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Abstract

Thermal waters from Quaternary volcanic rocks (predominantly andesites) discharge along faults in the Obama geothermal field of southwestern Japan. The chemistry of more than 100 thermal and ground water samples collected between 1936 and 2005 indicate that the Na-Cl hot spring waters are a mixture of “andesitic” magmatic, sea and meteoric waters. Mixing models and silica and cation geothermometry were used to estimate the SiO_2 and Cl composition and the temperature (~200 ^{o}C) of the reservoir fluids deep in the geothermal system. The isotopic data (^{18}O and D) are consistent with a mixed origin interpretation of the waters feeding the Obama hot springs; i.e. a large proportion of meteoric and sea waters, and a small magmatic component. Temperatures and chemical concentrations of the thermal waters were affected by the

1944-1959 salt production operations, but have recovered after closure of the salt factories; now they are similar to their pre-1940 values. In the future, the Obama geothermal field may be suitable for electric power generation, although heat and fluid extraction will require careful management to prevent or minimize reservoir cooling.

Keywords: Geothermal; Hydrochemistry; Geothermometry; Obama geothermal field; Japan.

1. Introduction

The Obama geothermal field (OGF) is located on the Shimabara Peninsula, west of the Unzen volcano, in the western part of Kyushu Island, southwestern Japan (**Fig. 1**). Spas fed by the Obama geothermal system (OGS) have historically been noted for their number and high temperature (IHES, 2002); thermal waters discharging along the seashore in Chijiwa Bay have been used for hot-spring therapy. The hot spring waters of the OGS have been classified as being of the NaCl-type (Saibi et al., 2006a); the proximity of the geothermal field to the coast facilitates the intrusion of seawater into the hydrologic system (Saibi et al., 2006b).

Watanabe (1958) noted that there were 76 wells in the OGF and despite its small surface extension (around 1.5 km^2) the hot water output was very large; i.e. 56,500 t/day. Later, Yuhara et al. (1986) measured a total flow rate of 8168 t/day from 22 wells in the area.

Production of salt (NaCl) through evaporation, enhanced by heat from the thermal waters, began in 1944 and has played an important role in the history of the OGF. The number of salt factories rapidly increased to 80 by 1951, at which time the total geothermal water extraction was about 50,000 m^3/day. The annual salt output was 7600 tons in 1948, whilst it averaged ~10,000 t/yr in 1952-1956, when there were 78 geothermal wells in the OGF with an average depth of about 100 m. With the help of pumps they extracted about 750 to 1800 m^3/day of hot fluids from the system; between 1800 and 2400 m^3 of hot water was needed to produce one ton of salt. All the geothermal wells were located very close to the coast. **Figs. 2a** to 2e and **Fig. 3** show for different times, the location of salt factories, artesian hot springs and sampled hot springs.

As a result of the over-pumping that accompanied commercial salt production, the Obama geothermal aquifer was increasingly affected by seawater intrusion, which raised the salinity and decreased the temperature of the waters to the point that boiling ceased in the wells. By 1950, the lack of boiling wells was becoming an increasing problem, and the hot springs were in danger of running dry.

In 1951 there were 84 hot springs, 14 of them artesian. In 1955 the number of salt factories was reduced to 40. At that time, only eight of the hot springs were artesian (see Fig. 2a) and the total dissolved solids (TDS) in the water reached 25,000 mg/L, which was three to four times the concentration before salt production began. The extraction of geothermal water was reduced from 50,000 to 32,000 m^3/day in 1955, without impacting salt production levels. The number of artesian hot springs more than doubled (from six to 12) between 1955 (Fig. 2a) and 1988 (Fig. 2e), especially in the northern part of the geothermal field.

On 17 September 1959, Typhoon 14 struck the Obama Spa, causing serious damage and leading to the abandonment of most of the salt factories by the end of that year. Also by that time, 53 hot springs showed a decline in flow rate, with only 24 being appropriate for use in public baths, hotels and inns, which prompted hot water production to be reduced to 8150 m^3/day. The last salt factory was closed in 1965.

Because of diminished exploitation the geothermal resource gradually recovered; i.e., the number of boiling wells grew to 11 by 1960, spring water temperatures rose and water salinities decreased. As a result, the present thermal spring characteristics are similar to those observed before 1940.

The paper focuses on the main changes in hot spring water chemistry, and in estimated reservoir temperatures. Chloride-enthalpy and silica-enthalpy diagrams, as well as cation and silica geothermometers were applied to hot spring water samples of the Obama geothermal system (OGS) collected and analyzed from 1936 to 1987, and in 2005, in order to investigate reservoir temperature changes caused by several decades of exploiting the resources of the OGF. Isotopic data (^{18}O and D) on waters from river, wells and springs, helped to resolve the origin of the hot spring waters, and to propose a new hydrological model for the Obama geothermal system.

2. Geologic setting

The Obama geothermal area is located in the southwestern part of the Beppu-Shimabara graben (Fig. 1), a structural depression affected by tectonic and volcanic processes (Tamanyu and Wood, 2003). The graben occurs at the junction of the Southwest Japan Arc and the Ryukyu Arc, and was formed either by extension associated with the subduction of the Philippine Sea Plate beneath the Eurasian Plate (Kamata and Kodama, 1993), or by right-lateral shear caused by oblique subduction of the Philippine Sea Plate beneath Kyushu island (Tsukuda, 1993). There are many Quaternary volcanoes within the graben, including Mts. Tsurumi, Kuju, Aso and Unzen (from east to west), which are accompanied by active geothermal systems (Fig. 1). A number of geothermal manifestations are found along the faults bounding the graben.

The Obama area is dominated by Quaternary volcanic formations (**Fig. 4**); the volcanics in the area of the OGF are primarily andesitic. Based on petrographic and macroscopic analysis of drill cuttings and core samples from well UZ-2, the subsurface stratigraphy at Obama is composed by the Unzen Volcanics and the Kuchinotsu Group (**Fig. 5),** both of Quaternary age (NEDO, 1988).

The Unzen Volcanics are found at the surface and to depths of about 500 m, and consist of hornblende andesite lavas and tuff breccias of the Takadake and Obama Formations. The lavas are intercalated by tuffs and silts of the Tatsuishi Formation that occur in the area at two depth levels in well UZ-2, i.e. at 197-291 m, and 447-512 m (Fig. 5). The reservoir in the OGF is mainly located in the Takadake and Obama Formations; the Tatsuishi Formation is of lower permeability. The Kuchinotsu Group, found between 512 and 1500 m depth (Fig. 5), corresponds to the basement rocks.

3. Water chemistry

Tables 1 and **2** show the chemistry data on hot spring, river, sea and rain waters collected from the Obama area. The composition of the OGF hot spring waters has been collated from several surveys including, 1- Nagasaki Prefectural Institute of Health and Environmental Sciences (IHES, 2002): 1936-1987 chemistry data;

2- New Energy Development Organization (NEDO, 1988): 1984 chemical and isotopic data;

3- Obama Town (OT, 2002): 2001 isotopic data; and

4- Kyushu Environmental Evaluation Association (KEEA, 2005): 2005 chemistry data.

In the past, researchers estimated the chemical composition of the Obama thermal water based on qualitative and quantitative analyses (weight and volume), although the exact methods used were not always recorded. Recent studies have quantitatively determined the chemistry of the water samples. The ionic balance provides an indication of the accuracy (and hence reliability) of the analyses, which is given by,

$$Balance(\%) = \frac{\sum Cations(meq/l) - \sum Anions(meq/l)}{\sum Cations(meq/l) + \sum Anions(meq/l)} \times 100$$

In this study, analyses exceeding an ionic balance of 5% were excluded from the data set.

Fig. 6 depicts the temperature and chemical changes recorded in the waters of hot springs N.4 and N.26, which have been sampled repeatedly; N.4 is located close to the coast, while N.26 is further inland (see Fig. 2c). Fig. 6 shows differences in concentrations due to varying degrees of mixing of the thermal waters with sea and fresh ground waters, similar to what is observed in the Reykjanes, Iceland, geothermal field (Sveinbjornsdottir et al., 1986). The figure shows that the waters of hot spring N.4 have higher temperatures and concentrations than N.26, except for SO_4 and HCO_3. In general, further inland the salinity of the thermal waters decreases, and is between 100 and 2500 mg/L.

The pH of the higher temperature (52 -102 ^{o}C) spring waters in the OGF is in the 7 to 8.5 range. The alkalinity of these waters can be explained by the depletion of HCO_3 (i.e. separation and loss of CO_2) during boiling (Truesdell, 1995). The TDS of the hot (>40 ^{o}C) spring waters range from 3850 to 25,900 mg/L.

The dominant ions in the hot spring waters are Cl and Na, with concentrations ranging from 2076 to 13,250 mg/L and 1107 to 7182 mg/L, respectively. Such values are commonly found in hot springs fed by fluids that rise rapidly (i.e. directly) from deep reservoirs, and thus can be used to resolve the character of the upflows in geothermal systems (Cortecci et al., 2005).

At Obama, most of the chloride in the thermal water is likely to come from seawater, while a small amount may be derived from HCl degassing from a magma chamber located beneath the geothermal system. Seawater very probably is the main source of the sodium. The concentration of sulfate in the thermal waters is also high (7.8 to 1575 mg/L), and in part probably derives from the oxidation of H_2S (up to 12 mg/L in the NaCl springs; Ellis, 1969) or from seawater.

The chemical data on the Obama hot spring waters have been divided into four groups according to periods of contrasting geothermal resource utilization: Group 1 corresponds to the initial stage when bathing was the primary use of the spring waters (1936-1940); Group 2 to the salt production stage (1948-1955); Group 3 to the period characterized by decreased salt production (1956-1959); and Group 4 to when the thermal springs were mainly used for bathing (1960-2005).

Fig. 7 shows a plot of sodium vs. chloride concentrations in the Obama hot spring and representative sea and river waters. The figure indicates that during the period of salt production (Groups 2 and 3) the Na and Cl contents in the thermal water increased, and that since these operations ceased in 1959 they are returning to their original values (pre-salt production times; Group 1).

We used chemical stochiometry to calculate the concentrations of SiO_2 in the water samples, based on the molecular weights of H_2SiO_3 and SiO_2. The SiO_2 content in seawater collected in 2000 from Chijiwa Bay near the Obama hot springs is 1.3 mg/L (Shinji Ohsawa, pers. comm., November 2008).

According to **Fig. 8** the water samples collected in the Obama area are of the alkali-chloride type. The figure also shows that chemical concentrations of the primary cations and anions present in the hot water discharges are generally lower than in seawater.

The Schöeller plots of Fig. 8 indicate that the Obama thermal waters are generally low in Br and HCO_3, as are the cold river waters of the area. The thermal waters have high concentrations of Mg, Ca, Na, K, Cl and SO_4, with seawater having higher amounts of Mg, Na, Cl, and SO_4. Analyses done in 1979-2005 show an average Li^+ content of 5.19 mg/L in the hot spring waters (Table 1), reflecting the predominantly andesitic composition of the host rocks (Nicholson, 1993).

The Mg concentrations in the Obama thermal waters range from 19.8 mg/L (1937 samples) to 1045 mg/L (1956 samples) (Table 1) and are hundreds to thousands of times higher than typical high-temperature geothermal brines, which generally are very low (0.01 to 0.1 mg/L; Nicholson, 1993). The high concentrations may indicate near-surface reactions, leaching of Mg from the host rocks and also mixing with seawater, which has elevated Mg contents.

The chemical characteristics of the Obama hot spring waters indicate that most of them have a major seawater component (Table 1). This is reflected, for example, by the high Ca (and to a lesser degree, Mg) concentrations in the thermal waters, which is evidence of mixing with the seawater that intrudes into the shallower parts of the geothermal field. Also, the B/Cl ratios in waters extracted from OGF wells in the 0.005 to 0.015 range (NEDO, 1988) confirm that mixing with seawater occurred (Giggenbach, 1992).

Bromide concentrations are generally low in geothermal fluids, except when there is mixing with seawater (Nicholson, 1993). The analytical results (**Table 3)** show that the Br/Cl ratio in Obama spring waters is small for Group 1, but is greater for Group 2, which corresponds to period of increased resource exploitation. Subsequently, elemental ratios stabilized during the periods when Groups 3 and 4 waters were collected.

The high Br/I ratios observed even after the extraction of salt was reduced and stopped could be explained by the contribution of organic matter in shallow near-surface reactions (Nicholson, 1993). After the end of salt production the Br/Cl also remained high for Groups 3 and 4 (Table 3) because the chloride contents in the hot waters of these two groups decreased drastically compared to those of Br.

From the ternary N_2-He-Ar diagram (**Fig. 9**) it can be inferred that the gases from the thermal water of OGF wells have a meteoric origin (Ohsawa, 2006). The

$Cl-SO_4-HCO_3$ ternary diagram (**Fig. 10)** proposed by Giggenbach (1988) indicates that all of the waters sampled from the Obama hot springs are typical of deep chloride waters, but also are similar in composition to seawater.

The K-Na-Mg diagram **(Fig. 11)** (after Giggenbach, 1988) indicates that none of the thermal spring waters are in full equilibrium with the host rocks and that they possibly have mixed with different types of water (Barragán et al., 2001).

Fig. 12 shows the change of major cation and anion concentrations in waters from selected Obama springs with time. They increased between 1936 and 1944, stabilized during 1944-1955, decreased from 1952 to 1970, and generally did not vary afterwards. Between 1936 and 1970 the changes in Cl and Na concentrations are greater than in SO_4, Ca, and Mg, especially during the 1945-1960 period.

The variations in spring water chemistry shown in Fig. 12 reflect changes in geothermal resource utilization, albeit delayed a few years. Higher levels of salt production or of thermal water extraction enhance seawater intrusion into the geothermal system. Once the salt factories started to close, fluid pressures in the OGF began to recover and seawater intrusion (and mixing with hot waters) diminished.

4. Silica and cation geothermometers

At the peak of salt production (1952-1956) the OGS was likely far from equilibrium, so that the geothermometric reservoir temperatures for that period may not be correct. The following geothermometers were used: (i) Na-K-Ca (Fournier and Truesdell, 1973); (ii) cationic composition (CCG) (Nieva and Nieva, 1987); (iii) silica (Fournier and Potter, 1982); (iv) silica (Giggenbach, 1992); (v) chalcedony (Fournier, 1992); (vi) amorphous silica (Fournier, 1992); (vii) silica (Verma, 2000), and (viii) K-Mg (Giggenbach, 1988).

A summary of the general principles, assumptions, limitations and applications of geothermometry to geothermal systems is given by Fournier (1981) and Giggenbach (1988). The CCG geothermometer is an effective tool for temperature estimation (OLADE, 1994), as it utilizes four equations based on the relative proportion of Na, K, Ca and Mg concentrations. A function of the Na/K ratio is used in the case of high temperature geothermal fluids with low Mg-content, as the Mg-based geothermometers reflect recent (proximal) equilibrium and not the reservoir temperature (Truesdell, 1995).

Reservoir temperatures inferred on the basis of geothermometry are given in Table 1. The highest temperatures are those indicated by the CCG geothermometer (Table 1; **Fig. 13**), whilst the lowest are given by the amorphous silica geothermometer. The temperatures indicated by the Na-K-Ca geothermometer are below those estimated by the CCG, which can be explained by the elevated Mg contents in the Obama thermal waters (Table 1). It is worth noting that the R correction factor of the Fournier and Potter (1979) Na-K-Ca geothermometer [i.e. R = (Mg x 100 /(Mg+Ca+K)] is greater than 50 for most of the Obama spring samples, thus suggesting that these Mg-rich fluids come from environments that may be considerably cooler than what is suggested by the Na-K-Ca geothermometry results. Also and because of these high Mg concentrations, the reservoir temperatures inferred by the K-Mg geothermometer are very low (5-43 ^{o}C; Table 1).

Changes in calculated OGF reservoir temperatures reflect the intensity and nature of the commercial operations in the area; particularly those related to salt production activities. Lower inferred temperatures correspond to periods of high cold seawater intrusion into the geothermal system.

Before the salt factories were opened the average reservoir temperature inferred using the CCG (T_{CCG}) was ~250 ^{o}C (Fig. 10). During the period of commercial salt extraction (from 1944 to 1959) those temperatures decreased to 200 ^{o}C. After the factories were closed the T_{CCG} gradually increased to ~220 ^{o}C. The silica geothermometers show similar trends (Fig. 12), despite being affected by silica precipitation caused by cooling and boiling processes.

Two hot spring water samples with low K concentrations, collected in 1971 and 1975, give estimated reservoir temperatures that are below those measured at the surface (discharge temperature) (Fig. 13), which point to a predominantly dilute, meteoric origin of the thermal spring waters.

5. Chloride-enthalpy model and Cl-Br relation

Mixing models like the enthalpy-chloride model of Fournier (1979) are very useful for determining chemical processes in active hydrothermal systems and for gaining understanding their hydrology. These models were applied to 96 samples of Obama hot spring waters in order to estimate silica and chloride contents in the reservoir fluids, i.e. before the fluids were affected by mixing/dilution and boiling processes as they ascended towards the surface. The reservoir fluid temperature for the four groups of hot spring groups (see Section 3) was estimated using the Na-K-Ca geothermometer; the results are shown as R1 (Group 1), R2 (Group 2), R3 (Group 3), and R4 (Group 4) in **Fig. 14.**

Two trends can be inferred from Fig. 14; i.e. (1) steam loss and boiling, wherein the remaining fluid loses enthalpy and mass, and its Cl concentration increases, and (2) mixing with seawater, which also results in a decrease in enthalpy and increase in Cl content. As indicated in **Table 4**, the amount of mixing for Groups 1 and 4 is similar and lower than that for Groups 2 and 3. In other words, the chloride content and the enthalpy of the produced fluids reflect the importance of seawater intrusion before the start, during and after the end of commercial salt extraction operations.

Fig. 15 shows a plot of bromide vs. chloride concentrations in Obama hot spring and representative sea waters. The figure indicates that during the period of salt production (Groups 2 and 3) the bromide contents in the thermal water increased, and that since these operations ceased in 1959 they are returning to their original values (pre-salt production times; Group 1).

6. Enthalpy-silica model

Enthalpy-silica relationships were applied to infer the temperature of the hot-water component in mixed waters and to estimate geothermal reservoir temperatures (Fournier and Truesdell, 1974; Truesdell and Fournier, 1977).

The enthalpy values used to estimate the Obama reservoir temperature (**Fig. 16)** were derived from measured spring discharge temperatures and steam table data (Keenan et al., 1969). The estimated reservoir temperatures and silica contents are presented in **Table 5**, and plotted as Ps-1 to Ps-4 (for Groups 1 to 4, respectively) in Fig. 16. Note that the temperatures are likely to be underestimated due to the likelihood of silica precipitation caused by cooling and boiling.

7. Isotope chemistry, hydrothermal fluid origin, and mixing processes

The deuterium and oxygen isotopic contents in thermal water are generally a good indicator of fluid origin (Craig, 1961), although several processes may affect them.

The discharge of springs located in coastal regions commonly show evidence of mixing of altered seawater and local continental (meteoric) water (Sveinbjornsdottir et al., 1986; Barragán et al., 2001). The OGF has many similarities with the Reykjanes geothermal field. Both show small surface thermal activity, and present the effects of seawater mixing phenomena due to their location near the coast and the high permeability of their volcanic rocks (Sveinbjornsdottir et al., 1986).

Data on the isotopic (^{18}O, D) composition of waters from 15 Obama wells and 15 Group 4 hot springs (analyzed in 1984; NEDO, 1988), from 17 Group 4 hot springs (analyzed in 2001; OT, 2002), from a river (analyzed in 1984) and local rainfall (analyzed in 1999; unpublished data, Geological Survey of Japan, 2010) are given in **Table 6** (no isotopic data for water samples from Groups 2 and 3 exist). The purpose of these analyses was to obtain a better understanding of the hydrological processes occurring in the OGF. As shown in **Fig. 17** the isotopic composition of cold waters clearly differ from that of thermal geothermal fluids.

All Obama geothermal waters from the NEDO and OT studies (i.e. those sampled in 1984 and 2001) plot close to the Global Meteoric World Meteoric Line (GMWL; Fig. 17), whose equation is ($\delta D = 8.13\ \delta^{18}O + 10.8$; Rozanski et al., 1993), thus indicating these waters have a local meteoric component. Also shown in Fig. 17 is another meteoric line proposed by Sakai and Matsubaya (1974) for Japanese precipitation ($\delta D = 8\ \delta^{18}O + 17$).

The apparent “oxygen shift” in the Obama thermal spring and well waters shown in Fig. 17 could be due to isotopic exchange with the host rocks and the result of mixing of local groundwater with ^{18}O-enriched magmatic water, such as the “andesitic water” of Taran et al. (1989). This andesitic fluid is inferred to undergo isotopic exchange with the reservoir rocks, lose steam during ascent, and, near the surface, mix with meteoric water (ground, river and sea waters) and boil, leading to thermal spring and well waters with an elevated heavy isotope content. The fraction of magmatic andesitic fluid that contributes to the formation of the Obama thermal waters is estimated at 0.08.

Using the mixing line with seawater shown in Fig. 17 the estimated proportion of seawater in Obama hot spring waters is about 35%, assuming an end point that has the same deuterium content as the local river water, and a level of seawater mixing consistent with the enthalpy-chloride relationships shown in Fig. 14.

8. Earlier proposed models for the Obama Geothermal System

Different fluid and heat sources have been proposed for the OGS. That is, lateral outflow to the west from Unzen volcano, recharge to the east from a magmatic source located beneath Chijiwa Bay, and flow from multiple geothermal systems. The temperature profile for the ~1400 m deep well UZ-2 (**Fig. 18)** shows an anomaly between 200 and 620 m below sea level elevation that would indicate a lateral flow of hot fluids from the Unzen volcano (Saibi et al., 2006b), thus confirming the suggestion made by Yuhara et al. (1986) that the heat source for the Obama hot springs may be the fluids coming from that volcanic system.

According to Matsushima and Kohno (2006) the surface manifestations in the OGF originate from emanations associated with a magmatic chamber located 15 km beneath Chijiwa Bay. Ohsawa (2006) suggested that the Obama hot springs are part of a “liquid-dominated, salty water geothermal system”, which is primarily recharged by hot fluids from a high-pressure magma reservoir. At shallow levels, the ascending thermal waters flow laterally toward the western coastal regions of the Shimabara Peninsula, where they cool conductively. Close to the surface the hot waters mix with cold groundwater to form the boiling or hot water of the Obama thermal spring system

(Ohsawa, 2006).

Fujimitsu et al. (2006) presented a large-scale hydrothermal model for the region beneath the Unzen volcano that incorporated the four known large geothermal systems on the Shimabara Peninsula, which are (from west to east): the Obama hot springs, the West Unzen High Temperature Body (WUHTB), the Unzen fumarolic field and the Shimabara hot springs. Their model included three fluid sources inferred from geodetic data collected during the 1990-95 Unzen volcanic eruption. Source A is beneath the Unzen volcano, while B is under the Unzen fumarolic area. Source C, below the WUHTB, is considered to be a magma reservoir at about 8 km depth.

9. New proposed conceptual hydro-geochemical model for the Obama geothermal system

A schematic hydro-geochemical cross-section of the OGS is presented in **Fig. 19,** which includes the three fluid sources in the Fujimitsu et al. (2006) model (See Section 8). The features for the eastern part of section were based on work done by Ohsawa (2006), while the locations of the magmatic sources beneath the OGS and the Unzen volcano are from Fujimitsu et al. (2006) and Ohta (2006). In this study, we focused mainly in developing the hydrothermal model for the Obama geothermal field (OGF).

The Obama geothermal reservoir is a two-phase, liquid-dominated system. A small amount of the deep-sourced hot water is inferred to move near vertically towards the surface, where it mixes with considerable amounts of (1) ground waters of meteoric origin, (2) intruded seawater and (3) high-temperature fluids coming from the eastern side of OGF (strong lateral flow from the Unzen volcano; Ohsawa, 2006), as is observed in the UZ-2 temperature log (Fig. 18).

The Obama thermal spring waters are in chemical disequilibrium with the surrounding rocks (Fig. 12). Geothermometers give different estimates for the deep reservoir temperature, with fluctuations reflecting variations in the measured hot spring discharge temperatures. Temperatures above 200 ^{o}C could be present in the deepest parts of the OGS as indicated by the CCG geothermometer, although estimated reservoir temperatures are in the 150-200 ^{o}C range, which would correspond to a medium-to-high temperature geothermal resource. Based on these inferred temperatures it may be feasible to produce electricity by tapping the OGS using conventional or non-conventional power generation technology. We recommend drilling deep geothermal wells in the eastern part of the OGF and under Chijiwa Bay with the purpose of identifying and characterizing the sources feeding the OGS and to evaluate its geothermal potential.

The main conclusions drawn from the present study can be summarized as follows:

(1) Hot spring waters of the OGS are primarily of the Na-Cl type.

(2) There is a significant seawater component in the Obama hot spring waters.

(3) Changes in reservoir temperatures estimated using silica and cation geothermometry reflect the effects of geothermal resource utilization. The impact of salt production shows a history of unsustainable fluid extraction (over-use) and heat mining of the Obama geothermal resource.

(4) The present state of the OGS is regarded as being “in recovery” following cessation of salt production and thermal fluid extraction.

(5) In the future, resource utilization should be managed to avoid overexploitation of the geothermal resource that would lead to seawater intrusion and lower of spring and well temperatures. This would require predictive reservoir modeling studies and a carefully designed well and spring monitoring program.

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Figures captions

Fig. 1. Map showing the location of the Obama and other geothermal fields in Kyushu Island, Japan. (a) black squares: geothermal areas related to Quaternary-Recent volcanic activity; black triangles: active volcanoes. (b) black open rectangle: location of the Obama geothermal field and of the area shown in Fig. 4.

Fig. 2. Location of hot springs and wells in the Obama geothermal field at different times. (a) Hot spring and well location maps. (a) to (e): Springs and wells given in Table 1.

Fig. 3. Location of hot springs and wells mentioned in Table 6.

Fig. 4. Geologic map of the Obama geothermal field (See Fig. 1b modified from NEDO (1988). The black squares indicate the positions of the sampled Obama hot springs. The location of this figure is shown in Fig.1b (black rectangle).

Fig. 5. Stratigraphic log for well UZ-2 (modified from NEDO, 1988); well location is shown in Fig. 4. Wellhead elevation: 132 m above sea level.

Fig. 6. Changes in the characteristics of the waters of hot spring N. 4 (black symbols and lines) and hot spring N. 26 (open symbols) with time. (a) temperature changes; (b) changes in TDS; (c) changes in Na and Cl concentrations; (d) changes in K, Mg, Ca, SO_4, HCO_3 and SiO_2 concentrations).

Fig. 7. Sodium-chloride plot for thermal, sea and river waters from the Obama geothermal field. Group 1: 1936-1944; Group 2: 1945-1955; Group 3: 1956-1959; Group 4: 1960-2005.

Fig. 8. Schöeller diagrams for the hot and cold waters of the Obama geothermal field.

Fig. 9. Relative He, Ar and N_2 contents in gas dissolved in Obama thermal well and sea waters (Nozaki, 1992) and in air (Ohsawa, 2006).

Fig. 10. Relative Cl-SO_4 and HCO_3 contents in thermal, sea, and river waters of the

Obama geothermal field. Group 1: 1936-1944; Group 2: 1945-1955; Group 3: 1956-1959; Group 4: 1960-2005.

Fig. 11. Ternary Na-K-Mg diagram mg/L for Obama hot spring waters (after Giggenbach, 1988). Group 1: 1936-1944; Group 2: 1945-1955; Group 3: 1956-1959; Group 4: 1960-2005.

Fig. 12. Concentrations (in mg/L) of the main components in Obama hot spring waters (also see Table 1) Group 1: 1936-1944; Group 2: 1945-1955; Group 3: 1956-1959; Group 4: 1960-2005. (a) changes in Na and Cl; (b) changes in K, Mg, Ca, HCO_3 and SO_4 ; (c) changes in TDS in mg/L; (d) changes of water temperatures (in ^oC).

Fig. 13. Change in estimated reservoir temperatures based on different geothermometers between 1936 and 2005. Group 1: 1936-1944; Group 2: 1945-1955; Group 3: 1956-1959; Group 4: 1960-2005.

Fig. 14. Chloride-enthalpy plot for Obama hot spring waters showing the reservoir water and the mixing, boiling, and cooling lines. Group 1: 1936-1944; Group 2: 1945-1955; Group 3: 1956-1959; Group 4: 1960-2005.

Fig. 15. Bromide-chloride plot for the hot water and seawater from the Obama geothermal field. Group 1: 1936-1944; Group 2: 1945-1955; Group 3: 1956-1959; Group 4: 1960-2005.

Fig. 16. Silica-enthalpy mixing model for the Obama hot spring waters. P_S indicates the silica concentration in the reservoir fluid. Group 1: 1936-1944; Group 2: 1945-1955; Group 3: 1956-1959; Group 4: 1960-2005.

Fig. 17. Plot of $\delta^{18}O$ versus δD, showing trends and shifts for waters from different geothermal fields (from Giggenbach, 1992). Also shown are the isotopic compositions of other types of waters. GMWL: Global Meteoric World Meteoric Line; lines parallel to it represent fractions of andesitic fluid that possibly contribute to the formation of the thermal waters (Giggenbach, 1992).

Fig. 18. Downhole temperature log for well UZ-2 (drilled in 1984).

Fig. 19. Hypothetical W-E section across the Obama geothermal field and the underlying deep sources, showing inferred hydrological processes and reservoir characteristics. Parts of the figure are based on the works of Fujimitsu et al. (2006), Ohsawa (2006) and Ohta (2006).

Table

Table 1

Chemical composition (in mg/L) and geothermometric temperatures (in ºC) for the hot spring waters in the Obama geothermal field from 1936 to 2005 (IHES, 2002; KEEA, 2005).

Spring number	Sample date	pH	T (°C)	TDS	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	SiO_2	Li^+	Br^-	I^-	%	Mass balance	A (°C)	B (°C)	C (°C)	D (°C)	E (°C)	F (°C)	G (°C)	H (°C)
1	1936/8		100	8041	2192	347.1	144.9	172.9	3910	300.6	244.4	256.57		2.2	15.8	0.1	1.100	164	199	246	194	179	73	203	12
4	1936/8		100	8077	2299	299.4	128.5	166.2	3959	400.8	142.8			3.4	27.5	0.1	1.092	155		227					13
7	1937/4		100	8234	2152	323.8	19.8	145.8	3561	146.3	235.4	218.03			6.2	0.4	1.251	162	187	241	179	166	62	189	5
3	1939/11		100	8470	2431	261.7	147.2	152.1	4186	321	269	94.86		10.6	10.8	0.1	1.090	147	134	210	116	107	14	132	15
22	1940/2			8360	2360	456	122	190	4370		311					2.1	1.071	174		266					9
5	1948/12			16,795	4729	658.5	370.8	80.5	8647	312.4						0.8	1.135	170		233					11
5	1951/2			20,701	5963	652.3	345.4	208.5	9871	1199						0.9	1.135	152		211					11
3	1954/3	8.2	85	24,992	7090	332.7	899.3	450	13,250	172.6	191.1	82.01		40.6	2	4.1	1.116	111	127	186	106	99	7	123	20
a	1954/3	8.2	86	20,560	5741	353.9	709.3	452	10,990	1251	182.5	104.78		36.9	2.5	0.0	1.045	121	140	199	122	113	19	138	19
b	1954/3	8.2	100	20,277	5725	324.1	633.4	385.7	10,620	1243	166.2	116.02		38.9	1	0.0	1.062	118	146	195	129	120	25	144	19
3	1954/5	7.7	85.5	24,992	6835	332.7	899.3	450	12,890	172.6	130.4	82.01		40.6	2	4.2	1.151	112	127	188	106	99	7	123	20
d	1954/5	7.8	90	22,323	5860	756.6	816.4	516.1	11,800	1471	186.4	98.63		39.6	2.6	0.0	1.043	153	137	239	118	110	16	134	13
a	1954/5	7.8	86	20,506	5557	353.9	709.3	452	10,710	1251	165.5	104.63		36.9	2.5	0.0	1.068	122	140	200	122	113	19	138	19
b	1954/5	8.0	100	20,277	5495	324.1	633.4	385.7	10,620	1243	162.9	116.02		38.9	1	1.5	1.075	120	146	197	129	120	25	144	19
4	1955/12	8.2	98.5	21,180	5449	314.6	658	394.8	10,280	1249	136.3	184.56		32	1.3	0.0	1.146	119	175	195	165	153	51	177	19
4	1956/1	8.2	98.5	21,280	5378	308.4	775.2	359.5	10,390	1303	134.1	197.03		34.8	1.4	0.1	1.141	119	180	193	170	158	55	182	20
17	1956/3	7.8	98	21,935	5279	300.1	747	457.2	10,310	1313	141.3	173.02		31.8	1.4	0.2	1.183	117	171	193	159	148	47	172	20
4	1956/3	8.2	98.5	21,280	5380	308	775	360	10,390	1300		196.95		35		0.5	1.149	119	180	193	170	158	55	182	20
c	1956/3		98.5	23,370	6172	324.5	739.2	349.2	11,700	146.8		156.02		34.8		3.1	1.203	117	164	191	151	140	41	164	20
d	1956/3	7.8	87	25,900	6118	328.9	1045	509.1	12,385	1575	168.2	140.48		37.8	1.6	0.0	1.170	115	157	189	143	133	35	157	21
12	1956/7		98	21,659	5273	219.3	771.3	390.8	9950	1342		123.71		30.6		1.4	1.207	106	150	177	134	124	28	149	23
17	1956/7		98	22,135	5392	288.8	795.4	395.8	10,430	1379		145.10		32.6		0.6	1.185	116	159	189	146	135	37	159	21
	1956/7		98	21,416	5304	263.3	747.3	383.3	10,010	1300		145.40		34.4		1.3	1.189	113	160	186	146	135	37	160	21
16	1958/11	7.8	71	21,200	6135	342.6	648.4	314.7	11,140	1341	81.6	200.26		36.6	0.3	0.2	1.060	120	181	195	172	159	56	183	18
17	1958/11	8.0	70	20,320	5791	328.1	620.1	331.4	10,640	1291	65.3	192.79		34.7	0.2	0.1	1.066	119	178	196	168	156	54	180	19

7	1958/11	7.8	63	18,300	5214	353	521.7	275.1	9471	1099	78.8	186.10	31.9	0.3	0.1	1.076	127	176	205	165	153	52	177	17
5	1958/3	7.6	67	15,720	4373	253.6	475	237.5	8040	985.1	118.2	151.17	28.1	0.3	0.4	1.085	121	162	194	149	138	39	162	20
4	1958/9	8.3	94	19,040	5413	286	558.4	329.5	9896	1171	138.8	173.02	33.4	0.5	0.2	1.070	116	171	192	159	148	47	172	19
7	1958/9	8.0	97	18,310	5209	283	516.8	296.8	9439	1105	120.9	186.26	30.8	0.4	0.1	1.079	118	176	193	165	153	52	177	19
7	1958/9	7.8	78	17,160	4903	280.8	487.3	288.8	8960	1058	56.4	172.71	31.2	0.6	0.2	1.070	120	171	195	159	148	47	172	19
8	1958/9	7.8	95	17,700	4960	266.9	504.4	313.3	9120	1028	97.6	199.56	30.3	0.6	0.1	1.087	117	180	192	171	159	56	183	20
c	1958/9	8.0	98	20,510	5795	346.8	560	322.2	10,560	1144	107.4	182.95	31.6	0.6	0.1	1.089	122	174	199	164	152	51	176	18
22	1959/12	7.9	71	14,050	3660	197	441	284	6970	893		134.63	23		0.2	1.129	115	155	188	140	130	33	154	22
11	1959/3	8.3	102	19,160	5607	305.5	563.3	318.9	10,240	1155	168.5	119.55	33.9	0.3	0.3	1.044	118	148	194	131	122	26	146	19
20	1959/3	7.7	94	20,770	5994	365.2	655.7	384.3	10,970	1322	131.4	183.33	36.7		0.6	1.048	122	175	199	164	152	51	176	18
3	1959/3	7.6	52	24,510	7182	420.6	744.7	364.1	13,030	153.1	143.9	130.71	39.8	0.3	3.8	1.112	122	153	199	138	128	31	152	17
6	1959/3	8.2	73	19,280	5556	330.3	548.7	302	10,120	1151	136.4	156.87	32.2	0.3	0.3	1.063	122	164	198	152	141	41	165	18
10	1961/2	8.2	81	14,130	4190	298.8	392.2	288.2	7630	745	310.3	91.94	27.5	1	0.1	1.020	128	133	206	113	105	13	130	18
18	1961/2	8.0	92	13,780	3976	285.6	379.5	278.1	7308	709.3	395.5	130.79	27.2	1	0.5	1.034	128	153	206	138	128	31	152	18
20	1961/2	7.8	84	14,100	4085	288.3	373.4	272	7421	741.2	298.6	121.17	27.7	1.1	0.1	1.046	128	148	205	132	123	27	147	18
2	1961/2	8.2		13,250	3755	280	371	256	6974	709	211	141.86	24		0.3	1.055	130	158	207	144	133	36	158	18
22	1961/9	8.0	74.5	10,810	2883	178	285	206	5329	511		137.71	19		0.8	1.151	121	156	195	142	131	34	156	21
29	1961/9	7.5	79	8835	2379	144	233	184	4375	472		117.71	16		0.8	1.135	120	147	192	130	121	25	145	21
4	1961/9	7.9	99	13,560	3740	270	367	258	6968	606		132.32	24		0.8	1.111	128	154	205	139	129	32	153	18
8	1961/9	7.8	98	13,350	3704	272	353	234	6870	620		130.79	24		0.4	1.108	130	153	206	138	128	31	152	18
22	1962/11	8.1	79	11,500	3328	246	305	233	5986	543		173.87	20		2.0	1.081	129	171	206	160	148	48	172	18
29	1962/11	7.3	83.5	10,250	2829	179	282	216	5266	517		143.86	18		0.6	1.103	122	159	196	145	134	36	159	20
4	1962/11	7.9	98.5	12,830	3609	271	338	255	6650	595		147.71	23		1.0	1.095	130	161	207	147	136	38	161	18
8	1962/11	7.8	97.5	12,390	3534	265	314	234	6476	575		160.02	22		0.8	1.087	130	166	208	153	142	43	166	18
22	1962/2	8.2	78.5	13,520	3563	243	382	265	6763	642		130.79	23		0.3	1.140	125	153	201	138	128	31	152	19
29	1962/2	7.2	79.5	9240	2484	158	264	196	4571	516		122.32	16		1.3	1.128	122	149	194	133	123	27	148	21
4	1962/2	7.8	99	13,890	3744	277	374	278	7004	700		108.48	24		0.5	1.122	129	142	206	125	116	21	140	18
8	1962/2	7.8	97	13,850	3732	279	357	255	6892	684		114.63	24		0.6	1.135	130	145	207	128	119	24	144	18
19	1963/10	7.5	71	10,070	2782	189.2	256	201.7	5083	527.5	168	154.33	18.4		0.0	1.094	125	163	200	150	139	40	164	20
22	1963/10	7.6	80	11,540	3286	248	280	222	6028	570		143.10	19		0.3	1.085	130	159	208	145	134	36	158	18
26	1963/10	7.7	79	8996	2437	161.8	234	179.6	4484	505.3	143	128.02	16.2		0.4	1.105	124	152	197	136	126	30	151	21
29	1963/10	7.9	84	10,630	2916	207	278	213	5371	564		136.94	18		0.7	1.113	127	156	202	141	131	34	155	19
4	1963/10	8.0	98	12,630	3493	264	317	251	6404	635		154.64	22		0.8	1.111	130	163	208	150	140	40	164	18
8	1963/10	7.8	96	12,340	3438	256	299	225	6300	603		156.17	21		0.4	1.110	130	164	207	151	140	41	165	18
22	1963/2	7.5	80	11,630	3282	250	308	231	6058	573		140.02	19		0.8	1.087	130	157	207	143	133	35	157	18
29	1963/2	7.5	83	10,260	2799	168	278	203	5239	523		145.40	17		0.1	1.114	120	160	193	146	135	37	160	21
4	1963/2	7.7	98	12,690	3600	263	334	255	6602	614		111.55	23		1.0	1.088	129	144	206	126	117	23	142	18

8	1963/2	7.7	97	12,560	3581	261	317	231	6557	602		105.40		23		0.6	1.088	129	140	206	123	114	20	138	18
22	1964/3	7.9	82	12,380	3380	256	324	240	6270	600		136.94		20		0.7	1.118	130	156	207	141	131	34	155	18
29	1964/3	7.2	84.5	11,450	3090	214	301	224	5820	541		150.02		19		0.0	1.124	126	162	201	148	137	39	162	19
4	1964/3	7.9	98.5	12,500	3390	260	313	230	6350	601		110.78		22		0.1	1.122	131	143	208	126	117	22	141	18
8	1964/3	7.9	98	12,300	3380	252	302	228	6250	592		103.09		21		0.2	1.118	130	139	207	121	112	18	137	18
26	1971/5	7.8	94	8740	2700	18	397.5	140.5	4491	748.5	220.5	5.69				4.0	1.003	49	18	101	-10	-11	-79	12	43
22	1975/12	7.7	93	9850	2780	317	200	176	5020	447	224	130.79		18		0.2	1.075	149	153	215	138	128	31	152	14
29	1975/12	7.9	94.1	8880	2520	258	195	158	4530	419	229	119.25		16		0.1	1.069	144	147	206	131	122	26	146	16
4	1975/12	7.9	98.5	9890	2720	333	273	163	5090	440	195	83.09		18		0.4	1.073	153	127	232	107	99	8	124	15
8	1975/12	8.1	100	9880	2830	34	271	155	5060	417	159	79.24		18		0.1	1.107	65	125	124	104	97	6	121	35
26	1977/12	7.6	95	9158	2735	276	192.2	111.1	4723	567.4	239.2	124.94		8.6		0.5	1.036	147	150	205	134	125	29	149	15
22	1978/7	7.5	96.7	9503	2739	262	204	113	4913	192.7	206.2	228.49		14.3		1.0	1.101	144	190	200	183	170	65	193	16
2	1979/10	8.1	99	9275	2788	303	194	192	4886	410	167.6	147.71	5.0	16.6		3.1	1.037	146	161	211	147	136	38	161	15
20	1979/12	7.8	98.1	9142	2679	278	192.5	195	4635	440	234.3	230.03	4.8	16.1	1.4	3.5	1.056	144	191	207	184	170	66	194	15
6	1979/12	8.2	100.2	9596	2938	309.7	182.1	179.6	4931	412	74.3	184.02	6.0	17.2		4.9	1.063	146	175	208	164	152	51	176	14
18	1979/7	7.6	87.8	9182	2668	325	189.7	109	4865	486.3	153.8	264.03	5.1	13.7		0.1	1.044	156	201	221	197	182	75	205	14
29	1979/7	7.5	79.1	8760	2553	281.3	185.3	105.3	4668	469.6	198.3	220.03	4.5	15.3	0.9	0.6	1.035	151	187	212	180	166	63	190	15
4	1979/7	7.4	99.3	9430	2622	296.9	193	105.3	4956	465	191.6	200.03	5.2	13.3		1.5	1.068	153	181	215	172	159	56	183	15
8	1979/7	7.6	92.2	9083	2630	337.5	181	104.4	4836	439	145.2	200.03	5.6	15.3		0.2	1.047	159	181	226	172	159	56	183	13
22	1983/6	7.9	94.5	8678	2540	260	215	130	4560	384	186	172.33		15.7		0.5	1.049	146	170	222	159	147	47	172	16
29	1983/6	7.4	88.3	8468	2520	240	215	128	4400	374	260	200.03		16		1.3	1.041	143	181	218	172	159	56	183	17
8	1983/6	8.1	96.5	9060	2660	360	185	106	4780	364	186	140.02		17		0.1	1.048	161	157	231	143	133	35	157	13
	1986/1	8.3	84	9118	2714	600	165.5	136.6	4959	368.4	152.5	234.80	5.9	15.1	3.9	2.9	1.002	185	192	281	186	172	67	195	8
23	1987/3	7.6	91	9060	2543	267.9	170.1	126.3	4503	355.1	209.3	215.72	6.9	23.7		2.3	1.108	148	186	208	178	165	61	189	15
24	1987/3	7.9	93.8	8940	2571	250	187.5	127.5	4608	364.9	183.7	197.18	6.4	22.6		1.8	1.078	144	180	202	170	158	55	182	16
28	1987/3	7.5	90	8510	2400	253	173.6	125.1	4326	345.4	238	205.26	6.1	22.4		1.6	1.083	147	182	208	174	161	58	185	16
29	1987/3	8.0	96	8792	2457	247	173.6	125.1	4361	350.2	192.2	202.80	6.5	21.6		2.2	1.112	145	182	204	173	160	57	184	16
10	1987/4	8.5	99.5	9270	2730	310	173.2	203.8	4964	380	150.6	66.16	5.3	20.8	0.3	1.6	1.040	148	116	215	93	87	-2	111	14
12	1987/4	8.4	98	8930	2692	285.7	169.6	180.7	4822	376	137.8	69.24	5.0	22.2	0.4	1.7	1.031	146	118	209	96	89	0	114	14
13	1987/4	8.5	97	8855	2653	309.5	166.1	184.6	4786	366	150.6	69.24	4.8	23.3	0.3	1.7	1.028	150	118	217	96	89	0	114	14
17	1987/4	8.3	96	9035	2615	273.8	173.2	165.4	4857	384	124.9	69.24	4.7	21.7	0.3	0.0	1.051	145	118	208	96	89	0	114	15
27	1987/4	7.6	69.5	3850	1107	108	91.1	107.6	2076	196	146.4	64.62	1.8	11	0.2	0.4	1.005	139	114	202	92	85	-3	110	20
4	1987/4	8.3	99.5	8845	2576	286	167.8	165.4	4716	370	141	72.32	4.6	22.3	0.2	0.7	1.050	148	120	213	98	91	2	116	14
7	1987/4	8.4	100.5	8815	2653	297.6	164.3	196.1	4786	360	128.1	73.86	5.4	23.8	0.3	2.0	1.027	147	121	214	100	93	3	117	14
8	1987/4	8.4	99.5	8735	2615	297.6	162.5	192.3	4716	350	131.3	69.24	5.0	24.5	0.3	1.9	1.032	148	118	215	96	89	0	114	14
9	1987/4	8.2	93.8	8765	2615	285.7	166.1	184.6	4751	356	112.1	72.32	5.1	23.3	0.3	1.8	1.035	146	120	211	98	91	2	116	14
	1987/4	8.4	91	8790	2653	285.7	164.3	176.9	4786	390	133.3	69.24	4.7	21.8	0.4	1.5	1.023	146	118	210	96	89	0	114	14

2005/4	8.5	97.4	8354	2800	260	120	130	4500	330	180		5.1	16		4.4	1.004	142		198	14

%: Ionic balance. Inferred reservoir temperatures. A: Na-K-Ca geothermometer (Fournier and Truesdell, 1973); B: Silica (Fournier and Potter, 1982); C: Cation composition geothermometer (CCG) (Nieva and Nieva, 1987); D: Silica (Giggenbach, 1992); E: Chalcedony (Fournier, 1992); F: Amorphous silica (Fournier, 1992); G: Silica (Verma, 2000); H: K-Mg (Giggenbach, 1988).

Table 2

Chemical composition (in mg/L) of different types of waters in the Obama geothermal field (NEDO, 1988). The location where the river water was sampled is shown in Fig. 4.

Type of water	Date	pH	T (^{o}C)	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	SiO_2
Sea	Dec. 1975		17.8	10250	358	1270	399	18650	2450	138	1.3 *
River	1984	7.3	16.2	5.94	2.31	2.19	6.43	5.50	2.10	37.20	51.70
Spring **	31/10/1999	7.0	17.8	5.80	2.20	2.50	5.70	5.40	5.10	36.40	40.10

* Sampled on 13/12/2000 (Ohsawa; pers. comm., November 2008).

** Geological Survey of Japan (2010); unpublished data.

Table 3

Br/Cl and Br/I ratios for each of the four spring groups

Parameter	Group 1	Group 2	Group 3	Group 4
Br/Cl	0.00132	0.00335	0.00325	0.00371
Br/I	0.41	23.47	81.24	51.44

Table 4

Results from the chloride-enthalpy model. The percentage of the seawater component in the hot springs decreased recently (Group 4) due to the cessation of hot water extraction by the salt factories. This led to the recovering of the enthalpy of the reservoir fluid in the Obama geothermal field

Group	Seawater (%)	Rain (%)	Chloride contents in the reservoir (mg/L)	Enthalpy of the reservoir fluid (Rn, n = 1, 2, 3, 4) (kJ/kg)
Group 1	10%	25%	3450	816.5
Group 2	30%	15%	11,400	667.0
Group 3	35%	35%	10,250	785.0
Group 4	20%	50-70%	6400	710.5

Table 5

Results from the SiO_2-enthalpy model. The estimated reservoir temperature increased in the Group 4 with the increasing of silica concentration in the reservoir fluid.

Group	Estimated reservoir temperature determined from the enthalpy-SiO_2 model (^oC)	Silica concentration in the reservoir fluid (mg/L) inferred from the enthalpy-SiO_2 model	Fraction of hot water in the mixed discharge
Group 1	191.5	227	0.91
Group 2	171.5	165	0.67
Group 3	177.0	182	0.89
Group 4	204.0	265	0.76

Table 6

Isotopic concentrations in hot spring, wells, river and rain waters from the Obama geothermal field (NEDO, 1988; OT, 2002). HS: hot spring; UZ: wells Location of hot springs and wells is given in Fig. 3, those of the river and rain water sampling points in Fig. 4.

Sample	Year	Cl (mg/L)	$\delta\ ^{18}O$ (‰)	δD (‰)
HS 1	1984	5095	-4.2	-36.1
HS 2	1984	4890	-4.2	-35
HS 3	1984	4960	-4	-31.9
HS 4	1984	4815	-4.3	-33
HS 5	1984	4695	-4.1	-33.1
HS 6	1984	4630	-4.5	-33.4
HS 7	1984	4740	-4.2	-31.9
HS 8	1984	4590	-4.5	-32.7
HS 9	1984	4550	-4.5	-34.1
HS 10	1984	4715	-4.5	-35.7
HS 11	1984	4855	-5.3	-36.2
HS 12	1984	4840	-4.3	-35.9
HS 13	1984	4800	-4.2	-32
HS 14	1984	5030	-4.2	-30.8
HS 15	1984	3975	-4	-34.7
HS 1	2001	4620	-4.5	-34.2
HS 2	2001	4680	-4.1	-34.2
HS 3	2001	4410	-4.5	-35.6
HS 4	2001	4560	-4.5	-34.9
HS 5	2001	4470	-4.5	-35.2
HS 6	2001	4470	-4.5	-34.6

HS 7	2001	4370	-4.6	-36.8
HS 8	2001	4470	-4.5	-36
HS 9	2001	4540	-4.5	-36.5
HS 10	2001	4650	-4.2	-36.1
HS 11	2001	4710	-4.1	-35.4
HS 12	2001	4530	-4.3	-35.3
HS 13	2001	4650	-4.2	-35.2
HS 14	2001	4620	-4.3	-34.2
HS 15	2001	4620	-4.3	-34.5
HS 16	2001	4720	-4.1	-33.6
HS 17	2001	4800	-4.2	-33.2
UZ-15	1984	3220	-5.3	-36.2
UZ-16	1984	4830	-4.3	-33.0
UZ-17	1984	4510	-4.5	-33.4
UZ-18	1984	4590	-4.1	-33.1
UZ-19	1984	4700	-4.5	-35.7
UZ-02	1984	4730	-4.2	-32.0
UZ-20	1984	4790	-4.2	-35.0
UZ-21	1984	4910	-4.2	-36.1
UZ-22	1984	4830	-4.0	-34.7
UZ-23	1984	4700	-4.3	-35.9
UZ-03	1984	4730	-4.2	-30.8
UZ-04	1984	4830	-4.0	-31.9
UZ-05	1984	4690	-4.2	-31.9
UZ-06	1984	4510	-4.5	-32.7
UZ-07	1984	4480	-4.5	-34.1
River water	1984	5.5	-7.4	-45.9
Rain water	1999	5.4	-7.37	-46.7

Figure 1

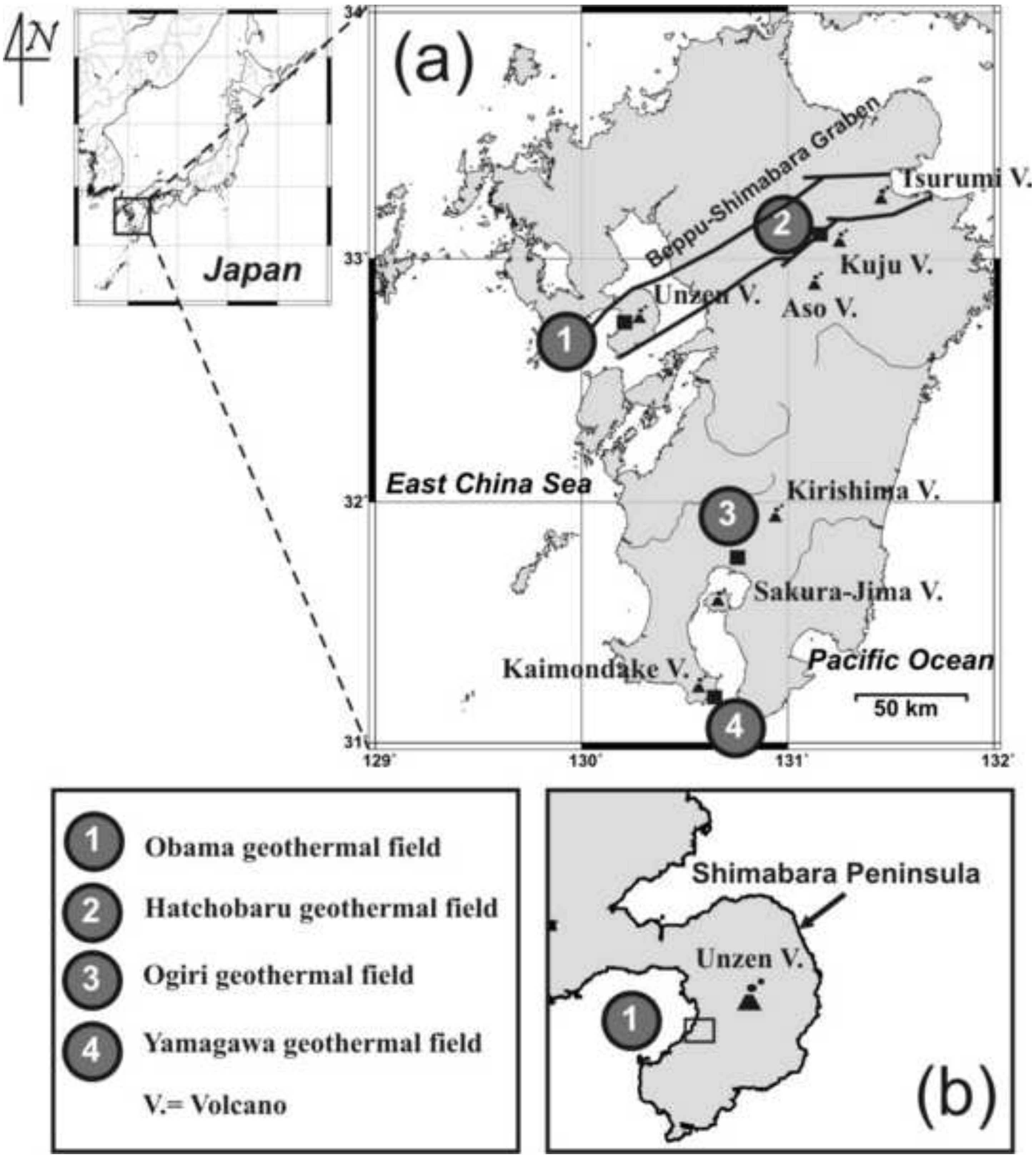
N
Japan
(a)
Beppu-Shimabara Graben
Tsurumi V.
Kuju V.
Unzen V.
Aso V.
East China Sea
Kirishima V.
Sakura-Jima V.
Kaimondake V.
Pacific Ocean
50 km
1
2
3
4
34°
33°
32°
31°
129°
130°
131°
132°
① Obama geothermal field
② Hatchobaru geothermal field
③ Ogiri geothermal field
④ Yamagawa geothermal field
V.= Volcano
Shimabara Peninsula
Unzen V.
1
(b)

Figure 2

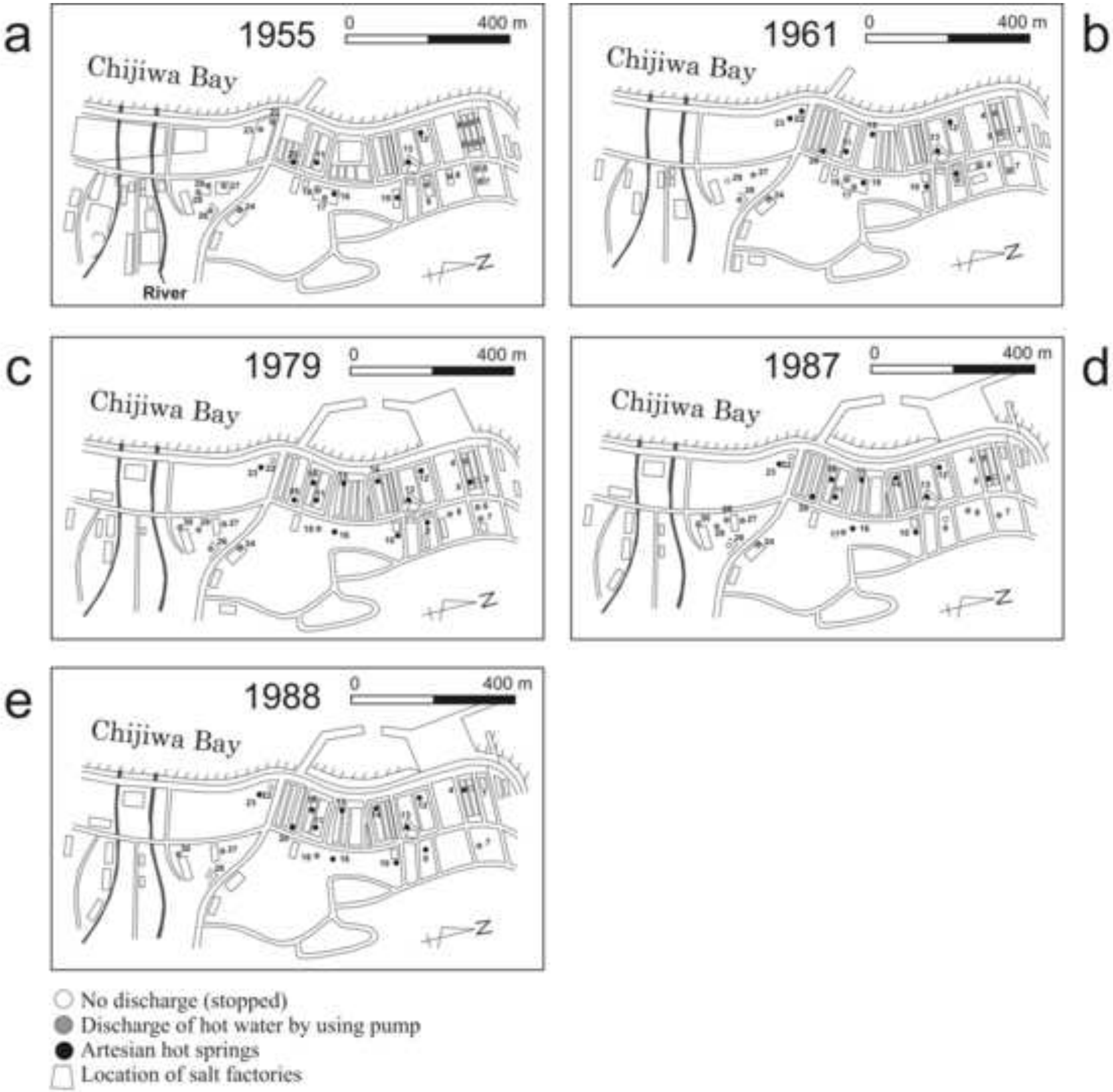
a
1955
0
400 m
Chijiwa Bay
River
b
1961
0
400 m
Chijiwa Bay
c
1979
0
400 m
Chijiwa Bay
d
1987
0
400 m
Chijiwa Bay
e
1988
0
400 m
Chijiwa Bay
N
○ No discharge (stopped)
● Discharge of hot water by using pump
● Artesian hot springs
▱ Location of salt factories

Figure 3

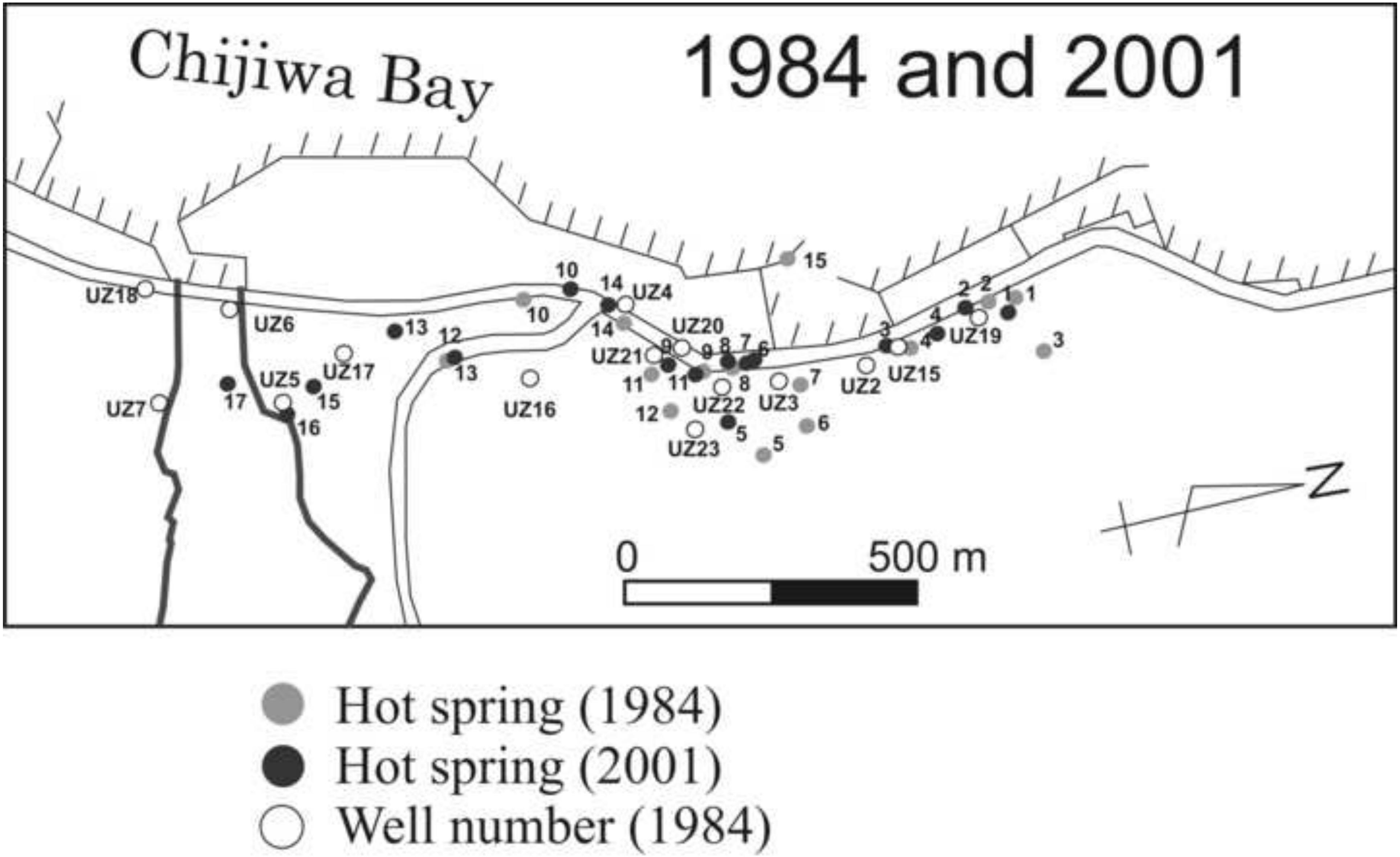
Chijiwa Bay
1984 and 2001
UZ18
UZ6
UZ7
UZ5
UZ17
17
15
16
13
12
13
10
10
UZ16
14
UZ4
14
UZ20
UZ21
9
9
8
7
6
11
11
8
12
UZ22
UZ3
7
5
UZ23
5
6
15
UZ2
UZ15
3
4
4
2
2
1
1
UZ19
3
N
0
500 m
● Hot spring (1984)
● Hot spring (2001)
○ Well number (1984)

Figure 4

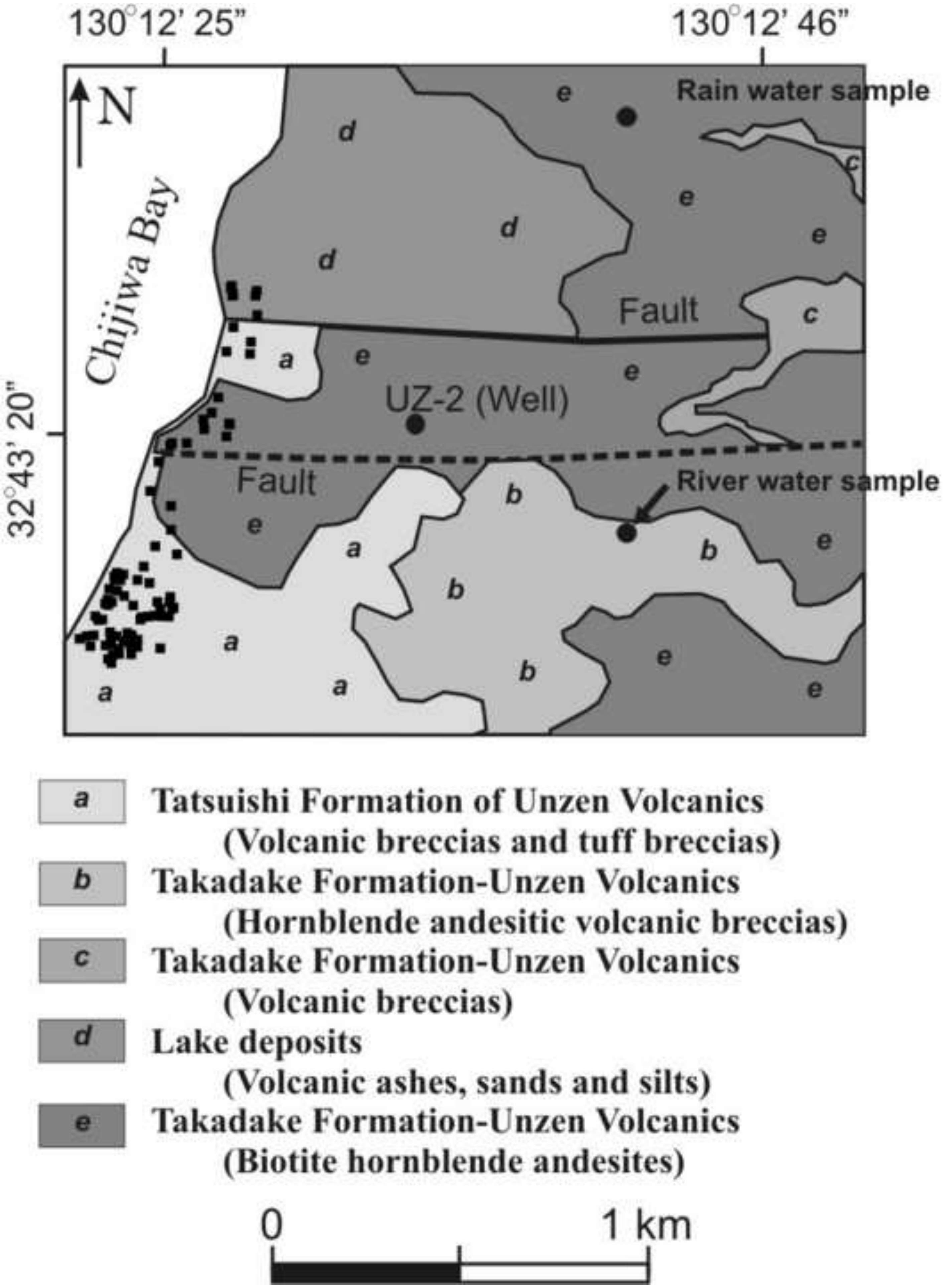
130°12' 25"
130°12' 46"
32°43' 20"
N
Chijiwa Bay
Rain water sample
River water sample
UZ-2 (Well)
Fault
Fault
a
b
c
d
e
a Tatsuishi Formation of Unzen Volcanics (Volcanic breccias and tuff breccias)
b Takadake Formation-Unzen Volcanics (Hornblende andesitic volcanic breccias)
c Takadake Formation-Unzen Volcanics (Volcanic breccias)
d Lake deposits (Volcanic ashes, sands and silts)
e Takadake Formation-Unzen Volcanics (Biotite hornblende andesites)
0
1 km

Figure 5

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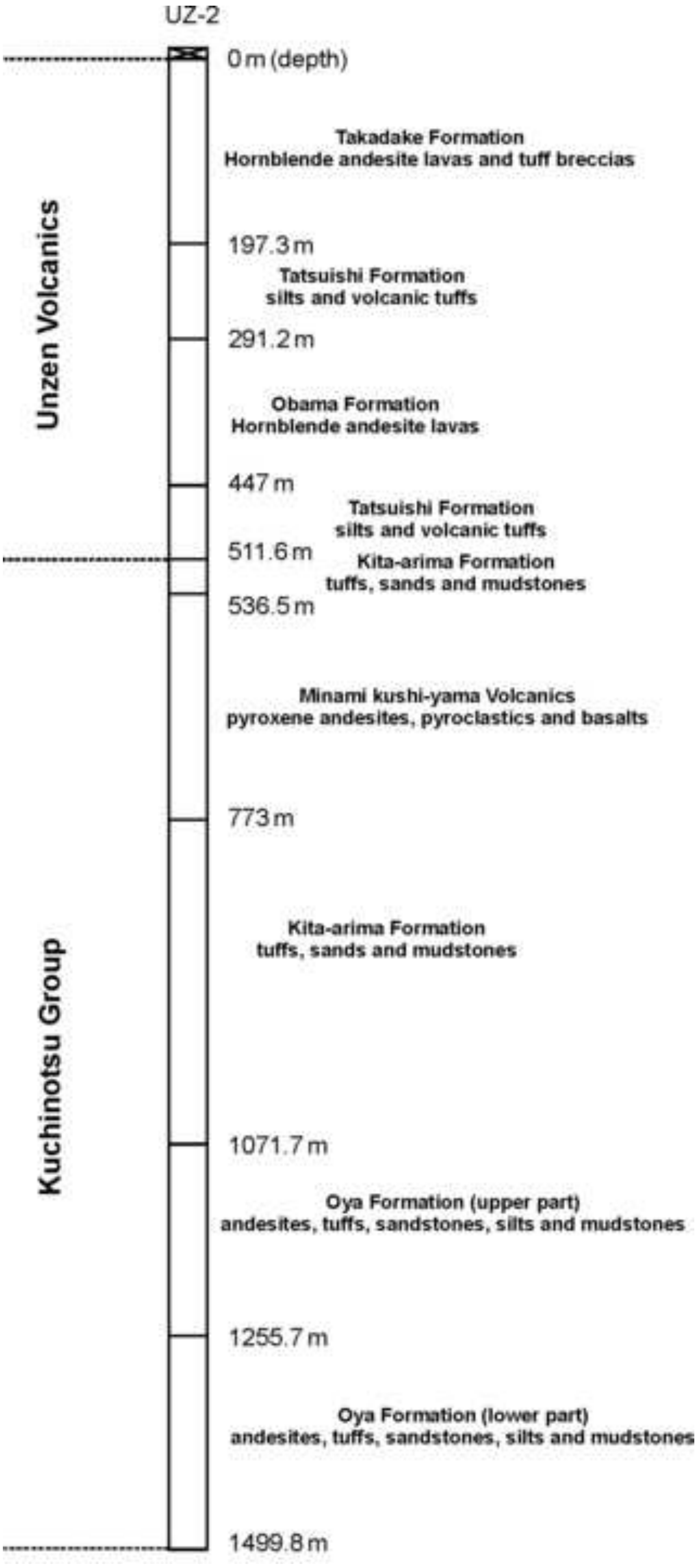

Figure 6

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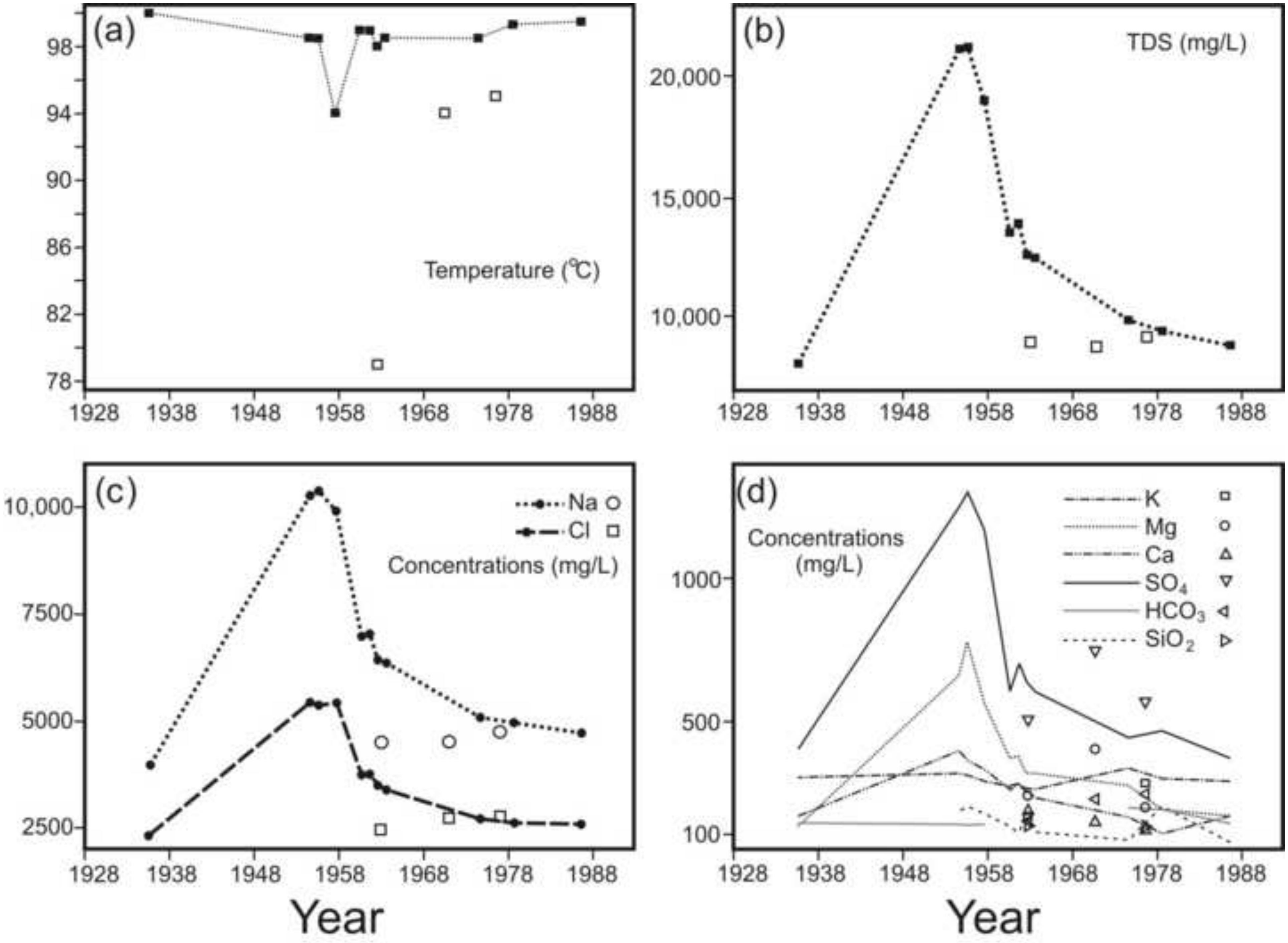

Figure 7

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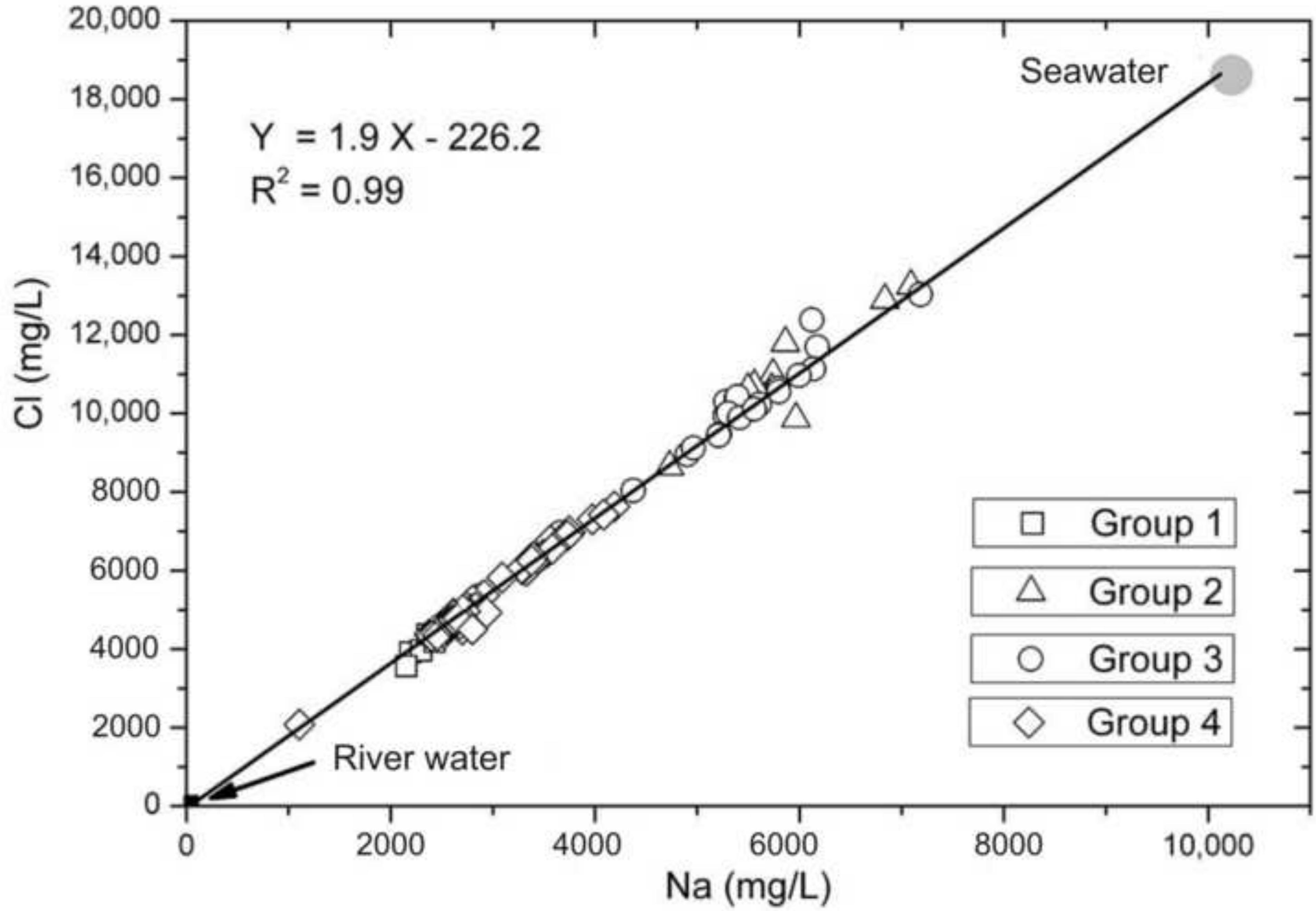

Figure 8

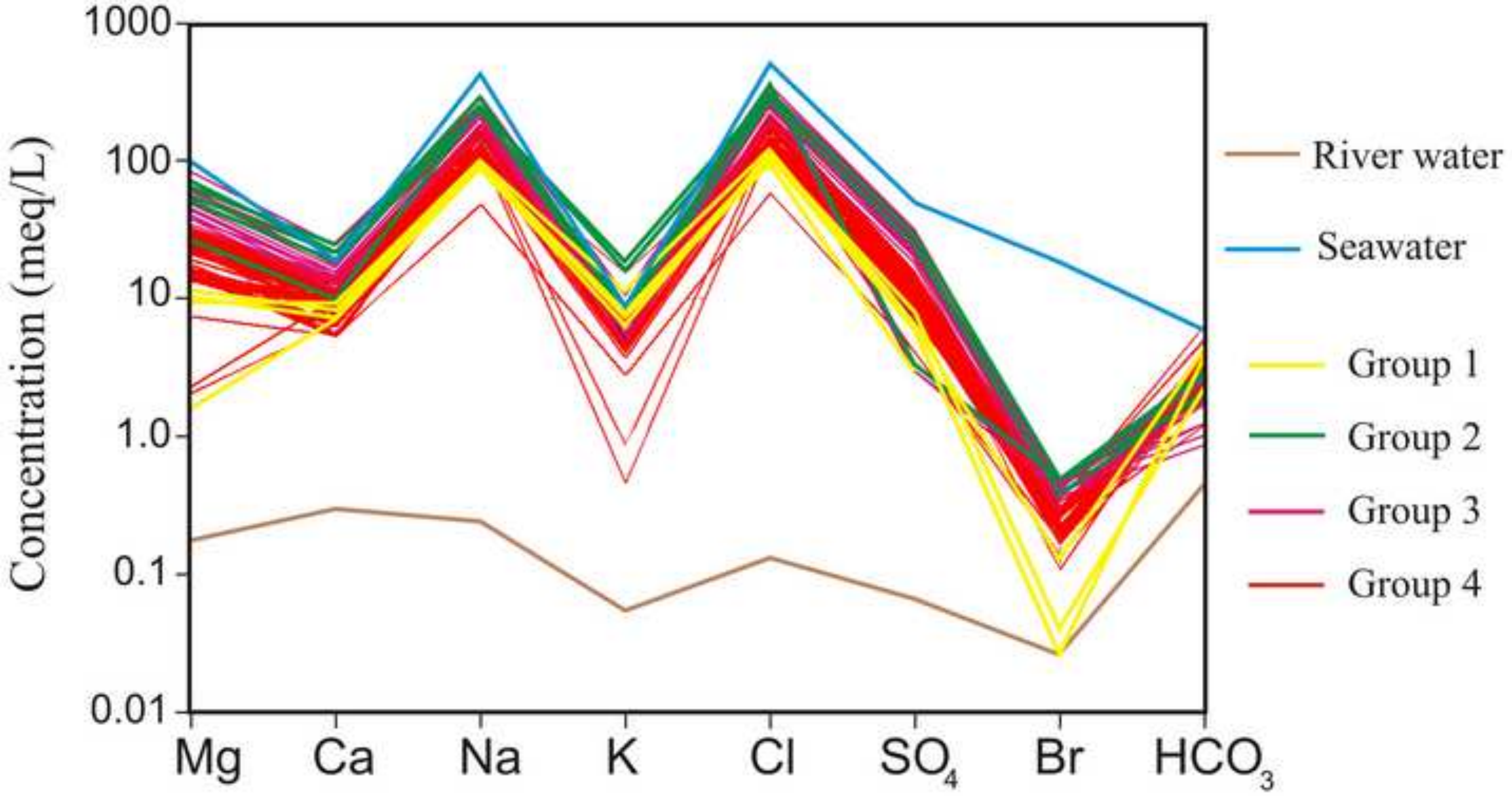
1000
100
10
1.0
0.1
0.01
Concentration (meq/L)
Mg
Ca
Na
K
Cl
SO4
Br
HCO3
River water
Seawater
Group 1
Group 2
Group 3
Group 4

Figure 9

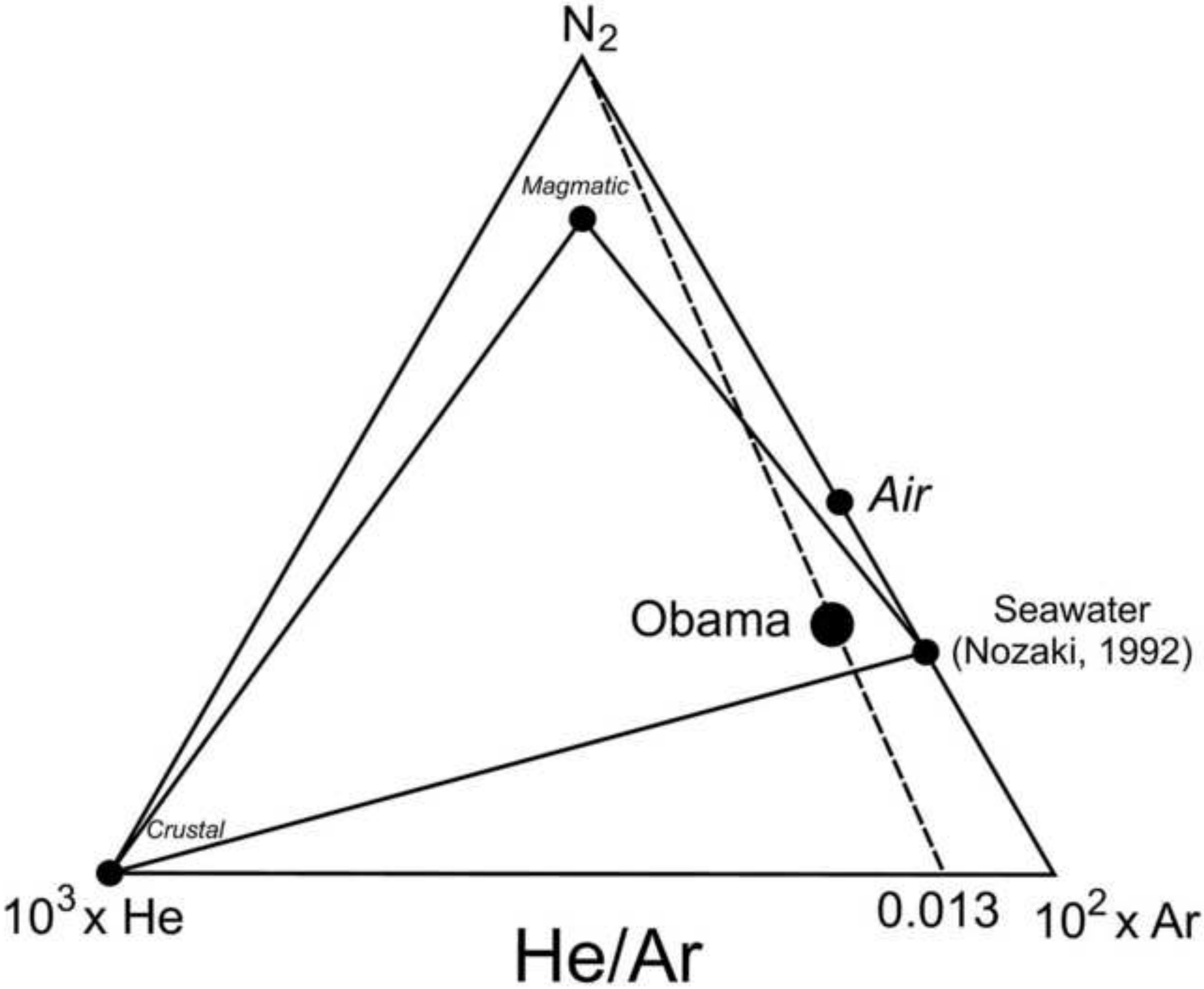
N_2
Magmatic
Air
Obama
Seawater
(Nozaki, 1992)
Crustal
10^3 x He
0.013
10^2 x Ar
He/Ar

Figure 10

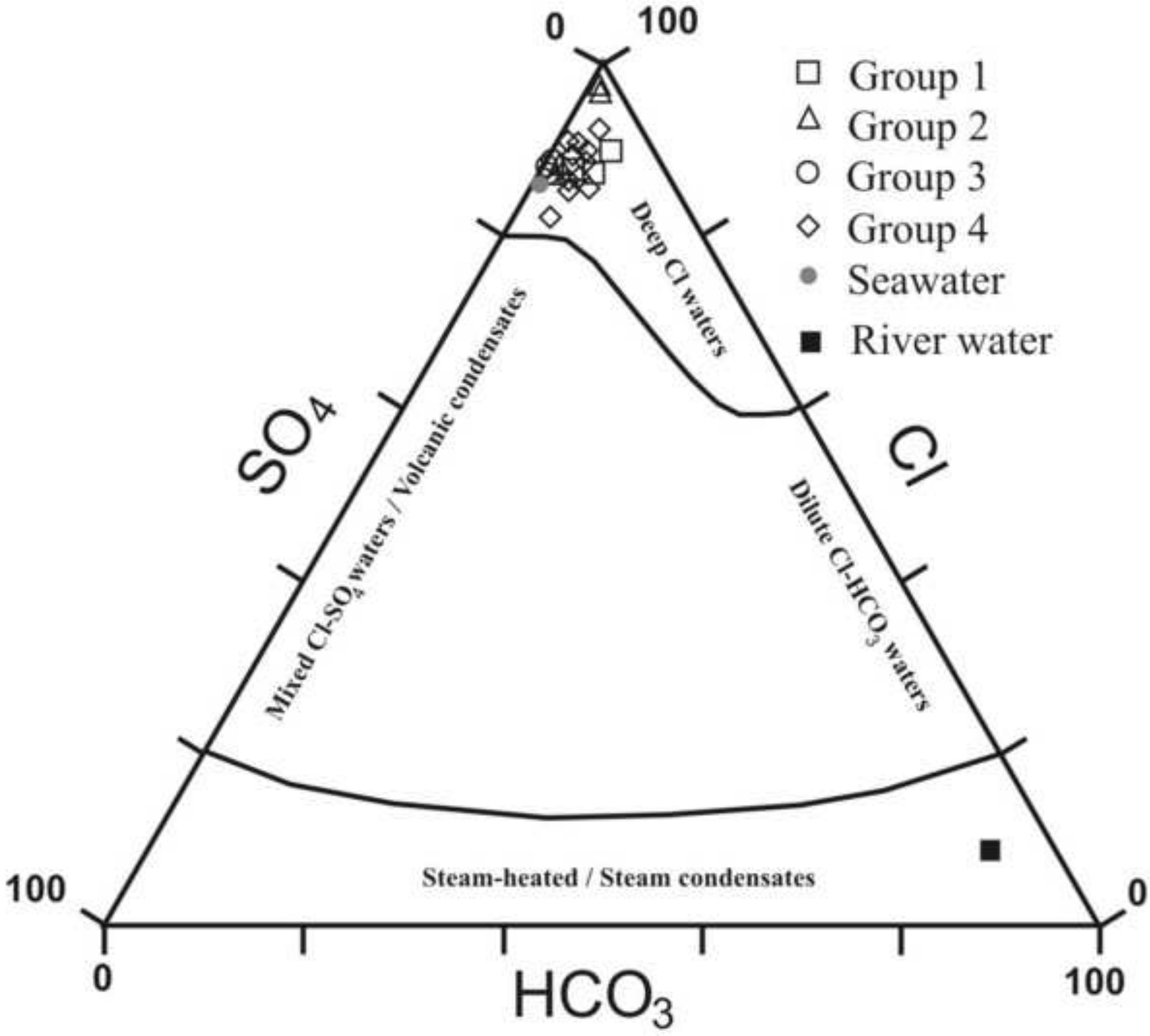
0
100
□ Group 1
△ Group 2
○ Group 3
◇ Group 4
● Seawater
■ River water
Deep Cl waters
SO_4
Cl
Mixed Cl-SO_4 waters / Volcanic condensates
Dilute Cl-HCO_3 waters
Steam-heated / Steam condensates
100
0
0
HCO_3
100

Figure 11

Click here to download high resolution image

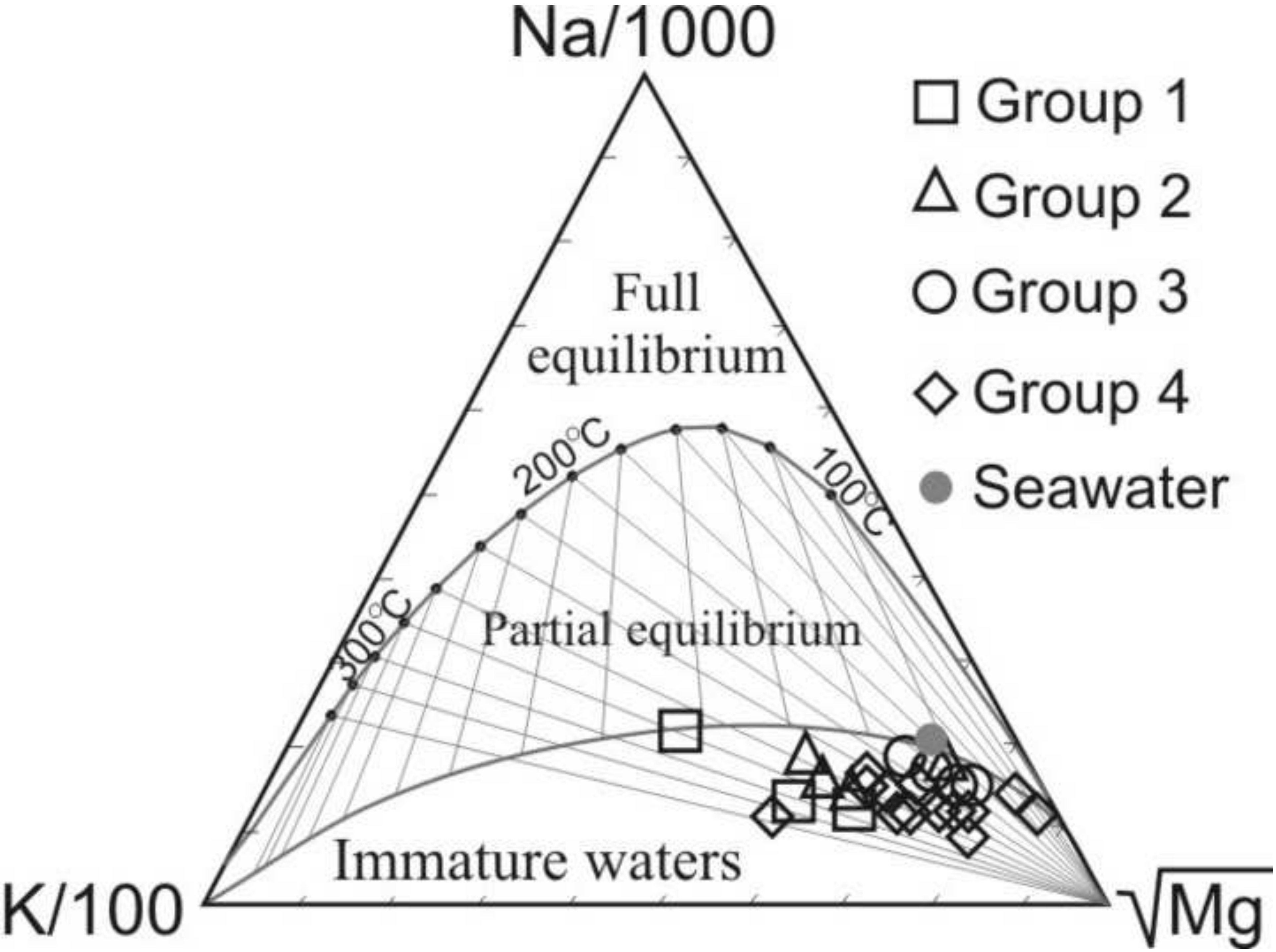

Figure 12

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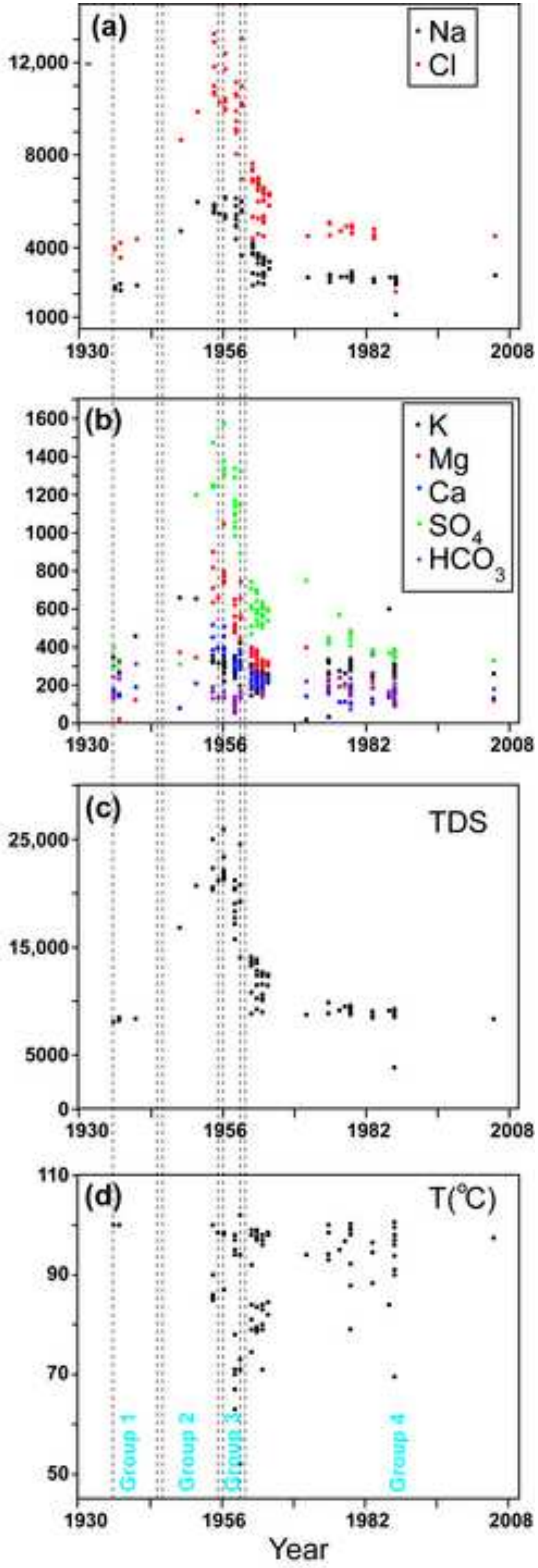
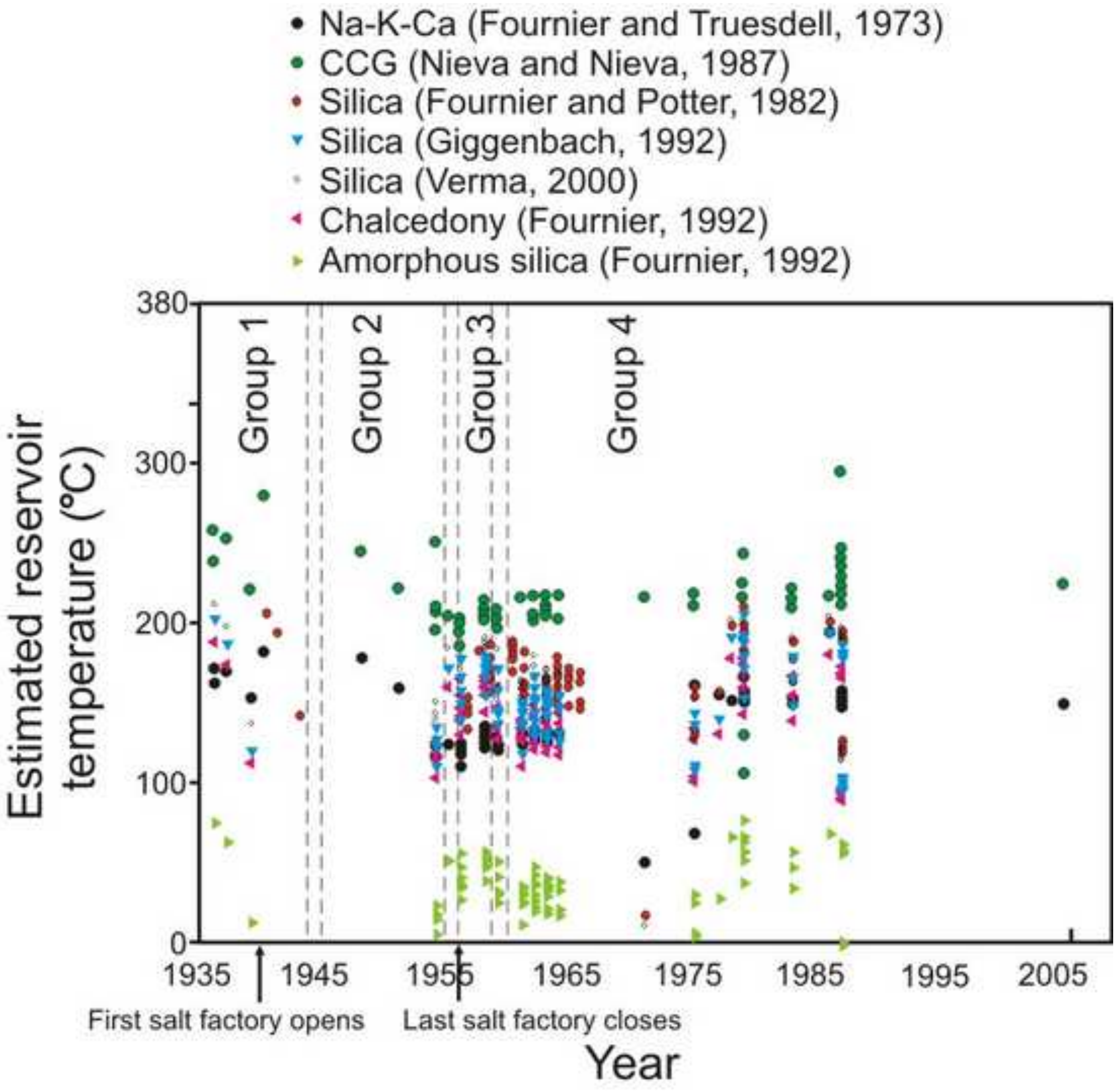


Figure 13



● Na-K-Ca (Fournier and Truesdell, 1973)
● CCG (Nieva and Nieva, 1987)
● Silica (Fournier and Potter, 1982)
▼ Silica (Giggenbach, 1992)
● Silica (Verma, 2000)
◀ Chalcedony (Fournier, 1992)
▶ Amorphous silica (Fournier, 1992)
Group 1
Group 2
Group 3
Group 4
Estimated reservoir temperature (°C)
380
300
200
100
0
1935
1945
1955
1965
1975
1985
1995
2005
First salt factory opens
Last salt factory closes
Year

Figure 14

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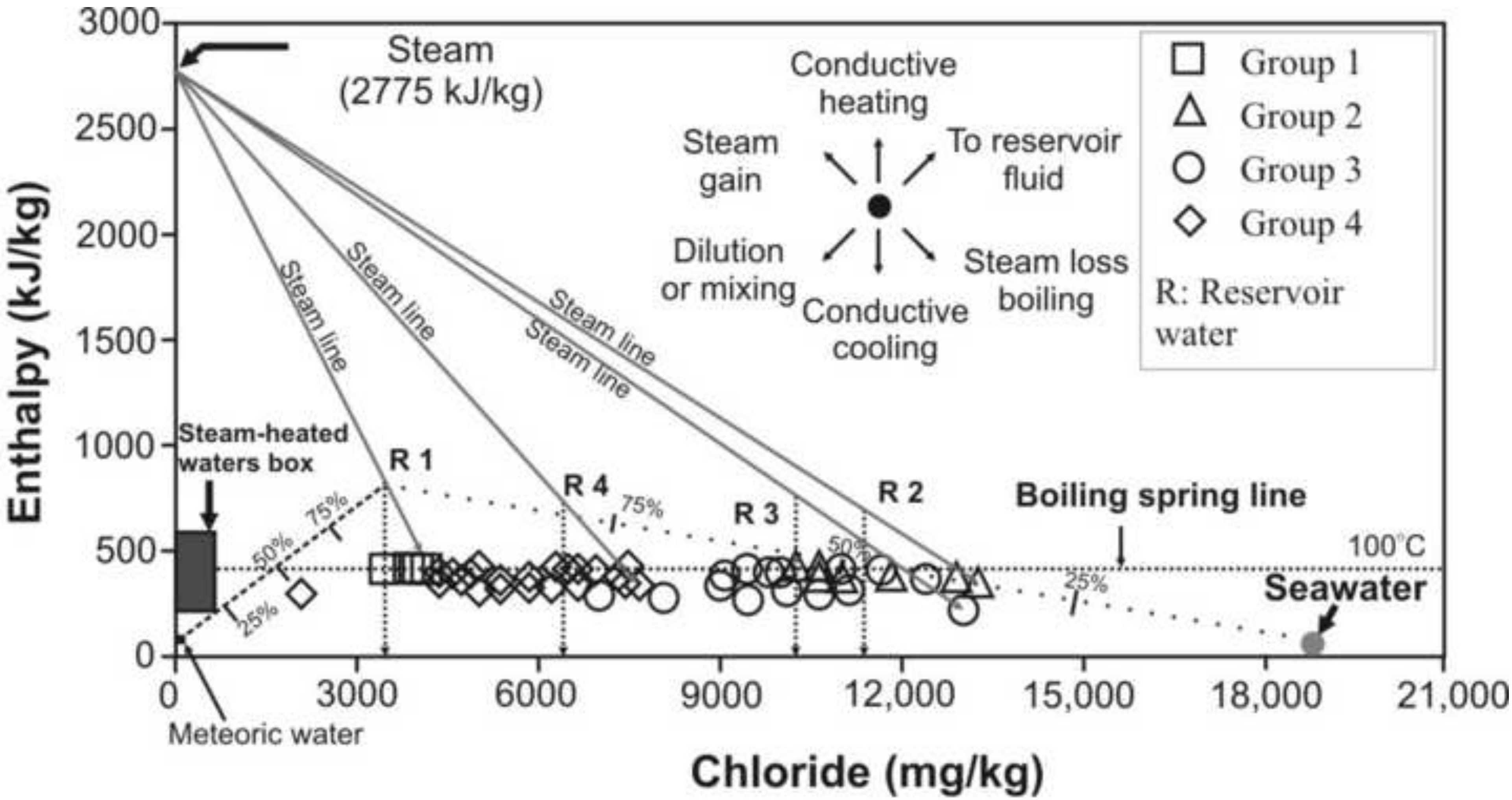

Figure 15

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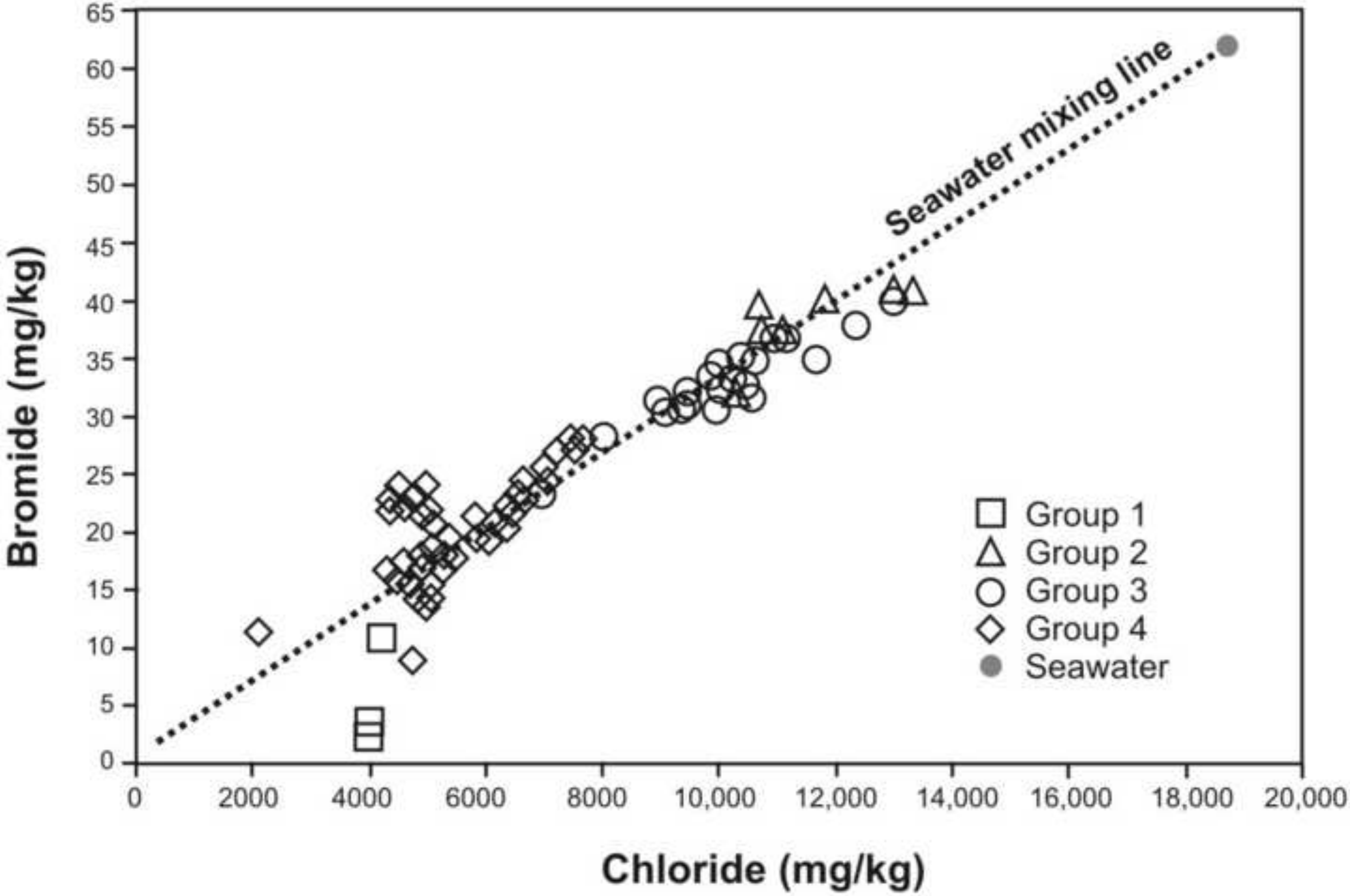

Figure 16

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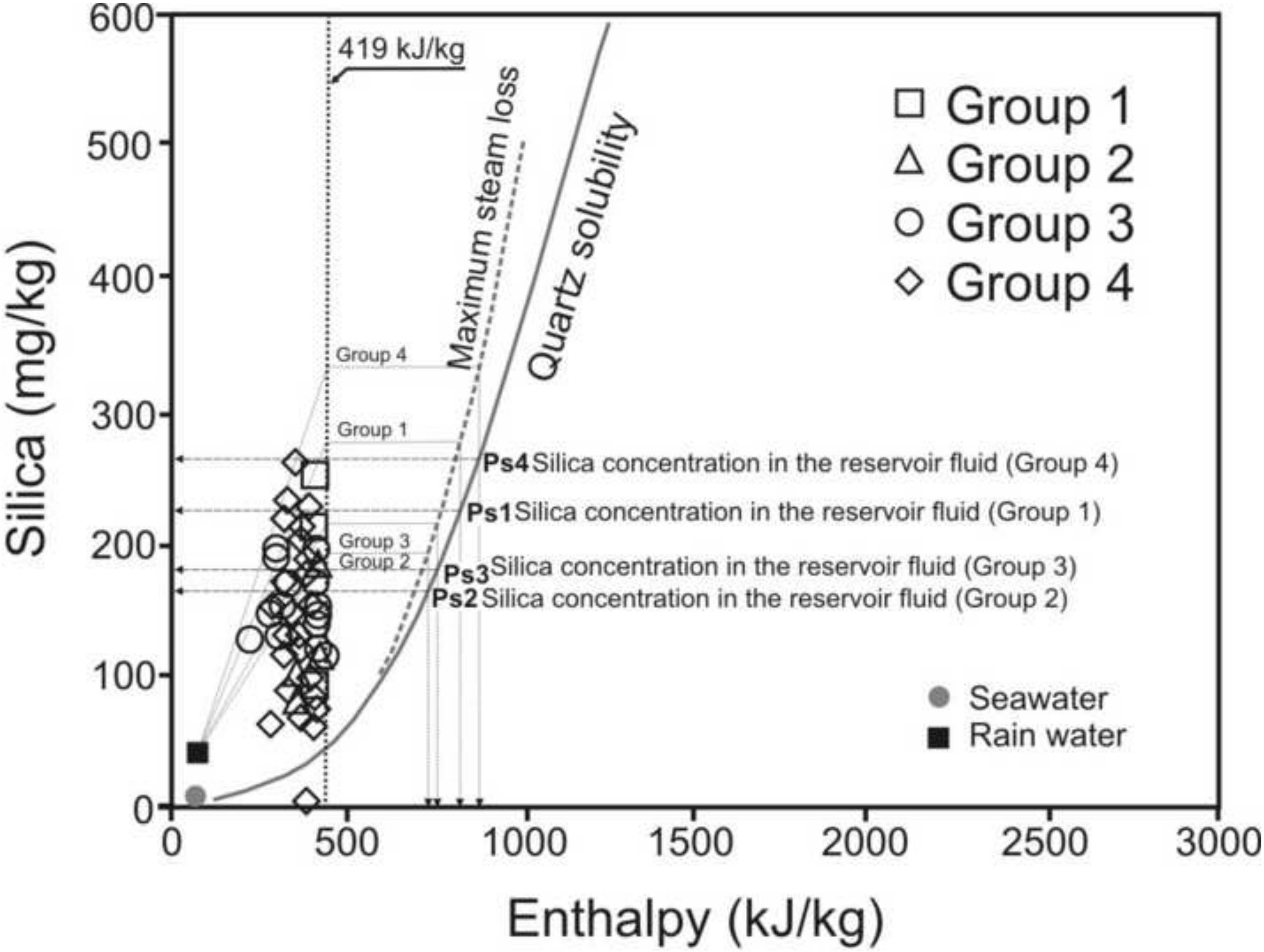

Figure 17

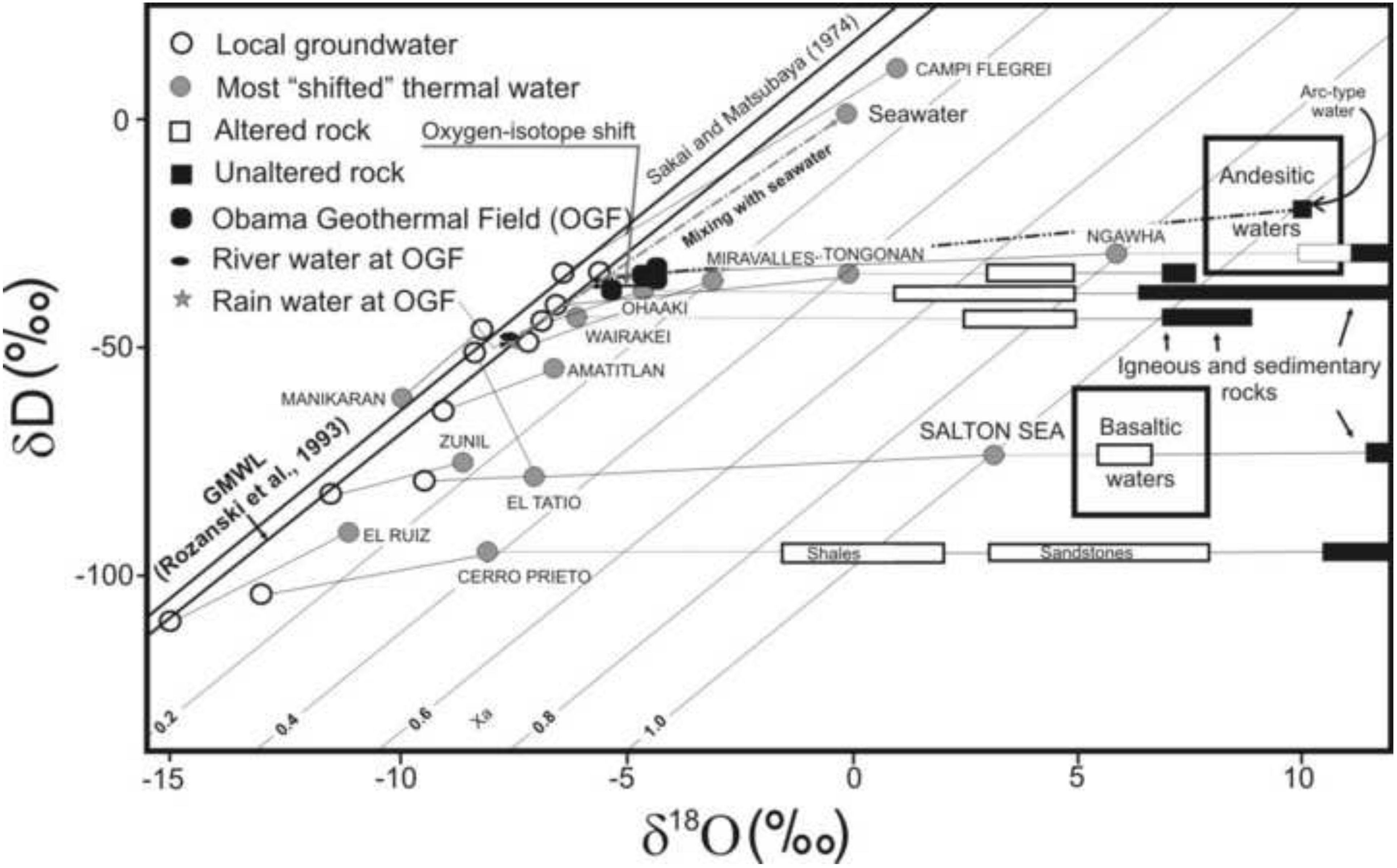
○ Local groundwater
● Most "shifted" thermal water
□ Altered rock
■ Unaltered rock
● Obama Geothermal Field (OGF)
▬ River water at OGF
★ Rain water at OGF
Oxygen-isotope shift
Sakai and Matsubaya (1974)
Mixing with seawater
GMWL
(Rozanski et al., 1993)
CAMPI FLEGREI
Seawater
Arc-type water
Andesitic waters
NGAWHA
MIRAVALLES-TONGONAN
OHAAKI
WAIRAKEI
AMATITLAN
MANIKARAN
ZUNIL
EL TATIO
EL RUIZ
CERRO PRIETO
SALTON SEA
Basaltic waters
Igneous and sedimentary rocks
Shales
Sandstones
0.2
0.4
0.6
Xa
0.8
1.0
0
-50
-100
-15
-10
-5
0
5
10
δD (‰)
δ^{18}O (‰)

Figure 18

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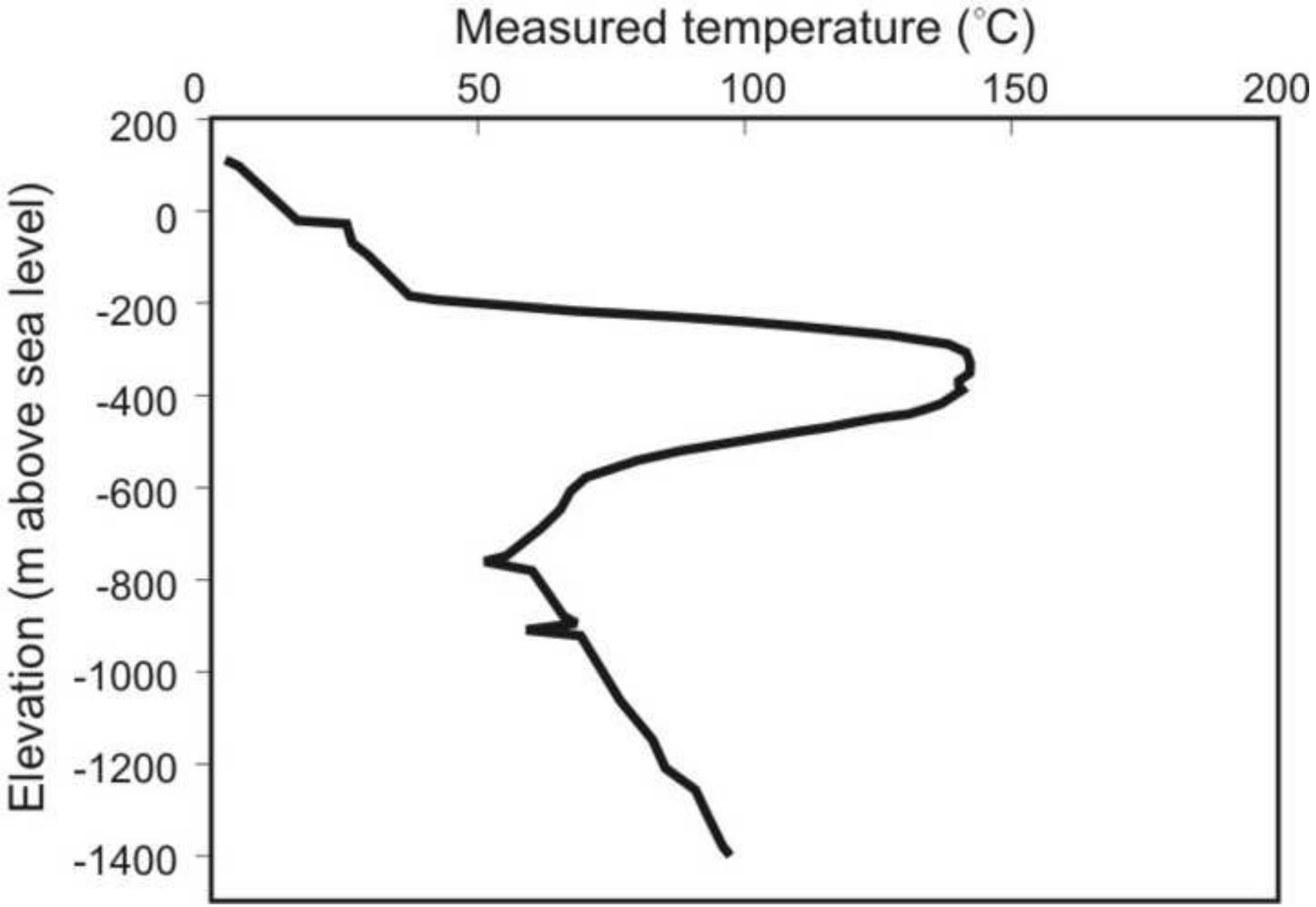

Figure 19

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