ABNORMALLY HIGH-PRESSURE GEOTHERMAL FIELD
− MUSADAKE AREA, HOKKAIDO, JAPAN

Nonaka, M.[1], Sugiyama, Y.[1], Akaku, K.[1], Yamada, Y.[1], and Okada, H.[2]

[1]JAPEX Research Center, 1-2-1, Hamada, Mihama-ku, Chiba 261-0025, Japan

[2]JAPEX (Japan Petroleum Exploration Co., Ltd), Sapia Tower 1-7-12, Marunouchi, Chiyoda-ku, Tokyo 100-0005, Japan

miyuki.nonaka@japex.co.jp

Keywords: *Musadake geothermal field, Abnormally high-pressure reservoir, Intrusion, Boiling, Fluid inclusion*

ABSTRACT

The Musadake geothermal field located in the eastern part of Hokkaido is an unusual field associated with abnormally high pressure. In 2014, an exploration well, SMMG-2D, was drilled in the Musadake area and produced 26 t/h of steam and 16 t/h of hot water at atmospheric pressure almost stably during a short-term discharge test over two weeks.

The well SMMG-2D recorded a maximum temperature of 333°C and a pressure about 5 MPa higher than hydrostatic pressure. It was drilled through a dacite intrusive body below impermeable mudstone, and Pressure Temperature Spinner logging data indicated that fractures in and around the dacite served as feed zones.

We analysed an assemblage of hydrothermal alteration minerals and performed fluid inclusion microthermometry of SMMG-2D. Wairakite, sulphide minerals such as sphalerite and galena, epidote, and platy calcite were identified as hydrothermal alteration minerals in the vicinity of the feed zones. The platy or saw-tooth appearance of the calcite observed in the intervals of the feed zones indicates boiling conditions. The homogenisation temperature was in the range of 325–380°C, which exceeds the static temperature of the feed zones (320°C).

The Musadake geothermal field is an unusual field with abnormally high pressure. The logging data, occurrence of hydrothermal alteration minerals, and fluid inclusion microthermometry for well SMMG-2D revealed hydrothermal activity near production zones. Although this high temperature and pressure well produced steam and hot water stably, the evaluation of this high-pressure reservoir remains problematic. In this report, we describe the geological setting, drilling data, logging data, and mineralogy of well SMMG-2D.

1. INTRODUCTION

The New Energy and Industrial Technology Development Organization (NEDO) started its Geothermal Development Promotion Survey in the Musadake geothermal field in 1993 and drilled exploratory wells in this area.

Despite temperatures high enough for development, the temperature distribution, permeable zones and reservoir characteristics have remained unknown, and some of the wells encountered abnormally high pressure below impermeable mudstone (NEDO, 2001, 2006).

To investigate the distribution of high temperatures and permeable zones in this field, two exploratory wells were drilled in a joint venture of Japan Petroleum Exploration Co., Ltd. (JAPEX), Mitsubishi Materials Corporation (MMC) and Mitsubishi Gas Chemical Company, Inc. (MGC) in 2013 and 2014.

The first well, SMMG-1D, was drilled in 2013 toward the west in the direction of an expected heat source, the Senpo volcano, and a maximum temperature of 273°C was recorded. However, the temperature decreased in the western, deeper part of the well, and the well was found to be non-productive.

However, the second exploratory well, SMMG-2D, was drilled toward the southwest from the same drilling site, and this well encountered high-temperature and high-pressure reservoirs.

2. GEOLOGY AND TECTONIC SETTING

In eastern Hokkaido, a compressive stress regime has been generated by the subduction of the Pacific Plate since the late Miocene (Hirose and Nakagawa, 1999) (Figure 1).

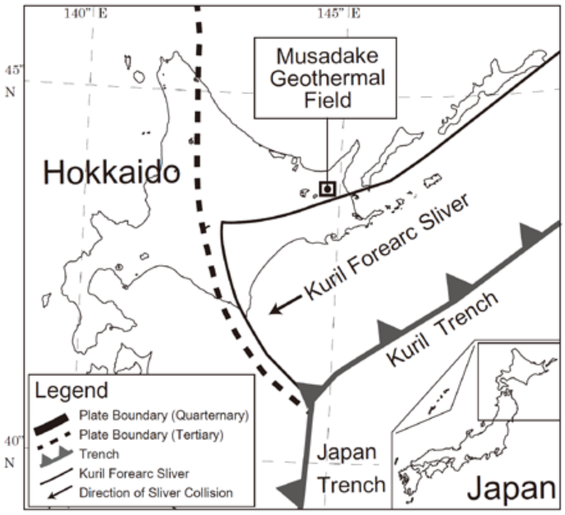

Figure 1: Tertiary to Quaternary tectonic map of Hokkaido (Hirose and Nakagawa, 1999) and the location of the Musadake geothermal field.

The Musadake geothermal field is located in the centre of the Akan-Shiretoko volcanic chain, one of several volcanic chains aligned en echelon in a NE–SW direction (Funayama and Nakagawa, 1991).

In this area, the Musadake-Shitabanupuriyama reverse fault extends NNE–SSW, and the Urappugawa fault extends WNW–ESE. There are also Quaternary volcanoes in this area, e,g. the Senpo and Musadake volcanoes (Figure 2).

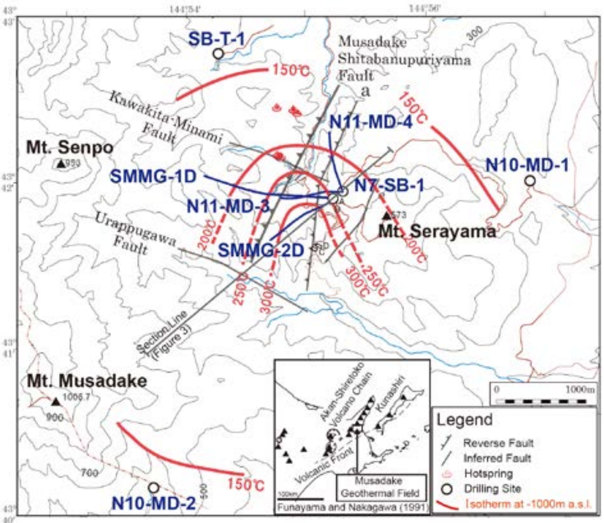

Figure 2: Map of the Musadake geothermal field.

The Musadake geothermal field is underlain by the Pleistocene Musadake volcanics, Pliocene Kawakita volcanics, the late Miocene Kawakita and Churui Formations and some intrusives.

The Musadake volcanics are composed of two-pyroxene andesite. The Kawakita volcanics is composed of pyroxene andesite, and is also associated with basaltic intrusives. The Kawakita Formation is divided into two units; the upper unit is mainly composed of tuffaceous siltstone and dacitic pyroclastics, and is sometimes associated with andesitic to basaltic intrusives, whereas the lower unit is composed of hard, compact mudstone. The Churui Formation is mainly composed of dacitic lithic tuff, tuff breccia, volcanic breccia and lavas. Dacite intrusions have been found only in certain wells.

3. DRILLING AND SHORT-TERM DISCHARGE TEST OF SMMG-2D

The second exploratory well, SMMG-2D, was drilled from the same drilling site as SMMG-1D, but oriented southwest toward the Musadake volcano. Overflow of mud during drilling occurred abruptly below the mudstone unit of the lower Kawakita Formation. We increased the mud weight from a specific gravity of 1.1 to 1.4–1.6. While drilling downward, depending on the balance between the mud weight and formation pressure, overflow and lost circulation occurred.

These indications of permeable zones were distributed mainly in and around the dacite intrusion (Figure 3). Although the intrusive dacite itself is massive and compact, fractures are present.

Pressure Temperature Spinner (PTS) measurement was carried out before the short-term discharge test, which took place 190 days after an injection test. The recorded maximum temperature was 333°C in the area around the intrusion, and abnormally high pressure was observed.

A two-week discharge test of this well was carried out in June 2015. At the end of this test, the well was producing 26 t/h of steam and 16 t/h of hot water at atmospheric pressure almost stably. The PTS measurements during production showed that feed zones coincided with expected fracture depths in and around the intrusion and that two-phase fluids were flowing into the wellbore with flashing in the reservoir.

A hot water sample taken from a weir box had a neutral pH, high Cl^- and Ca^{2+} concentrations (20000 mg/L and 1000 mg/L respectively) and a low SO_4^{2-} concentration (50 mg/L). The SiO_2 concentration was 1200 mg/L.
Nearly 2 vol% of this sample consisted of non-condensable gas in steam, mainly CO_2 (about 93 mol%).

Geothermometers of quartz, Na–K and K–Mg indicated temperatures of about 300°C, which is slightly lower than the measured static temperature of the feed zones (320–330°C).

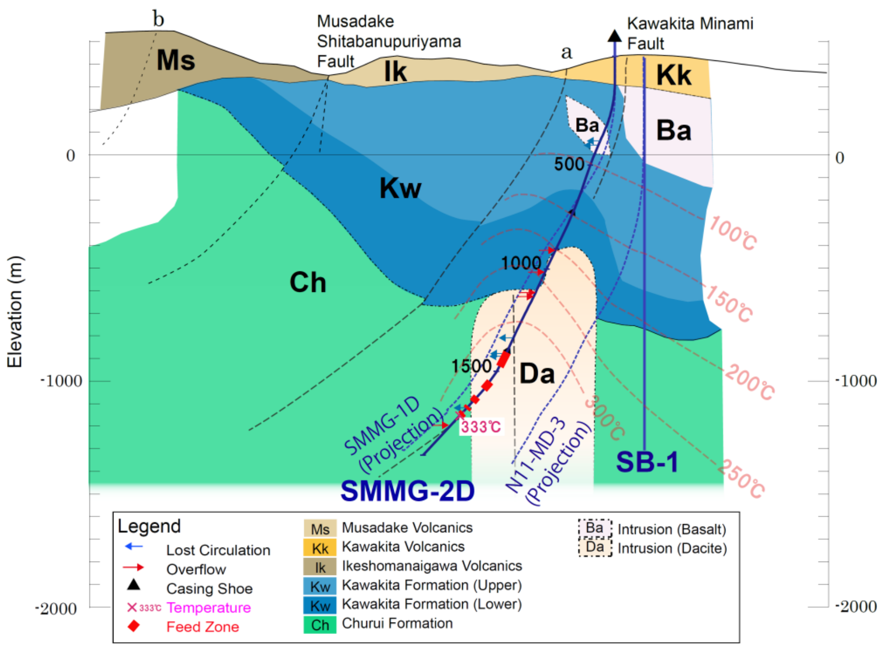

Figure 3: Cross section of the Musadake geothermal field along SMMG-2D and SB-1.

4. ANALYSIS OF SMMG-2D DRILL CUTTINGS

4.1 Alteration Minerals

We identified the assemblage of hydrothermal minerals based on microscope observations of the drill cuttings, polarizing microscope observations of thin sections and X-ray diffraction (XRD) analysis (Figure 4). Clay minerals, zeolite, epidote, calcite and sulfide minerals were identified as the hydrothermal alteration minerals.

Clay minerals were identified from almost all depths. Smectite was found in Kawakita volcanics and the upper Kawakita Formation, illite/smectite and chlorite/smectite mixed layers were found in the lower Kawakita Formation, and chlorite was found mainly in the Churui Formation.

Wairakite, epidote and sulfide minerals (sphalerite and galena) were identified from the intervals of feed zones.

Platy or saw-tooth calcite was observed from within the depths of 1650–1675 m.

4.2 Fluid Inclusions

For measurement of homogenisation temperature, we collected vein quartz and calcite samples and measured homogenisation temperatures (Th). Because of the small sizes of the drill cuttings, suitable samples for these Th measurements were collected only from limited depths near the boundary of the dacite intrusion and the Churui Formation. The measured homogenisation temperatures ranged from 325 to 380°C.

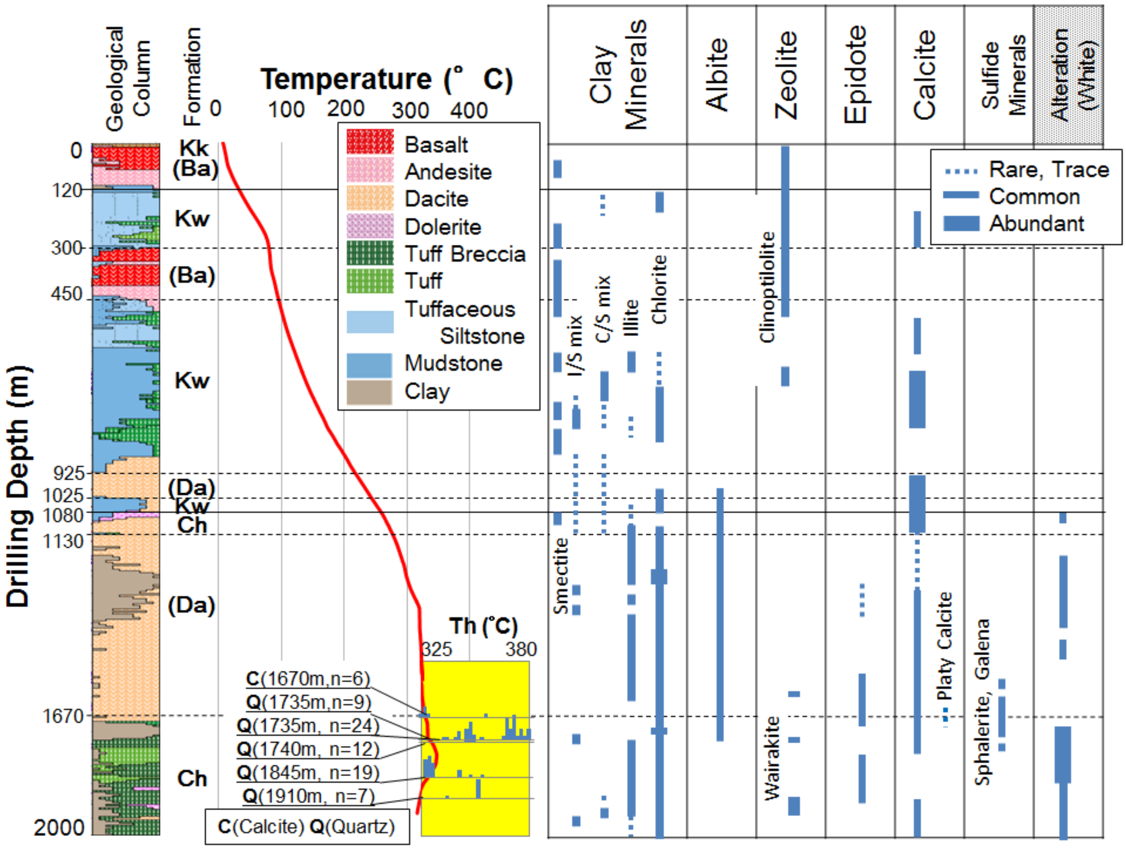

Figure 4: Geology, subsurface temperatures, homogenisation temperatures (Th) and results of thin-section and X-ray diffraction (XRD) analyses of SMMG-2D. Lithology data in the shaded column represent macroscopic observations of the cuttings.

5. TEMPERATURE AND PRESSURE DATA FROM THE WELLS OF THE MUSADAKE AREA

Temperature and pressure profiles measured after sufficient standing time are shown in Figure 5. These data are considered to represent formation temperature and pressure.

The temperature profiles of these wells were shown in Figure 5(a). Although temperatures over 200°C are recorded for wells SB-T-1, N11-MD-3, N11-MD-4, SMMG-1D and SMMG-2D, temperature inversion was observed for the western deeper part of SMMG-1D. Based on the distribution of these data, the high temperatures of this field are inferred to extend south of SMMG-2D (Figure 2).

The measured pressures of the wells and formation pressures inferred from drilling data are shown in Figure 5(b). The solid lines of N11-MD-3, N11-MD-4, SMMG-1D and SMMG-2D show the results of PTS logging over open-hole intervals. Circles on the solid lines indicate depths of the inferred permeable zones from drilling parameters and/or PTS data (only for SMMG-1D and 2D). The other symbols for N10-MD-1, N10-MD-2, N7-SB-1 and SB-T-1 show the estimated formation pressures based on drilling fluid density and mud level in the well during lost circulation.

SB-T-1, N7-SB-1, N10-MD-1 and N10-MD-2 showed hydrostatic pressures. However, N11-MD-3 and N11-MD-4 showed high reservoir pressures, approximately 2–6 MPa above hydrostatic pressures. In SMMG-1D, pressures of the assumed feed points were almost equal to the hydrostatic pressure. In SMMG-2D, pressures at assumed feed points were abnormally high, about 5 MPa higher than hydrostatic pressure.

The wells drilled in the high-temperature zone of the Musadake field (SMMG-2D and N11-MD-3) showed abnormally high reservoir pressures, and data from the wells distant from the centre of the system were consistent with hydrostatic pressures. Furthermore, considerable pressure differences even between close wells (e.g. SMMG-1D and N11-MD-3) indicates poor lateral connectivity.

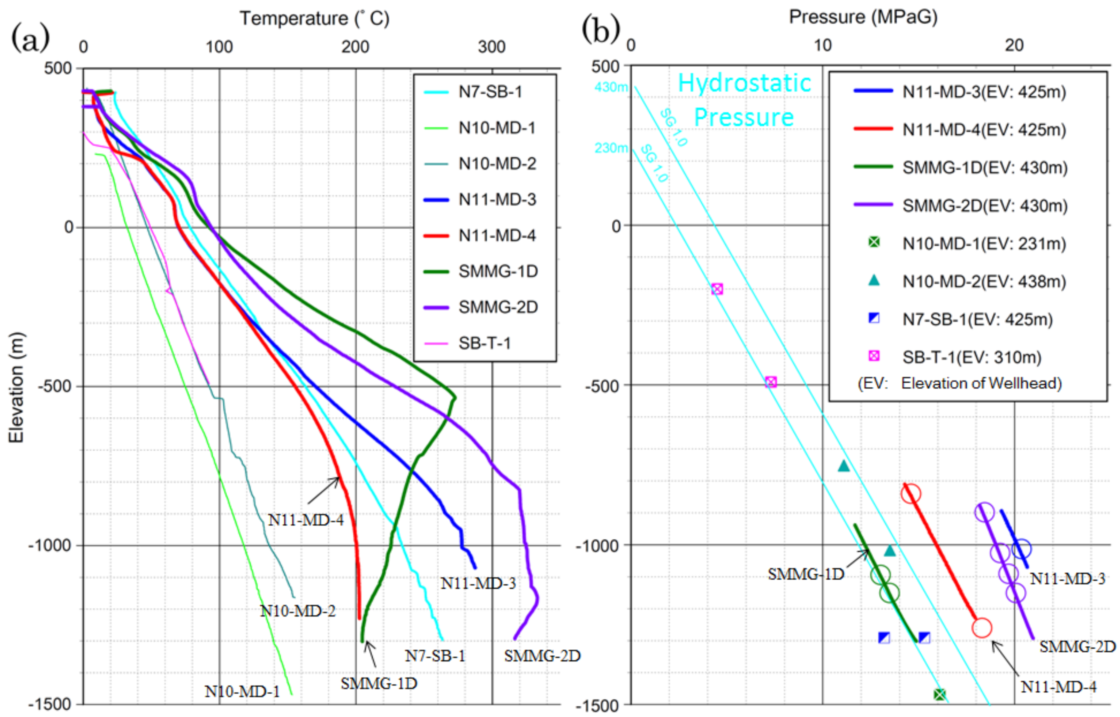

Figure 5: (a) Temperature and (b) pressure profiles for each well in the Musadake geothermal field. Solid lines of N11-MD-3, N11-MD-4, SMMG-1D and SMMG-2D show the results of PTS logging of open-hole intervals. Circles on the solid lines indicate the positions of estimated permeable zones. Other symbols represent estimated pressures at the depths of lost circulation calculated from the density and level of drilling fluid.

6. DISCUSSION

6.1 Temperature consideration: petrological analysis

Homogenisation temperatures (Th) of fluid inclusions of SMMG-2D range from 325 to 380°C, which are higher values than the measured static temperature (320–330°C) (Figure 4). A Th higher than the present temperature generally indicates cooling of a geothermal system. However, Th values have a wide range of temperatures, a minimum temperature consistent with the measured temperature and platy or saw-tooth calcite, which are associated with boiling conditions (Simmons and Christenson, 1994), were observed in drill cuttings. These facts indicate that boiling may have occurred in this formation.

6.2 Pressure consideration: simple modelling

According to Donaldson et al. (2002), abnormally high pressure can be caused by several factors (e.g. compaction, tectonic compression, faulting, an unusually high geothermal temperature gradient, mineral phase changes or osmosis).

In this field, based on the tectonic setting and the high gas content of the fluid, tectonic compression and the presence of a gas cap below the low-permeability layer (Henley, 1984) are possible causes of the high pressure.

For another possible cause of high pressure, we examined how much the effects of fluid density differences and temperature differences contribute to high pressure.

We assumed a high-temperature permeable zone (reservoir) surrounded by a low-permeability zone connected to an average temperature gradient with hydrostatic pressure at a lateral boundary through a deep permeable layer.

A simple two-dimensional numerical model (10000 m wide and 4000 m deep) was applied with a cylindrical reservoir of 1000 m in width and 3000 m in height. The reservoir was assumed to be a permeable zone ($k = 1\times10^{-14}$ m^2) surrounded by a low-permeability zone ($k = 1\times10^{-17}$ m^2) connected to a lateral boundary of constant temperature and pressure through a permeable layer ($k = 1\times10^{-15}$ m^2) at its base (Figure 6).

The reservoir temperature was set to a constant 300°C, and the lateral boundary was set at an average temperature gradient (3°C/100 m) and hydrostatic pressure. The top surface boundary was set to a temperature of 15°C and atmospheric pressure. We ran a 10000-year simulation for this model using the TOUGH2 simulator and compared the pressure at the reservoir top to that at the lateral boundary (normal hydrostatic pressure).

About 6 MPa overpressure could be created at the top of the reservoir in this simple model.
Therefore, such a structure and the differential pressure created by the fluid density difference may be one of the factors of this abnormally high pressure.

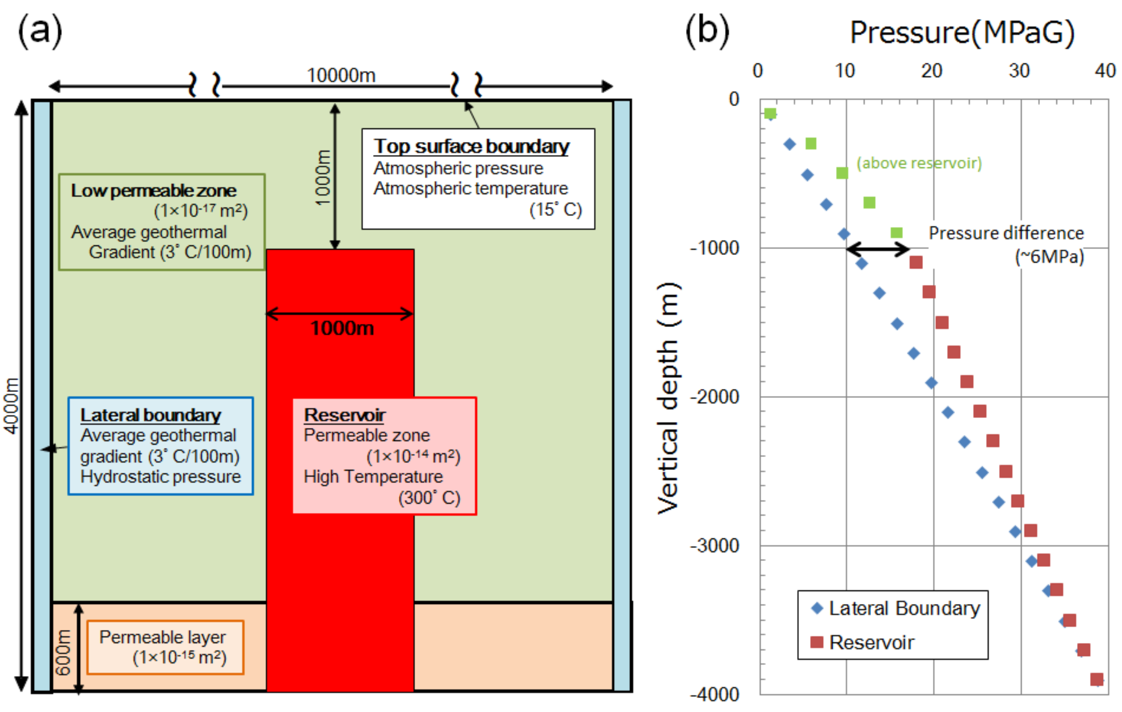

Figure 6: (a) Two-dimensional numerical model and (b) Pressure distribution of the reservoir and lateral boundary.

CONCLUSIONS

The Musadake geothermal field is an unusual field characterized by abnormally high local pressure.

Based on the results of drilling, wireline logging and petrological analysis, high-temperature (over 300°C) hydrothermal activity is present underground in this field.

Fluid density differences created by temperature differences are a possible cause of the abnormally high pressure in this field.

Although SMMG-2D successfully produced steam and hot water during a two-week discharge test, this abnormally high-pressure reservoir should be investigated further.

ACKNOWLEDGEMENTS

The authors thank JAPEX, MMC and MGC for their permission to submit this paper, Mr. T. Sato of Geothermal Energy Research and Development Co., Ltd. (GERD) for providing modelling data and advice for reproducing abnormally high pressure, and reviewer for their helpful comments. Drilling of the wells SMMG-1D and SMMG-2D was subsidised by the Japan Oil, Gas and Metals National Corporation (JOGMEC).

REFERENCES

Donaldson, E.C., Chilinger, G.V., Robertson, Jr., J.O. and Serebryakov, V.A.: Introduction to abnormally pressured formations. *in* Chilingar, G.V., Serebryakov, V.A., and Robertson, Jr., J.O. (eds.) *Origin and Prediction of Abnormal Formation Pressures*. Elsevier, pp. 1 – 9. (2002).

Funayama, A. and Nakagawa, M.: Geology and petrology of Musa volcano, east Hokkaido. *Journal of Mineralogy, Petrology and Economic Geology* (in Japanese), 86, pp. 410–423. (1991).

Henley, R.H.: Gaseous components in geothermal processes: in Henley, R.H., Barton, Jr.P.B., Tryesdell, A.H. and Whitney, J.A. (eds.) *Fluid-Mineral equilibria in hydrothermal systems*. Reviews in Economic Geology Volume 1, pp. 45 – 56. (1984).

Hirose, W. and Nakagawa, M.: Neogene volcanism in Central-Eastern Hokkaido: Beginning and evolution of arc volcanism inferred from volcanological parameters and geochemistry. *The Journal of the Geological Society of Japan (in Japanese)*. 105, pp. 247 – 265. (1999).

Geothermal Energy Research and Development Co., Ltd. (GERD) : Report on integrated analysis of the Musadake area with magnetotelluric survey reprocessing and newly acquired data (in Japanese). 139p. (2016).

New Energy and Industrial Technology Development Organization (NEDO) : *Report of Geothermal Development Promotion Survey in the Musadake area* (in Japanese). 1074p. (2001).

New Energy and Industrial Technology Development Organization (NEDO) : *Report of Geothermal Development Promotion Survey in the Shibetsu-Serayama Area* (in Japanese). 156p. (2006).

Simmons, S.F. and Christenson, B.W.: Origins of Calcite in a boiling geothermal system. *American Journal of Science*, 294, pp. 361–400. (1994).