Origin of some gases from the Takinoue geothermal area in Japan

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(Received June 23, 1987; Accepted October 3, 1988)

Chemical and isotopic compositions were analyzed on geothermal steam from fumaroles and wells in the Takinoue geothermal area. The distribution of deuterium and oxygen-18 in water samples suggests that the fumarole steam discharge is formed from the rising geothermal fluid through a single-step steam separation process at temperatures of approximately 150–240°C. On the basis of N2/Ar, He/Ar and CO2/N2 ratios, and δ13C values of carbon dioxide in steam, it is concluded that the gas components dissolved in the Takinoue geothermal waters are mixtures of magmatic gases and meteoric waters.

INTRODUCTION

Geothermal fluids have been investigated to evaluate temperatures in geothermal reservoirs using solute or gas chemical geothermometers (e.g., Fournier and Rowe, 1966; Fournier and Truesdell, 1973; D’Amore and Panichi, 1980; Arnorsson and Gunnlaugsson, 1985). Dissolved constituents of geothermal fluids are derived mainly from reservoirs and/or surrounding rocks through water-rock interactions. Studies of isotopic ratios suggest that the waters in most hydothermal systems are mainly of meteoric origin (Craig, 1963; Panichi and Gonfiantini, 1978; Giggenbach, 1978; Kiyosu, 1986). However, the origin of gas components such as carbon and sulfur species in geothermal fluids has not yet been well discussed.

Yoshida (1984) found that the gases (N2, He and Ar) of the Matsukawa vapor-dominated geothermal fields are mixtures of deep-seated gases and atmospheric air dissolved in groundwater. Similarly, Kiyosu (1986) concluded that small amounts of volcanic gases must have been incorporated into the geothermal fluids from the Onikōbe area in Japan. However, the presence of magmatic gases in geothermal systems has not been clearly demonstrated.

The Takinoue hot water dominated type geothermal area is one of the most active geothermal systems in Japan (Fig. 1). Since May 1978, a power plant of 50 MW has been in full operation with geothermal steam from many production wells. Based on chemical and isotopic steam compositions, an attempt is made to relate the fumarole steam to the underground geothermal fluids. The origin of the various gas species in the Takinoue geothermal field is discussed also.

GEOLOGICAL OUTLINE OF GEOThERMAl FIELD

The Takinoue hot water type geothermal area, Iwate Prefecture, is situated in the Hachimantai volcanic group which belongs to the Nasu volcanic zone. The geology of the Takinoue geothermal field has been described by Nakamura and Sumi (1981). The Neogene sedimentary sequence, the Tamagawa welded tuffs and Quaternary volcanic rocks are recognized in the Takinoue geothermal area. The Neogene rocks are subdivided from lower to upper in section into the Obonai formation,
Fig. 1. Location of sampling points in the Takinoue geothermal area, Japan. 1~14: fumaroles; A, B, C, D and E: wells. A and B: SP-1; C: SP-2; D: KD-1; D and E: SP-3.

characterized by dacite and dacitic tuff; the Kunimitoge formation, consisting of black shale, dacitic tuff, andesitic tuff and altered andesite; the Takinoue-onsen formation, characterized by alternating beds of argillaceous rocks; and the Yamatsuda formation which is composed of sandstone, siltstone and tuff. Weak alkaline NaCl type hot springs and fumaroles are widespread in the area. Acid-sulfate thermal waters issue from mud pots in the surface alteration area. These waters have formed secondarily by surface mixing of groundwater with SO₄ from oxidation of H₂S and condensed steam from a boiling geothermal system at depth.

The rock alteration in this area consists of montmorillonite and chlorite zones. Secondary minerals such as pyrophyllite, kaolinite and alunite occur locally around fumaroles and acid hot springs (Kimbara et al., 1979).

Geothermal fluids are found in the highly permeable zones created by fault and fracture systems associated with folding in the Neogene sedimentary sequence (Sato, 1982).

**EXPERIMENTAL PROCEDURES**

Steam samples were collected from the main area of fumarole activity and wells from 1984 to 1985 by means modified from Ozawa's method (1966). Figure 1 shows the location of wells (A, B, C, D and E) and fumaroles (1~14) where samples were collected. The fumarolic temperatures were measured with a mercury thermometer.

The analytical methods used to determine water, carbon dioxide and hydrogen sulfide in the samples are similar to those used by Ozawa (1967). Other gases were analyzed by the gas chromatographic method (Yoshida, 1984; Kiyosu, 1985).

Isotopic analyses of water were carried out by established methods (Bigeleisen et al., 1952;
Friedman, 1953; Epstein and Mayeda, 1953). The carbon dioxide in the samples was precipitated as BaCO₃, then reconverted to CO₂ using phosphoric acid.

Hydrogen, oxygen and carbon isotope ratios were determined on a dual collector mass spectrometer. The results are given in terms of δ value:

\[ \delta X(\%) = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 10^3 \]

where \( X \) indicates D, ¹⁸O or ¹³C; \( R \) refers to D/H, ¹⁸O/¹⁶O or ¹³C/¹²C. The standard for hydrogen and oxygen in all cases is SMOW and that for carbon is PDB.

The overall reproducibility of samples was ±2.0‰ for hydrogen and ±0.1‰ for oxygen and ±0.2‰ for carbon.

**RESULTS AND DISCUSSION**

**Chemical composition of geothermal steam**

The analytical results for gas constituents are presented in Table 1. Total gas concentrations, exclusive of H₂O, are somewhat lower than those found for Matsukawa (Yoshida, 1984) and Onikobe (Kiyosu, 1986). The contents of gases in the fumarole steam vary, whereas those in well samples show a small variation.

The relative contents of the three main constituents, CO₂, H₂S and R-gas (alkali residual gases) are given in Fig. 2. It is evident that the data points fall into three areas. That is, steam samples in the Takinoue fumaroles are divided into three groups: 1) CO₂ type, 2) CO₂-H₂S type and 3) H₂S type. The CO₂ rich type steam is found around the central zone of fumarole activity, while the last two types of steam area associated with the main fumarole activity. The H₂S poor fumarole steam samples suggest that hydrogen sulfide is removed from the steam in the upflow. It seems likely that oxidation of hydrogen sulfide occurs when rising steam encounters meteoric water.

On the contrary, the well steam corresponds to the H₂S rich type. The well steam samples suggest that the composition of gas in the reservoir fluids is uniform. Conversely, the production wells at the Matsukawa geothermal field are divided into two groups: CO₂ type and H₂S type wells. CO₂ rich wells are located in a zone of weak alteration and other wells are located in the zones where hydrous minerals such as mont-

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**Table 1. Chemical composition of gas samples from the Takinoue geothermal area (vol.%)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temp. °C</th>
<th>H₂O</th>
<th>Gas</th>
<th>CO₂</th>
<th>H₂S</th>
<th>N₂</th>
<th>H₂</th>
<th>CH₄</th>
<th>Ar x 10⁻²</th>
<th>He x 10⁻⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-1</td>
<td>97.0</td>
<td>99.93</td>
<td>0.07</td>
<td>95.2</td>
<td>1.55</td>
<td>0.80</td>
<td>1.14</td>
<td>1.29</td>
<td>1.85</td>
<td>0.305</td>
</tr>
<tr>
<td>T-2</td>
<td>98.0</td>
<td>99.90</td>
<td>0.10</td>
<td>88.3</td>
<td>7.97</td>
<td>0.97</td>
<td>1.90</td>
<td>0.78</td>
<td>2.29</td>
<td>0.266</td>
</tr>
<tr>
<td>T-3</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>92.7</td>
<td>4.33</td>
<td>0.52</td>
<td>1.85</td>
<td>0.64</td>
<td>0.66</td>
<td>0.286</td>
</tr>
<tr>
<td>T-4</td>
<td>99.0</td>
<td>99.96</td>
<td>0.04</td>
<td>76.1</td>
<td>15.1</td>
<td>5.33</td>
<td>2.80</td>
<td>0.58</td>
<td>12.2</td>
<td>0.699</td>
</tr>
<tr>
<td>T-5</td>
<td>99.0</td>
<td>99.96</td>
<td>0.04</td>
<td>80.2</td>
<td>12.3</td>
<td>4.78</td>
<td>2.27</td>
<td>0.39</td>
<td>10.5</td>
<td>0.583</td>
</tr>
<tr>
<td>T-6</td>
<td>98.0</td>
<td>99.95</td>
<td>0.05</td>
<td>81.8</td>
<td>12.5</td>
<td>3.07</td>
<td>0.58</td>
<td>2.03</td>
<td>5.52</td>
<td>1.14</td>
</tr>
<tr>
<td>T-7</td>
<td>98.0</td>
<td>99.92</td>
<td>0.08</td>
<td>81.7</td>
<td>13.8</td>
<td>0.79</td>
<td>3.04</td>
<td>0.65</td>
<td>1.84</td>
<td>0.575</td>
</tr>
<tr>
<td>T-8</td>
<td>98.0</td>
<td>99.94</td>
<td>0.06</td>
<td>70.5</td>
<td>24.6</td>
<td>0.61</td>
<td>3.90</td>
<td>0.38</td>
<td>1.52</td>
<td>0.111</td>
</tr>
<tr>
<td>T-9</td>
<td>97.0</td>
<td>99.94</td>
<td>0.06</td>
<td>76.0</td>
<td>18.0</td>
<td>0.87</td>
<td>4.99</td>
<td>0.22</td>
<td>2.20</td>
<td>0.12</td>
</tr>
<tr>
<td>T-10</td>
<td>98.6</td>
<td>99.93</td>
<td>0.07</td>
<td>58.7</td>
<td>32.5</td>
<td>4.32</td>
<td>3.37</td>
<td>1.01</td>
<td>9.59</td>
<td>7.83</td>
</tr>
<tr>
<td>T-11</td>
<td>98.0</td>
<td>99.96</td>
<td>0.04</td>
<td>58.9</td>
<td>22.9</td>
<td>9.74</td>
<td>6.73</td>
<td>1.51</td>
<td>22.8</td>
<td>15.7</td>
</tr>
<tr>
<td>T-12</td>
<td>98.0</td>
<td>99.98</td>
<td>0.02</td>
<td>71.3</td>
<td>24.1</td>
<td>1.87</td>
<td>0.39</td>
<td>1.20</td>
<td>3.92</td>
<td>1.61</td>
</tr>
<tr>
<td>T-13</td>
<td>—</td>
<td>99.67</td>
<td>0.33</td>
<td>61.8</td>
<td>32.6</td>
<td>1.61</td>
<td>3.46</td>
<td>0.50</td>
<td>3.53</td>
<td>0.368</td>
</tr>
<tr>
<td>T-14</td>
<td>—</td>
<td>99.62</td>
<td>0.38</td>
<td>69.5</td>
<td>26.8</td>
<td>0.77</td>
<td>2.29</td>
<td>0.63</td>
<td>1.41</td>
<td>0.485</td>
</tr>
<tr>
<td>KD-1</td>
<td>—</td>
<td>99.94</td>
<td>0.06</td>
<td>72.2</td>
<td>20.6</td>
<td>4.47</td>
<td>0.52</td>
<td>2.09</td>
<td>12.7</td>
<td>1.57</td>
</tr>
<tr>
<td>SP-1</td>
<td>—</td>
<td>99.98</td>
<td>0.02</td>
<td>61.1</td>
<td>30.2</td>
<td>2.05</td>
<td>5.87</td>
<td>0.74</td>
<td>4.00</td>
<td>0.765</td>
</tr>
<tr>
<td>SP-2</td>
<td>—</td>
<td>99.97</td>
<td>0.03</td>
<td>73.8</td>
<td>18.7</td>
<td>2.72</td>
<td>2.70</td>
<td>2.03</td>
<td>5.48</td>
<td>1.31</td>
</tr>
<tr>
<td>SP-3</td>
<td>—</td>
<td>99.96</td>
<td>0.04</td>
<td>65.2</td>
<td>26.9</td>
<td>4.23</td>
<td>1.95</td>
<td>1.65</td>
<td>6.95</td>
<td>1.82</td>
</tr>
</tbody>
</table>

*T: Fumarole. KD, SP: Well.*
morillonite, kaolinite and alunite are distributed (Yoshida, 1984). This suggests that H$_2$S concentrations in the reservoir fluids increase with increasing contribution of hydrothermal alteration. The H$_2$S concentration is probably controlled by the activity of sulfur in the water-rock interactions (Giggenbach, 1981; Kiyosu, 1987).

Although variation in fumarole gas chemistry is observed in the Takinoue geothermal field, its cause is not yet clear from the present study.

**Isotopic composition of steam**

Isotopic data for deuterium and oxygen-18 are given in Table 2 and Fig. 3. Fumarolic steam from Takinoue range from $-71.5\%$ to $-83.5\%$ for $\delta$D and from $-10.9\%$ to $-14.5\%$ for $\delta^{18}$O and $\delta^{13}$C$_{CO_2}$ in Table 2.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\delta$D</th>
<th>$\delta^{18}$O</th>
<th>$\delta^{13}$C$_{CO_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-1</td>
<td>$-78.0$</td>
<td>$-12.2$</td>
<td>$-5.5$</td>
</tr>
<tr>
<td>T-2</td>
<td>$-83.5$</td>
<td>$-14.5$</td>
<td>$-5.8$</td>
</tr>
<tr>
<td>T-3</td>
<td>$-75.4$</td>
<td>$-11.6$</td>
<td>$-6.1$</td>
</tr>
<tr>
<td>T-4</td>
<td>$-72.1$</td>
<td>$-11.4$</td>
<td>$-7.4$</td>
</tr>
<tr>
<td>T-5</td>
<td>$-74.3$</td>
<td>$-10.9$</td>
<td>$-7.6$</td>
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<tr>
<td>T-6</td>
<td>$-76.2$</td>
<td>$-11.6$</td>
<td>$-7.2$</td>
</tr>
<tr>
<td>T-7</td>
<td>$-75.4$</td>
<td>$-11.6$</td>
<td>$-6.1$</td>
</tr>
<tr>
<td>T-8</td>
<td>$-72.1$</td>
<td>$-11.4$</td>
<td>$-7.4$</td>
</tr>
<tr>
<td>T-9</td>
<td>$-80.9$</td>
<td>$-13.3$</td>
<td>$-6.2$</td>
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<tr>
<td>T-10</td>
<td>$-81.9$</td>
<td>$-12.3$</td>
<td>$-7.5$</td>
</tr>
<tr>
<td>T-11</td>
<td>$-72.5$</td>
<td>$-12.0$</td>
<td>$-6.1$</td>
</tr>
<tr>
<td>T-12</td>
<td>$-74.2$</td>
<td>$-11.7$</td>
<td>$-8.3$</td>
</tr>
<tr>
<td>M. W.</td>
<td>$-69.0$</td>
<td>$-11.0$</td>
<td>$-6.8$</td>
</tr>
</tbody>
</table>

*M. W.: Kakkondagawa, river water. T: Fumarole.*
are consistently lighter than the surface water ($\delta D = -69.0\%$ and $\delta^{18}O = -11.0\%$). Similar results were observed in low temperature fumaroles around some volcanoes in northeastern Japan (Kiyosu, 1983). This is interpreted to be a result of liquid-vapor separation by boiling, probably before or after the mixing of ground water with geothermal fluids as described below. The well waters exhibit an oxygen isotope shift of up to 2.7% relative to waters on the local meteoric water line having the same deuterium concentration (Matsubaya et al., 1985). This indicates that the reservoir water is meteoric in origin.

The isotopic variation of geothermal fluids during their rise to the surface results from deep thermal waters that boil with decreasing pressure and dilution by surface waters (Giggenbach and Stewart, 1982).

According to Akeno (1978) the various solute geothermometers in the Takinoue deep wells give reservoir temperatures of 220° to 260°C. Therefore, we assume that the temperatures of the original deep thermal waters before steam separation or dilution, and meteoric waters are 240° and 10°C, respectively. The isotopic compositions of thermal water and steam after boiling were calculated for the temperature range 100° – 240°C using the following equations (1), (2) and (3) by assuming that underground steam separation from single phase thermal waters is a single-step process.

\[
\begin{align*}
\delta_s &+ \delta_w (1 - y_s) = \delta_o \\
\delta_s &= (H_o - H_w) / (H_s - H_w) \\
\delta_w &= \delta_o + 10^3(\alpha - 1)y_s
\end{align*}
\]

where $\delta_w$, $\delta_s$ and $\delta_o$ are the isotopic compositions of thermal water and steam after boiling and original deep thermal water, respectively. $y_s$ indicates a steam fraction. $H_w$, $H_s$ and $H_o$ are the enthalpies of the thermal water and steam at the

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**Fig. 3.** Isotopic diagram of steam and water formed from an original deep water of 240°C at various separation temperatures or after dilution with local groundwater in the Takinoue area. Small open and closed circles and tie lines show calculated isotopic compositions of steam and water separated at the indicated temperatures. Open circles: data points for steam samples from fumaroles; Closed circles: NaCl type hot spring water samples (Kiyosu, unpublished data); C-2: well sample (Matsubaya et al., 1985). M. W. L.: meteoric water line.
separation temperature and original deep thermal water, respectively. $\alpha$ is the equilibrium constant between liquid and steam waters. In Fig. 3, variations in isotopic compositions of steam and water after steam loss are given as a function of temperature. Steam separation accompanying adiabatic-expansion from 100° to 240°C leads to a decrease in $\delta D$ and $\delta^{18}O$ of steam and an increase in isotope compositions of thermal water. Some data points for CO$_2$–H$_2$S and H$_2$S type fumarolic steam, and NaCl type hot spring water lie close to the lines representing steam separation from undiluted deep water at temperatures ranging from 140° to 200°C. These separation temperatures are consistent with the deuterium (H$_2$–H$_2$O) temperatures of 140° – 220°C for some Takinoue fumaroles obtained by Kiyosu (1987).

On the other hand, the isotopic compositions of the diluted thermal water produced by mixing deep thermal water with local surface waters and steams from its diluted water are obtained by combining the following equations (4), (5) with (3).

\[
\delta_D y_o + \delta_m (1 - y_o) = \delta_w \quad (4)
\]
\[
y_o = \frac{(H_w - H_m)}{(H_o - H_m)} \quad (5)
\]

where $y_o$ represents the fraction of deep thermal water and $H_m$ is the enthalpy of meteoric water. $\delta_m$ indicates the isotopic composition of meteoric water. Data points for CO$_2$ and CO$_2$–H$_2$S type fumaroles occupy positions close to the steam line separated from the original diluted water.

The variation in isotopic composition of fumarole steam is, therefore, likely to reflect the effects of dilution and steam separation of approximately 200°C from the original deep liquid phase during their ascent to the surface.

Isotopic composition of carbon dioxide

Carbon isotope composition of CO$_2$ in the fumarole steam (Table 2) ranges from $-5.5$ to $-8.3\%$ with an average of $-6.8\%$, in good agreement with those in values associated with steam from wells ranging from $-6.4$ to $-7.9\%$ (Yamamoto, 1981). This indicates that the carbon dioxide of fumarolic and well samples at Takinoue comes from a uniform carbon source. These values are in accordance with those from Matsukawa but lighter than the mean $-3.4\%$ at Onikôbe (Kiyosu, 1986). The carbon isotopic composition of CO$_2$ dissolved in surface water is found to be $-6.8\%$ which is close to the atmospheric CO$_2$ value.

Kiyosu (1984) found that volcanic carbon dioxide as well as net-carbon discharges from some active andesite volcanoes in northeastern Japan have varying isotope ratios from $-2$ to $-10\%$ showing a trend that the $\delta^{13}C$ value becomes lighter as groundwater is increased. This variation may indicate that mixing of carbon dioxide derived from other carbon sources with volcanic carbon occurred. On the other hand, the magmatic carbon has an isotopic composition in the range $-6$ to $-8\%$ (e.g., Allard et al., 1977; Deines, 1980) which is consistent with the volcanic carbon. Because the carbon isotope composition is mostly similar to that of magmatic carbon, the geothermal carbon dioxide in Takinoue does not appear to be significantly contaminated with other CO$_2$ sources such as organic matter of $\delta^{13}C = -25\%$ or marine limestone ($\delta^{13}C = -1$ to $1\%$) during its ascent to the surface from the reservoir.

Mixtures of magmatic and atmospheric carbon could account for the Takinoue geothermal CO$_2$ described below.

Origin of geothermal gases

N$_2$/Ar ratios of the fumarole and well gas samples are plotted against the He/Ar ratios together with those of the Matsukawa geothermal system (Fig. 4). The data points from both geothermal areas occupy positions along a line that Kiyosu (1985) has evaluated in northeastern Japan as having originated from meteoric water toward magmatic gas. The mixing ratio of magmatic gases in the Takinoue and Matsukawa geothermal fluids is $\sim 0.1$ and $\sim 1.0\%$.

Yoshida (1984) pointed out that a small part of these gas components at Matsukawa is deriv-
Gases from Takinoue geothermal area, Japan

Fig. 4. Relationship between N2/Ar and He/Ar ratios of geothermal gases. Open and closed circles indicate the Matsukawa well samples (Yoshida, 1984) and Takinoue samples, respectively. KD-1, SP-1, SP-2 and SP-3: wells; 1～14: fumaroles. ◊: air dissolved in water at 10°C (N2/Ar=41, He/Ar=1.5 × 10^-4). Solid line shows calculated simple mixing between magmatic gases (N2/Ar=4250, He/Ar=2.1) and air dissolved in water at 10°C (Kiyosu, 1985). The figures beside the curve indicate a fraction of the magmatic component in the mixing.

...ed from a deep seated source, not from the reservoir. The same conclusion was obtained in the Onikobe geothermal system (Kiyosu, 1986).

As shown in Fig. 5, although there is a correlation between CO2/N2 and N2/Ar ratios, the data points deviate from the mixing line which represents the composition of magmatic gas mixtures for all andesitic volcanoes with air dissolved in groundwater (Kiyosu, 1985). One possibility for this deviation is that an extraneous carbon dioxide has been added into geothermal gases with a constant CO2/N2 ratio, representing a mixture of magmatic gases and air dissolved in groundwater. However, the carbon isotope of geothermal CO2 would not point to such a possible soil or biogenic origin. The other possibility is that even if these gases are completely dissolved in the deep thermal water, vapor-liquid separation of thermal waters during their ascent to the surface leads to variations in the ratio of gases present in a well discharge.

Assuming that the geothermal fluids originate from the mixing of volcanic gases and meteoric water at depth prior to boiling, fumarolic steam corresponds to vapor phase formed by adiabatic boiling of the deep fluids. According to Giggenbach (1980), the discharge gas content Xce,i is represented by

\[ X_{ce,i} = X_{ce}(1 - y + yB)z = X_{ce}D_i^z \]  (6)
where \( X_{i,l} \) indicates the mole fraction of liquid; \( y \) is a fraction of vapor; \( B \) represents the coefficient describing the distribution of gases between vapor and liquid phase; \( D = 1 - y + yB \). The plus and minus signs refer to vapor gain or loss, respectively. Based on gas components, \( C_1 \) and \( C_2 \), the gas ratio is defined by the following pressure independent equation derived from equation (6),

\[
\frac{X_1}{X_2} = \frac{(X_1/X_2)(D_1/D_2)^{1/2}}{(X_1/X_2)_{M} + (1-f)(X_1/X_2)_{m}}.
\]

At the same time, the geothermal fluids are mixtures of magmatic gases and meteoric water as represented in the following equation (Kiyosu, 1985):

\[
(X_1/X_2)_{c} = f(X_1/X_2)_{M} + (1-f)(X_1/X_2)_{m},
\]

where \( M \) and \( m \) refer to magmatic gases and meteoric water, respectively; \( f \) represents the fraction of magmatic gases. The variation in \( N_2/Ar \), \( He/Ar \) and \( CO_2/N_2 \) ratios of geothermal fluids expected from the boiling and mixing at 240°C can be evaluated using equations (7) and (8) and is shown in Figs. 6 and 7.

In summary, the variations in \( N_2/Ar \) and \( He/Ar \) ratios are due to mixing, not boiling. Conversely, the \( CO_2/N_2 \) ratio varied due to the boiling process. From Fig. 7, it is also found that the gas components released from the Takinouge geothermal system correspond to gases complete-
Fig. 6. Relationship between $N_2/Ar$ and $He/Ar$ ratios of vapor and liquid phases separated from an original deep water of 240°C. Closed circle represents well samples. $y$ is a fraction of vapor. $f$ indicates a fraction of magmatic gases. $\ominus$: air dissolved in water at 10°C.

Fig. 7. Relationship between $CO_2/N_2$ and $N_2/Ar$ ratios of vapor and liquid phases separated from an original deep water of 240°C. Closed circle represents well samples. $y$ is a fraction of vapor. $f$ indicates a fraction of magmatic gases. $\oplus$: magmatic gases.
Acknowledgments—The authors wish to thank Dr. H. Shigeno of the Geological Survey of Japan for comments on the earlier version of this manuscript. This study was supported in part by Japanese Grant-in-Aid for Scientific Research, Nos, 58045062 and 59045067.

REFERENCES


Giggenbach, W. F. (1978) The isotopic composition of waters from the El Tatio geothermal field, Nor-

Fig. 8. Plot of $\delta^{13}$C values of CO₂ versus CO₂/N₂ ratios. Dotted and closed circles indicate the well (Yamamoto, 1981) and fumarole samples, respectively. $\phi$: magmatic gases dissolved in water at 240°C which were calculated using data from Kiyosu (1984, 1985) (CO₂/N₂=2170, $\delta^{13}$C CO₂ = $-4.0\%$).

ly dissolved in the deep liquid phase at depth, and that the geothermal gases in this area are derived from a mixture of magmatic gases and meteoric water.

Figure 8 shows the plots of $\delta^{13}$C value for the carbon dioxide versus CO₂/N₂ ratio in liquid phase from the Takinoue geothermal area. The CO₂/N₂ ratios of gases vary widely because of the boiling process, but $\delta^{13}$C value of carbon dioxide is rather uniform at approximately $-6$ to $-8\%$. Most of the data points lie close to the mixing line between magmatic gases and CO₂ dissolved in surface water, although the contribution from the volcanic source appears to be small. This finding is consistent with the results obtained from the relationship between CO₂/N₂ and N₂/Ar ratios.
Gases from Takinoue geothermal area, Japan


