Journal of Hydrology 511 (2014) 295–309

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# Occurrence of old groundwater in a volcanic island on a continental shelf; an example from Nakano-shima Island, Oki-Dozen, Japan

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ARTICLE INFO

*Article history:*
Received 6 April 2013
Received in revised form 18 January 2014
Accepted 22 January 2014
Available online 31 January 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Michel Bakalowicz, Associate Editor

*Keywords:*
Groundwater system in an island
Island on the continental shelf
Groundwater age
Coastal aquifer
Sea-level change

SUMMARY

Groundwater residence times in Nakano-shima Island, Oki-Dozen, Japan, which is situated on the continental shelf, are discussed based on groundwater-age indices (CFCs, $^{3}H$, and $^{14}C$), stable isotopic ratios of hydrogen (δD), oxygen ($\delta^{18}O$), carbon ($\delta^{13}C$), and noble gases ($^{3}He/^{4}He$ and $^{4}He/^{20}Ne$). Samples were taken from springs, shallow wells (up to 5 m deep), water-supply wells (about 10–100 m deep), and the hot spring well (866 m deep). δD and $\delta^{18}O$ of all the samples plot along meteoric water lines, indicating a meteoric water-origin. Isotope values of the hot spring water were slightly lower than other samples. Most samples from springs, shallow wells, and the water-supply wells contained higher CFCs and $^{3}H$ while samples from two water-supply wells (W4 and W7) and the hot spring well showed much lower CFCs concentrations. This result indicates that mixing ratios of old groundwater that is free of CFCs and $^{3}H$ were higher for these samples. $^{14}C$ concentrations of samples with lower CFCs were measured, and corrected for addition of $^{14}C$-free dissolved inorganic carbon. The corrected $^{14}C$ concentration of the hot spring water was lower than that of the water-supply well, indicating mixing of much older groundwater in the hot spring water. Because of lower corrected $^{14}C$ concentration and lower δD and $\delta^{18}O$ values, groundwater from the hot spring well is considered to be recharged in a colder climate than present day. Because the island is situated on the continental shelf, the seafloor around the island was most likely widely exposed during the last glacial period. One possible explanation for the existence of groundwater showing lower δD, $\delta^{18}O$, and $^{14}C$ concentrations, such as the hot spring water, is that fresh groundwater, recharged when sea level was lower, still remains after transgression without being replaced by salt water.



## 1. Introduction

Groundwater residence times on islands can be short because of the limited recharge area and limited areal extent of aquifers (Falkland, 1991) and have often been discussed based on age-tracers such as chlorofluorocarbons (CFCs), tritium ($^{3}H$), and sulfur hexafluoride ($SF_6$) used for groundwater recharged after the 1950s (Koh et al., 2005; Heilweil et al., 2009; Gourcy et al., 2009; Stuart et al., 2010). Groundwater recharged during the last glacial period is revealed to remain in coastal aquifers and sub-seafloor formations (Hathaway et al., 1979; Groen et al., 2000; Edmunds, 2001), and it has been interpreted that the deposition of low-permeability clayey formations during transgression after the Last Glacial Maximum (LGM) has delayed the intrusion of salt water into sub-seafloor formations (Groen et al., 2000; Tokunaga et al., 2011). Thus, the effects of long-term climate change, hydrogeological architecture, and the sea-floor topography should be taken into account to better understand the groundwater flow system in coastal areas. The same can be said for the groundwater flow system in volcanic islands, especially for those located on continental shelves because the seafloor from the mainland to such islands was most likely exposed above sea level during the last glacial period, and hence, the existence of old but fresh groundwater recharged during the last glacial period would be expected.

While the hydrogeological structures of volcanic islands exhibit a wide ranges of characteristics depending on local circumstances, such as type of eruption, variation of volcanic rocks, presence of

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http://dx.doi.org/10.1016/j.jhydrol.2014.01.048
0022-1694/

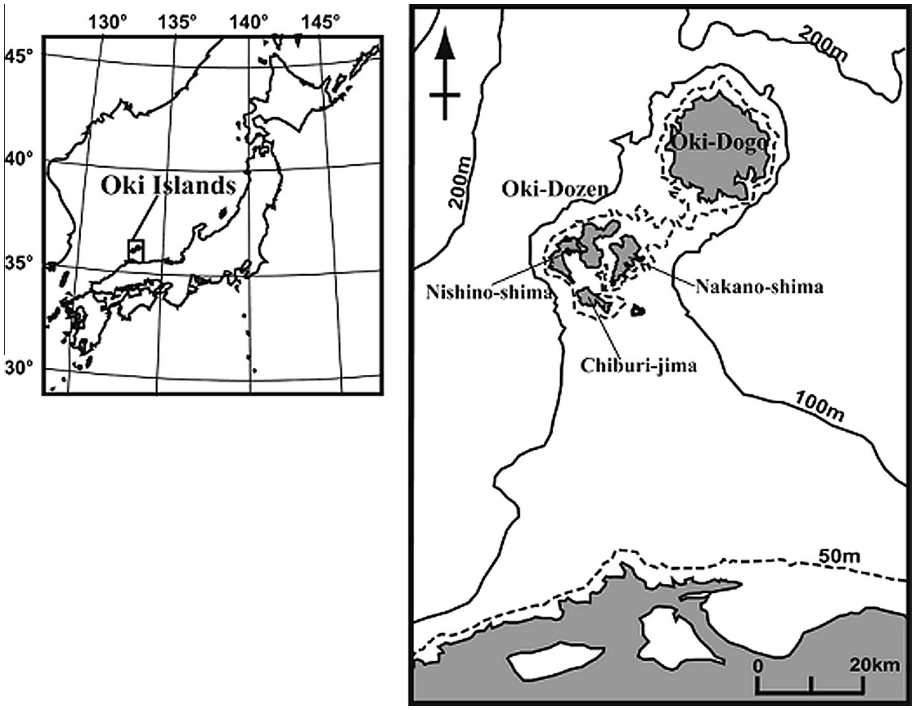


**Fig. 1.** Location of Nakano-shima Island. Depth contours of the sea floor are shown in the on the right.

dikes and intrusive bodies, and degree of weathering (e.g. Peterson, 1993; Custodio, 2004; Herrera and Custodio, 2008; Koh et al., 2012), a commonly recognized hydrogeological feature is a freshwater lens formed on salt water (Peterson, 1972, 1993). The distribution of fresh/salt water and hydrogeological processes including the effect of long-term sea-level change and seafloor topography have not been the focus of previous studies. Nakano-shima Island, Oki-Dozen, Japan, is about 50 km north of mainland Japan, and is situated on the continental shelf (Fig. 1). The land area of this volcanic island is about 33.5 $km^2$ and the highest elevation is 246 m. The island's river-water system is poorly developed, and hence, the water supply is totally dependent on groundwater. Shallow hand-dug wells were originally used for water supply, then, deeper water-supply wells were developed through the 1990s to provide a stable and safe water supply. Furthermore, the hot spring well (screen interval is 580–866 m deep) was constructed in the early 1990s. The chloride concentration of water from the hot spring well is lower than 350 mg/L, which is much lower than that of sea water. For achieving appropriate groundwater management, a good understanding of the groundwater system in the island is very important. In this study, residence times, water chemistry, and isotopic composition of groundwater in the island are analyzed and the possible effect of long-term climate change on the groundwater system is discussed.

## 2. Geological outline of the study area

The Oki Islands consist of the Oki-Dozen Islands and Oki-Dogo Island (Fig. 1). The Oki-Dozen Islands were formed by volcanic activities which occurred about 6 Ma. After the caldera-forming activity, a part of the somma, i.e., the rim of the old volcanic caldera, and a central cone became three main islands (Tiba et al., 2000). The Nakano-shima Island is a part of the east somma. Most of the island is covered by trachybasalt to trachyandesite lava about 300–400 m thick and penetrated by many dikes (Tiba et al., 2000) (Fig. 2). In the northern part of the island, the trachybasalt to trachyandesite lava is partly covered by alkali olivine basalt that erupted about 2.8 Ma (Kaneko and Tiba, 1998). The geological column from the hot spring well reveals that volcanic rocks overlie Miocene sedimentary rocks (Tiba et al., 2000). The sedimentary rock sequence consists of the Mita, the Ichibu, and the Ama formations in ascending order (Fig. 3). The Mita formation was deposited in a coastal plain and shallow marine environment (Tiba, 1975; Naemura and Shimada, 1984) and contains sandstone, mudstone, and tuff (Tiba et al., 2000). The Ichibu formation was deposited in a marine environment (Tiba, 1975; Naemura and Shimada, 1984) and contains mainly breccia tuff, mudstone, and sandstone (Tiba et al., 2000). The Ama formation consists of sandstone that was deposited in a shallow marine environment. Groundwater in the lava is considered to flow mainly through fractures (Tsukimori, 1984).

## 3. Methods

### 3.1. Sampling procedure

Groundwater samples were collected from springs, shallow wells, water-supply wells, and a hot spring well in June 2009, September 2010, and September 2011. Shallow wells are manually dug wells down to about 5 m deep while water-supply wells and the hot spring well are borehole wells. Sampling locations are shown in Fig. 2. Screens of water-supply wells are in volcanic rocks, while that of the hot spring well is in sedimentary formations (Fig. 3). Temperature, pH, electric conductivity (EC), and concentration of dissolved oxygen (DO) were measured at the sampling sites, and then water samples were collected. A peristaltic pump was used for sampling from springs and shallow wells, while attached submerged pumps and an attached air-lift pump were used for sampling from water-supply wells and the hot spring well, respectively, on June 2009 and September 2010. A Bennet pump was used