description of vein systems reflecting each stage of alteration are necessary, in particular focusing on overprinted alteration assemblages. Also, further study on the composition of the geothermal fluid and on water-rock interaction will help to confirm the proposed magmatic component to the system and understand its neutralization. Additional lithologic, volcanologic and structural studies will also contribute to the understanding of the volcano-tectonic evolution of this area, necessary to place the present hydrothermal system in a context of magmatic activity.

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