温泉科学（J. Hot Spring Sci.），70，70–79（2020）

短　　報

Abnormal Discharge of High-temperature Hot Spring Water Observed at the Abandoned Well in the Okuhida Hot Spring Area during the Earthquake Swarm Occurred at Gifu-Nagano District, Central Japan

Muga YAGUCHI[1)]

(Received Jun. 4, 2020, Accepted Jun. 29, 2020)

岐阜–長野地方の群発地震に伴って観測された奥飛騨温泉郷の枯渇源泉の異常湧出

谷　口　無　我[1)]

要　　旨

2020年4月下旬から長野県中部–岐阜県飛騨地方を震源とする地震が頻発し，この地震活動に伴って奥飛騨温泉郷の枯渇源泉から高温泉が再湧出した．奥飛騨温泉郷は活火山の焼岳の西方約4kmに位置するため，今回観測された高温泉の再湧出現象が焼岳の火山活動に起因するかどうかを調べるために，温泉水の主要化学組成および水素・酸素安定同位体組成を分析した．

その結果，再湧出した温泉水は天水を主体とする中性の Na-HCO_3・Cl 型で，地化学温度計による推定では温泉貯留層の温度は142–177℃と推定された．本研究で推定した温泉水の起源，水質および貯留層温度はいずれも既往研究による報告と同質・同等であり，今回観察された枯渇源泉からの高温泉の再湧出が最近の焼岳の火山活動の変化に起因する証拠は見出せなかった．

キーワード：焼岳，奥飛騨温泉郷，地震，異常湧出，化学・安定同位体（δD，$\delta^{18}O$）組成，地化学温度計

Abstract

Since late April 2020, earthquakes in the central Nagano Prefecture and the Hida region of Gifu Prefecture have increased. During this seismic activity, an abnormal discharge of high-temperature hot spring water was observed at the abandoned well in the Okuhida hot spring area. As the Okuhida hot spring area is located about 4 km west of Yakedake volcano, the major chemical and stable isotopic compositions of hydrogen and oxygen of the discharged

[1)] Department of Volcanology Research, Meteorological Research Institute, Japan Meteorological Agency, 1–1 Nagamine, Tsukuba, Ibaraki 305–0052, Japan. E-mail：myaguchi@mri-jma.go.jp [1)] 気象庁気象研究所火山研究部　〒305–0052　茨城県つくば市長峰1–1.

water were analyzed to investigate whether this abnormal discharge phenomena is caused by the volcanic activity of Yakedake volcano.

The analysis revealed the water was predominantly meteoric in origin, having a neutral pH and Na-HCO_3・Cl type, and the reservoir temperature was estimated to be 142–177℃ by the geochemical thermometer. The origin, water quality, and reservoir temperature estimated in this study were comparable to those in previous studies ; no evidence was found that the abnormal discharge observed at the abandoned well was caused by recent changes in the volcanic activity of Yakedake volcano.

Key words : Yakedake volcano, Okuhida hot spring area, earthquakes, abnormal discharge, chemical and isotopic (δD and $\delta^{18}O$) compositions, geothermometer

1. Introduction

Since approximately 2 : 00 am on April 22, 2020, frequent earthquakes have occurred in the central Nagano Prefecture and the Hida region of Gifu Prefecture (Fig. 1a and b). In this region, seismicity was also active in 1998, and the maximum seismic intensity of 5-lower was observed on August 7, 1998 (Gifu Meteorological Office, 2020). In 2020 activity, the maximum seismic intensities of 4 were observed on April 23 in Matsumoto City of Nagano Prefecture and on May 19 and 29 in Takayama City of Gifu Prefecture, and after that, earthquakes with seismic intensity 2–1 continued to occur (Fig. 1c and Gifu Meteorological Office, 2020 a and b). The recent earthquake information is available on the web site of the seismic intensity database of Japan Meteorological Agency.

During this seismic activity, an abnormal discharge of high-temperature hot spring water from an abandoned hot spring source well in the Okuhida hot spring area of Takayama City was observed. The Okuhida hot spring area consists of five hot spring groups, Shin-Hodaka, Tochio, Shin-Hirayu, Fukuji, and Hirayu Onsen (Fig. 2). There are many high-temperature hot springs in this area (maximum outlet temperature is about 98℃), and one of the assumed heat sources of these hot springs is an active volcano, such as Yakedake that is located 4 km east of the hot spring area (Furuta, 2020). Based on chemical and isotopic analyses, the origin of those hot spring waters is considered mostly meteoric, but it has been pointed out that the hot spring waters may contain a small amount of volcanic fluid (Mizutani *et al*., 1980 ; Koji *et al*., 2016). Therefore, in this study, the major chemical and stable isotopic compositions of hydrogen and oxygen of the water sampled at the abandoned well were analyzed to investigate whether the abnormal discharge is caused by the volcanic activity.

2. Hot spring sample and Analyses

Abnormal discharge of high-temperature hot spring was observed at an abandoned well of the Okuhida Garden Hotel YAKEDAKE in the Shin-Hirayu hot spring group (Fig. 2). According to an interview with the hotel, detailed information on this abandoned well, such as a drilling data and hot spring analysis data, has already been lost, but the bottom depth of this well was 50 m, the outlet temperature was 70℃ or more, and the discharged rate was about 500 L/min, at the time when the source was in use. This well stopped about 30 years ago due to scale clogging

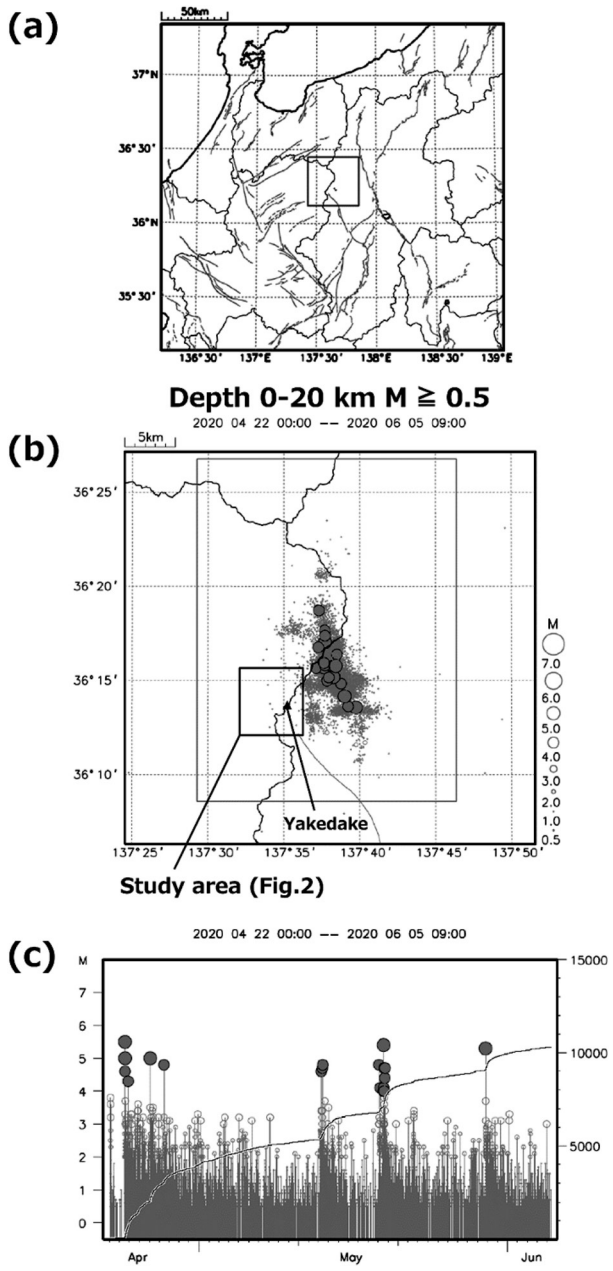

Fig. 1 Seismic activity around the Gifu-Nagano district (modified after original data from Japan Meteorological Agency). (a) Index map. (b) Epicentral map. (c) Magnitude—Time diagram of earthquakes.

and was abandoned. The well was once cleaned more than 10 years after it stopped, but the hot spring water was not discharged and was abandoned.

The abnormal discharge reported in this paper was a temporary phenomenon, observed twice from 07 : 00 on May 10 to 15 : 00 on the following day and from 07 : 00 to 09 : 20 on May

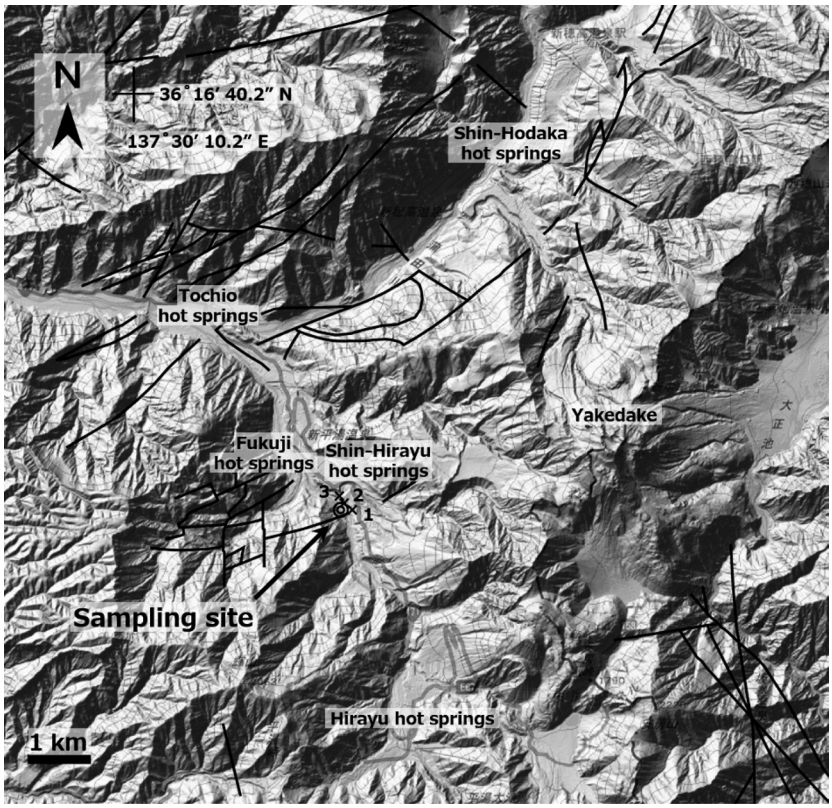

Fig. 2　Index map of sampling site and Okuhida hot spring area. Base map was created by overlaying the standard and shaded relief map of the Geographical Survey Institute of Japan and a seamless geological map of the Geological Survey of Japan. The double circle (◎) shows the abandoned well. Cross marks (×) are source wells currently in use near the abandoned well. The solid lines show the fault and estimated fault.

19 (Fig. 3a and b). Afterward, the water discharge stopped again (Fig. 3c). The water was collected at approximately 08 : 30 on May 19, and the temperature was 77℃.

Analyses were conducted at the Meteorological Research Institute. The pH and electrical conductivity were measured using a handheld pH/EC meter (Horiba, D-74) equipped with a glass electrode (Horiba, 9615S-10D) for the pH measurement and a platinum-platinum black electrode (Horiba, 3552-10D) for the EC measurement. The concentrations of F, Cl, and SO_4 were measured by using ion chromatography (Thermo Scientific, Dionex Integrion HPIC), and Na, K, Ca, Mg SiO_2 were measured by using a microwave plasma atomic emission spectrometer (Agilent, 4210 MP-AES). The total alkalinity as HCO_3^- was determined by titration with H_2SO_4 to the final pH of 4.8 (Hach, AL-DT). Stable isotope ratios (δD and $\delta^{18}O$) were analyzed by using a cavity ring-down spectrometer (Picarro, L2140-i) and reported in per mil (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW). The analytical results are listed in Table 1.

Fig. 3 Photograph of the abandoned well. During the abnormal discharge (May 19, 2020 ; a and b). After the discharge stops (May 27, 2020 ; c).

3. Results and Discussion

3.1 Isotopic composition

As the δD and $\delta^{18}O$ values of hot spring waters in the Okuhida area are almost the same as the value of river water in the area, the hot spring waters are considered basically meteoric. However, it is suspected that the hot spring waters in this area either contain volcanic water or are affected by evaporation because some hot spring waters have δD and $\delta^{18}O$ values close to the volcanic gases of Yakedake volcano (Sugiura and Mizutani, 1978 ; Mizutani *et al*., 1980 ; Koji *et al*., 2016). Further investigation is needed to determine whether the reason for such a heavy isotope ratio is due to the contribution of volcanic gas or evaporation, but in any case, the δD and $\delta^{18}O$ values of the hot spring water collected in this study is in good agreement with the meteoric line; there is no effect of volcanic water or evaporative concentration (Fig. 4).

3.2 Geochemical feature of the sampled water

In general, hot springs containing magmatic volatiles have low pH and are rich in SO_4^{2-} and Cl (e.g., Iwasaki, 1976). However, the hot spring water collected in this study has a neutral pH of 7.23 with a Na-HCO_3・Cl type and does not contain much SO_4^{2-} (Table 1). This quality is very

Table 1　Analytical results of the discharged water sampled on May 19, 2020, with reference values for the Okuhida hot spring area.

Hot springs	Sample Date	Temp ˚C	E.C. S/m	pH	F mg/L	Cl mg/L	SO_4 mg/L	Na mg/L	K mg/L
Discharged water from abandoned well [1]	May 19, 2020	77	0.306	7.23	1.1	398	3.6	532	37.3
Data below the broken line are references									
Source well near the abandoned well 1 [2]	Nov. 16, 2000	57.2	N.D.	6.67	1.0	382	0.5	514	35.3
Source well near the abandoned well 1 [3]	July 7, 2010	70.8	N.D.	7.00	1.2	350	N.D.	527	38.5
Source well near the abandoned well 2 [4]	Sep. 26, 2011	67.1	N.D.	6.69	1.0	152	5.9	280	25.6
Source well near the abandoned well 3 [5]	July 5, 2013	56.3	N.D.	6.68	0.9	96	6.4	195	18.9
Shin-Hirayu [6]	May－Sep., 2012	28.7－68.2	0.037－0.34	5.75－7.21	N.D.	13－422	14－32	35－614	2.7－29
Hirayu [6]	May－Sep., 2012	49.0－74.8	0.121－0.0184	6.10－6.63	N.D.	86－281	34－222	121－258	7.6－26
Fukuji [6]	May, 2012	47.7－67.1	0.086－0.123	6.25－6.58	N.D.	13－90	15－33	116－193	12－19
Tochio [6]	Sep., 2012	63.2	0.08	7.14	N.D.	123	13	121	5.2
Shin-Hodaka [6]	May, 2012	63.0－82.3	0.068－0.174	6.27－7.74	N.D.	70－230	33－51	125－333	12－36

Hot springs	Ca mg/L	Mg mg/L	HCO_3 mg/L	SiO_2 mg/L	δD ‰	$\delta^{18}O$ ‰	Geothermometer Na-K[7]	Na-K-Ca[8]	SiO_2[9]
Discharged water from abandoned well [1]	71.0	26.0	1305	193	-81.6	-11.26	152	142	177
Data below the broken line are references									
Source well near the abandoned well 1 [2]	117	50.8	1408	135	N.D.	N.D.	150	124	155
Source well near the abandoned well 1 [3]	110	31.2	1407	135	N.D.	N.D.	156	130	155
Source well near the abandoned well 2 [4]	99.1	35.8	982.0	202	N.D.	N.D.	178	108	181
Source well near the abandoned well 3 [5]	85.5	30.8	828.6	180	N.D.	N.D.	184	96	173
Shin-Hirayu [6]	23－106	3.2－65	160－1183	61－143	-80.4－-74.5	-11.72－-11.15	117－230	35－125	111－157
Hirayu [6]	39－274	10－92	151－780	52－146	-84.5－-80.4	-12.58－-11.56	104－222	58－125	102－158
Fukuji [6]	43－53	3.3－16	465－545	122－130	-78.1－-75.8	-11.46－-11.40	188－197	91－108	147－151
Tochio [6]	32	0.2	208	119	-79.6	-11.87	112	69	146
Shin-Hodaka [6]	16－49	1.8－12	124－510	66－213	-83.6－-76.3	-11.48－-10.11	145－198	101－150	114－183

* N.D., No data.; E.C., Electrical conductivity; Si is expressed as SiO_2.

[1] Sampled at the point marked with "◎" in Fig. 2. Analyzed in this study.

[2] Source well located at the point marked with "×1" in Fig. 2. Data from the website of the Okuhida Garden Hotel YAKEDAKE.

[3] Source well located at the point marked with "×1" in Fig. 2. Data from Nagano Pharmaceutical Association (2010).

[4] Source well located at the point marked with "×2" in Fig. 2. Data from Nagano Pharmaceutical Association (2011).

[5] Source well located at the point marked with "×3" in Fig. 2. Data from Nagano Pharmaceutical Association (2013).

[6] Data from Koji et al., (2016).　[7] Truesdell (1976).　[8] Fournier and Truesdell (1973).　[9] Fournier (1977).

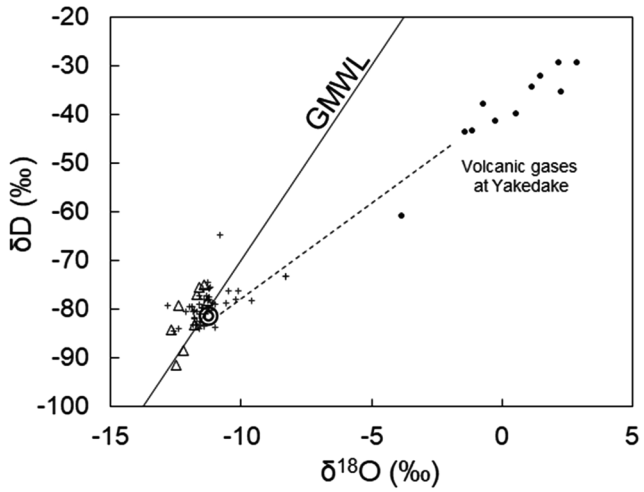

Fig. 4 δD-δ^{18}O diagram for sampled water and the Okuhida hot spring area. ◎, water sampled on May 19, 2020 ; ●, volcanic gases of Yakedake (Sugiura and Mizutani, 1978) ; +, hot spring waters in the Okuhida hot spring area (Sugiura and Mizutani, 1978 ; Koji *et al*., 2016) ; △, river water in the Okuhida hot spring area (Sugiura and Mizutani, 1978 ; Koji *et al*., 2016) ; GMWL, global meteoric water line (δD=8・δ^{18}O+10) from Craig (1961).

similar to the hot spring water currently in use at the Okuhida Garden Hotel YAKEDAKE (Table 1). Furthermore, the neutral Na-HCO_3・Cl type has been typical in the Okuhida hot spring area for more than 40 years (Mizutani *et al*., 1980 ; Kawamoto *et al*., 1984 ; Koji *et al*., 2016 ; Furuta, 2020). Therefore, the effect of abnormal volcanic activity cannot be detected based on the chemical composition of the hot spring water that discharged from the abandoned well.

3.3 Estimation of reservoir temperature using geothermometer

If the volcanic activity of Yakedake increases, underground temperatures may rise. To investigate this possibility, the reservoir temperature of the hot spring discharged from the abandoned well was estimated by applying a geochemical thermometer. There are various methods and application conditions for geochemical thermometers, but here, I used a Na-K geothermometer (Truesdell, 1976 ; Equation 1), a Na-K-Ca geothermometer (Fournier and Truesdell, 1973 ; Equation 2), and a SiO_2 geothermometer (Fournier, 1977 ; Equation 3), which have been applied in the analysis of geothermal resources in the Okuhida hot spring area (Koji *et al*., 2016).

Na-K (Truesdell, 1976) :

$$T\,(℃) = \frac{855.6}{\log\,(Na/K) + 0.857} - 273.15 \qquad (1)$$

**Na and K in mg/L*

Na-K-Ca (Fournier and Truesdell, 1973) :

$$T\,(℃) = \frac{1647}{\log (Na/K) + 4/3\,[\log (Ca^{1/2}/Na) + 2.06] + 2.47} - 273.15 \qquad (2)$$

**Na, K and Ca in mg/L*

SiO_2, no stream loss (Fournier, 1977) :

$$T\,(℃) = \frac{1309}{5.19 - \log SiO_2} - 273.15 \qquad (3)$$

**SiO_2 in mg/L*

As a result, the reservoir temperature of the hot spring water discharged from the abandoned well was estimated to be 142–177℃ (Table 1). Although we must be cautious that the same source should be compared to investigate the temporal change of the reservoir temperature because the reservoir temperature varies even in a narrow area, the estimated temperature of 142–177℃ is within the range estimated from the analytical value of the source wells near the abandoned well (96–184℃ : Table 1) and is also reasonable as the previously estimated reservoir temperature in the Okuhida hot spring area (approximately 150–200℃ : Mizutani *et al*., 1980 ; Koji *et al*., 2016). Therefore, based on this estimation, there is no evidence that the abnormal discharge observed at the abandoned well was caused by the underground temperature change due to the volcanic activity of Yakedake volcano.

4. Concluding remarks

During the seismic activity at the Gifu–Nagano district, abnormal discharge phenomena of high-temperature hot spring water from the abandoned well in the Okuhida hot spring area was observed. To investigate whether the abnormal discharge was caused by the volcanic activity of Yakedake volcano, the major chemical and stable isotopic compositions of hydrogen and oxygen were analyzed, and the reservoir temperature was estimated by applying geothermometers. As a result, no evidence was found that this abnormal discharge was caused by an increase of volcanic activity of Yakedake volcano.

Although the relationship between earthquakes and hot spring anomalies has not been completely clarified, many abnormal phenomena associated with earthquakes have been reported in Japan as well as overseas, such as changes in water level, discharge rate, outlet temperature, chemical composition, and color appearance (e.g., Nishimura, 1999 ; Okusawa and Tsukahara, 2002 ; Itaba and Koizumi, 2007 ; Itadera *et al*., 2011 ; Sasaki, 2012 ; Cox *et al*., 2015). As shown in Figure 2, the abandoned well, in which the abnormal discharge was observed this time, is located at the position where many faults exist, and it is assumed that the groundwater flow, including the hot spring water, in this area is restricted by these faults (e.g., Akiyama, 1978). Therefore, it may be reasonable to interpret that the abnormal discharge of the high-temperature hot spring water observed this time is caused by the change in the underground flow path due to the recent frequent earthquakes in the Gifu–Nagano district.

Acknowledgments

I wish to express my sincere gratitude to the staff at Okuhida Garden Hotel YAKEDAKE for providing sample water and valuable information and to Genki I. Matsumoto, professor emeritus of Otsuma Women's University, for providing comments and suggestions on a draft of this paper. Also, the prompt handling of the review process by Dr. Hideyuki Nagashima, Editor-in-chief of JHSS, and valuable comments by two anonymous reviewers are deeply acknowledged.

References

Akiyama, S. (1978) : Geology of Oku-Hida District. J. Hot Spring Sci., **29**, 135–148 (in Japanese).

Cox, S.C., Menzies, C.D., Sutherland, R., Denys, P.H., Chamberlain, C. and Teagle, D.A.H. (2015) : Changes in hot spring temperature and hydrogeology of the Alpine Fault hanging wall, New Zealand, induced by distal South Island earthquakes. Geofluids, **15**, 216–239.

Craig, H. (1961) : Isotopic Variations in Meteoric Water. Science, **133**, 1702–1703.

Fournier, R.O. (1977) : Chemical geothermometers and mixing models for geothermal systems. Geothermics, **5**, 1–4.

Fournier, R.O. and Truesdell, A.H. (1973) : An empirical Na-K-Ca geothermometer for natural waters. Geochim. Cosmochim. Acta, **37**, 1255–1275.

Furuta, Y. (2020) : Okuhida Hot Spring Area. "Hot Springs in Japan" supervised by The Japanese Society of Hot Spring Sciences, 112–113, Asakura Publishing Co.,Ltd., Tokyo (in Japanese).

Geographical Survey Institute of Japan (2017) : Available at https://maps.gsi.go.jp/ (accessed May 28, 2020).

Geological Survey of Japan (2019) : Seamless geological map of Japan, V2. Available at https://gbank.gsj.jp/seamless/ (accessed May 28, 2020).

Gifu Meteorological Office (2020a) : Available at https://www.jma-net.go.jp/gifu/jishin_kaisetsu/jishin_kaisetsu20200519.pdf (in Japanese) (accessed May 28, 2020).

Gifu Meteorological Office (2020b) : Available at https://www.jma-net.go.jp/gifu/jishin_kaisetsu/jishin_kaisetsu20200529.pdf (in Japanese) (accessed June 15, 2020).

Itaba, S. and Koizumi, N. (2007) : Earthquake-related Changes in Groundwater Levels at the Dogo Hot Spring, Japan. Pure appl. geophys. **164**, 2397–2410.

Itadera, K., Kikugawa, J. and Daita, Y. (2011) : Changes in temperature and discharge of hot spring waters observed in Hakone spas caused by the 2011 off the Pacific coast of Tohoku Earthquake. Bull. Hot Spring Res. Inst., Kanagawa Pref., **43**, 39–43 (in Japanese).

Iwasaki, I. (1976) Chemistry of Hot Springs—Introduction of Ingredients in Hot Springs—. J. Hot Spring Sci., **27**, 42–69 (in Japanese).

Japan Meteorological Agency : Seismic intensity database. Available at : https://www.data.jma.go.jp/svd/eqdb/data/shindo/index.php?ByPref=43 (in Japanese) (accessed June 15, 2020).

Kawamoto, H., Abe, S., Matsuzawa, K., Shimozawa, H. and Iijima, N. (1984) : Geochemical study on Okuhida hot springs by the Correlation Matrix. J. Hot Spring Sci., **34**, 1–12 (in Japanese, title transrated).

Koji, S., Sasaki, K., Ueda, A. and Nakamoto, T. (2016) : Geochemical study on geothermal resources in Okuhida Hot Spring area at the western flank of Mt. Yake, Gifu. Chikyukagaku (Geochemistry) **50**, 97–114 (in Japanese with English abstract).

Mizutani, Y., Sugiura, T. and Hamajima, Y. (1980) : Isotopic and Chemical Compositions and Underground Temperature of Thermal Waters from Yakedake Geothermal Area, Gifu, Japan. J. Geotherm. Res. Soc. Japan, **2**, 63–70 (in Japanese with English abstract).

Nagano Pharmaceutical Association (2010) Hot spring analysis report for Yakedake Tenno-sen Uguisunoyu No. 1 (English title translated from the original written in Japanese).

Nagano Pharmaceutical Association (2011) Hot spring analysis report for Yakedake Tenno-sen Uguisunoyu No. 2 (English title translated from the original written in Japanese).

Nagano Pharmaceutical Association (2013) Hot spring analysis report for Yakedake Tenno-sen Uguisunoyu No. 3 (English title translated from the original written in Japanese).

Nishimura, S. (1999) : The Effect of Earthquake on the Hot-spring and Groundwater. J. Hot Spring Sci., **48**, 142–152 (in Japanese with English abstract).

Okuhida Garden Hotel YAKEDAKE (web page) : Analysis Table. Available at https://www.okuhida-gh.com/spa/bunseki.php (accessed May 28, 2020).

Okusawa, T. and Tsukahara, H. (2002) : Temporal Variation in Chemical Composition of Ground Water from the Matsushiro Earthquake Swarm Area at an Earthquake. J. Hot Spring Sci., **51**, 147–163 (in Japanese with English abstract).

Sasaki, N. (2012) : Visible Changes of Hot Spring Waters Observed after the 2011 off the Pacific Coast of Tohoku Earthquake—A Case of Mikado Hot Spring, Kagawa—. J. Hot Spring Sci., **61**, 306–309 (in Japanese).

Sugiura, T. and Mizutani, Y. (1978) : Variations in Isotopic and Chemical Compositions of Fumarolic Gases from Yakedake Volcano, Honshu, Japan. Bull. Vol. Soc. Japan, **23**, 241–248 (in Japanese with English abstract).

Truesdell, A.H. (1976) : Summary of section III Geochemical techniques in exploration. Proc. 2nd U. N. Symposium on the Development and Use of Geothermal Resources, San Francisco, 1975, v.1, liii–lxxix, U.S Government Printing Office, Washington, D.C.