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Chloroﬂuorocarbon apparent ages of groundwaters from west Hawaii, USA

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SUMMARY

The volcanic coastal aquifers of west Hawaii supply drinking water to the area's residents and nutrient-rich groundwater discharge to the nearby oligotrophic coastal waters. Despite the societal and ecological importance of the water in these aquifers, very little is known about the ages and recharge areas of the groundwater. We therefore determined aquifer recharge areas and groundwater residence times by sampling 18 locations for the oxygen and hydrogen isotopic composition of groundwater and chlorofluorocarbon (CFC) apparent groundwater ages. We sampled water supply wells, coastal wells, and coastal ponds. We applied a $\delta^{18}O$/altitude gradient and well-established lapse rates to find that groundwater recharge predominantly occurs in the area's maximum rainfall zone. Furthermore, the isotopic data suggest that fog drip contributes to aquifer recharge. A single-water source model yielded recharge years ranging from the mid-1960s to mid-1980s for ten samples (56% of samples). Alternatively, a simple binary mixing model, with one water source recharging before1940 and the other after 1940, indicated that 14 samples (78% of samples) contained young water that recharged the aquifer between the mid-1970s and mid-1980s. We also find that CFCs can be used to distinguish between water originating from different aquifers in the area.

1. Introduction

Large volcanic islands located in humid tropical regions have unique characteristics that promote groundwater recharge and flow. These islands typically have high elevations and receive large volumes of rainfall annually. Their basaltic aquifer materials are often fractured, contributing to high permeability. Furthermore, younger islands typically exhibit immature landscapes with poorly developed drainage systems, making infiltration rates extremely high. Combined, these factors make the potential for high volumes of groundwater flow possible and likely. People living in such settings therefore depend either on rain catchment systems or groundwater for their water supply. Hawaii island is one location where these characteristics are exemplified, making groundwater one of Hawaii's most important natural resources (Oki et al., 1999a).

Despite the prolific groundwater resources on the island of Hawaii, little is known about aquifer geometries, aquifer recharge areas, groundwater residence times, and groundwater flow paths in the region. This study is therefore primarily aimed at answering two hydrologic questions: (1) Where are the recharge areas for west Hawaii fractured basalt aquifers? and (2) What are the residence times for water in these aquifers? To address these questions, we present an integrated approach that uses oxygen and hydrogen isotopes of water, $\delta^{18}O$/altitude gradients, and lapse rates to determine that groundwater mainly recharges from a zone of maximum precipitation on west Hawaii. We demonstrate below how apparent groundwater ages from CFCs can be established for the area's fairly pristine aquifers and that these groundwaters are relatively young. We further show that CFCs can distinguish groundwater in the basal aquifer from groundwater in high-level aquifers, which may help constrain the extent of high-level aquifers.

Oxygen and hydrogen isotopes are proven tracers for establishing recharge areas in locations with rapid elevation changes like the Hawaiian Islands. The progressive removal of heavier water isotopes in orographic precipitation is known as the altitude effect. This effect causes the stable oxygen and hydrogen isotopic compositions of precipitation to become relatively depleted in ^{18}O and ^{2}H with increasing elevations in a predictable and measurable manner (Ingraham, 1998). Recharge altitudes and approximate recharge

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areas of groundwater samples can therefore be established from $\delta^{18}O$/altitude gradients in such settings (Scholl et al., 1996).

Anthropogenic activities related to industrial, commercial, and household applications prompted manufacture and release of CFCs into the atmosphere beginning in the 1930s (CFC-11 and CFC-12) and 1940s (CFC-113; Plummer and Busenberg, 2000, 2006a; Happell et al., 2006). CFCs were banned in the United States in 1995 (Cook et al., 2003) to curtail their deleterious effects on Earth's ozone layer. CFCs are generally stable under oxic conditions and are water soluble, so they have been imbibed into Earth's hydrologic cycle through precipitation, infiltration, and groundwater recharge. CFC incorporation into the hydrologic cycle has closely followed CFC production and release, making CFCs excellent tracers and age determination tools for water younger than ~60 years (Plummer and Busenberg, 2000). CFC data have provided important information about residence times and groundwater flow paths at numerous research sites (e.g. Happell et al., 2006; Plummer et al., 2000; Darling et al., 2010) and have been used more recently by Koh et al. (2012) and Ako et al. (2013) in volcanic settings.

The data in this study will provide an important base-line from which to evaluate how changing climatological patterns, land-use practices, urbanization, and groundwater withdrawal rates impact the quantity and quality of west Hawaii groundwater. Our study also enhances the current understanding of fractured basalt rock aquifers, particularly in coastal settings.

2. Materials and methods

2.1. Subsurface geology and groundwater occurrence of West Hawaii

Hawaii Island is composed of numerous lava flows with variable thicknesses and compositions. Permeability is heterogeneous, but high overall (Stearns and MacDonald, 1946). Aa lava clinker zones, voids between lava flow contacts, cooling joints normal to flow surfaces, and lava tubes contribute to the aquifer's high permeability (Stearns and MacDonald, 1946). Fractures in the rocks and the aforementioned characteristics facilitate rapid groundwater transport through the area's unsaturated zones and aquifers (Oki et al., 1999b).

All Hawaiian volcanoes contain low permeability and low hydraulic conductivity dike complexes, which are typically associated with rift zones (Takasaki and Mink, 1985). The northwest rift zone of Hualalai Volcano bisects the study area (Fig. 1). The rift zone consists of a 1.9–4.0 km wide and 21.1 km long subaerial portion as well as a submarine portion (not shown; Oki, 1999; Flinders et al., 2013). Oki (1999) considered the rift zone a groundwater divide and no-flow boundary. We also adopt this interpretation. Dikes are thought to be most abundant within central rift zones and are hydrologically important because they may extend vertically and laterally for thousands of meters (Oki et al., 1999b). Aquifers at higher elevations and in general association with the rift zone are locally referred to as high-level aquifers (Fig. 2). Groundwater in high-level aquifers may flow parallel to rift zones, leak from rift zones into the basal lens (Scholl et al., 1996), and/or become compartmentalized by the more permeable intruded rocks, creating isolated and slightly leaky groundwater reservoirs (Scholl et al., 1996; Oki et al., 1999b). The exact geological mechanism that impounds water in these high-level aquifers is not understood (e.g. Oki et al., 1999b; Tillman et al., 2014b). Regardless of the mechanism, high-level aquifers typically have water levels >12 m above mean sea level (MSL) (Oki et al., 1999b).

Fresh groundwater near dike-free coastal areas exists in a freshwater lens which floats on denser saltwater according to Ghyben-Herzberg principles. In this aquifer, seawater mixes with

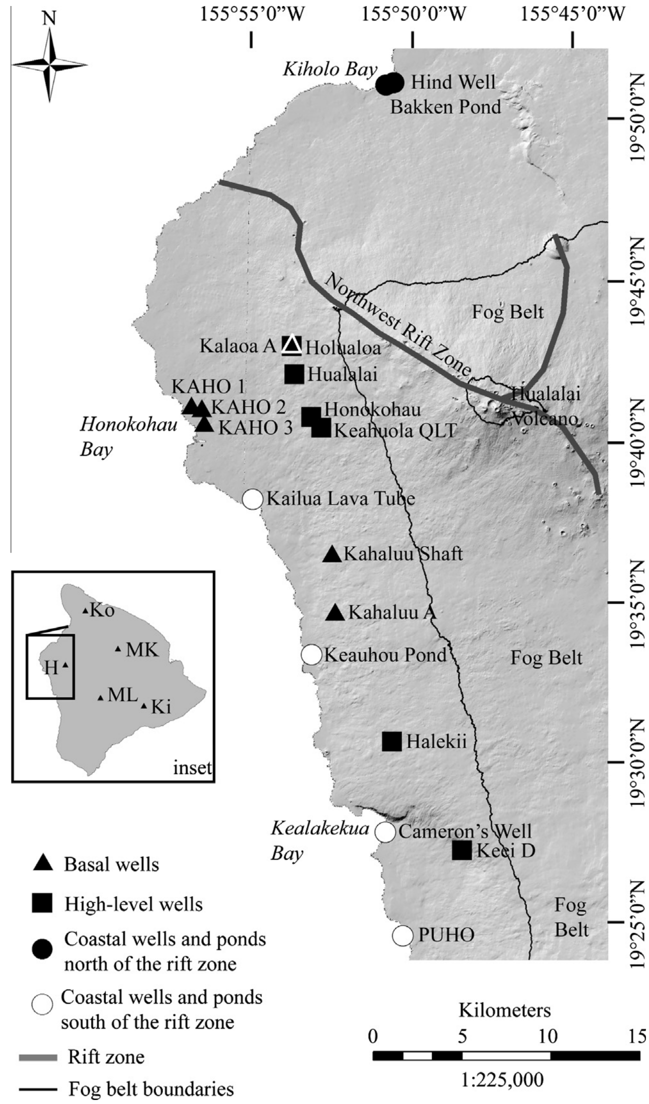

Fig. 1. Map of sample locations. Areas east of the lower fog belt boundary (975 m) lie within the fog belt. Hualalai's summit (2521 m) is above the upper fog belt boundary (2255 m). Kalaoa A is a basal well sample located within undistinguishable proximity, at the scale of this figure, to Holualoa Well and is outlined in white. Locations of the five mountains of Hawaii Island are shown in the inset map: Ko = Kohala, MK = Mauna Kea, H = Hualalai, ML = Mauna Loa, and Ki = Kilauea.

the freshwater, forming a transitional area within the aquifer that is composed of brackish water. Regardless of composition, water in this aquifer is locally called basal water (Fig. 2). This aquifer generally has water levels <3 m above MSL (Oki et al., 1999b). At the shoreline, this water leaves the aquifer as fresh to saline groundwater discharge depending on the discharge location.

2.2. Climate of West Hawaii

Coastal areas of west Hawaii experience little variation in seasonal air temperature (mean annual temperature = 23.7 °C). Near the coast, high temperatures vary between 26 and 29 °C and low temperatures approach 21 °C (Nullet and Sanderson, 1993). The tallest topographic feature in the immediate area is Hualalai Volcano (2521 m). Hualalai's summit has a mean annual air temperature of 10.6 °C.

In west Hawaii, east-flowing sea breezes converge daily with approximately west-flowing northeast trade winds. The trade winds pass between Mauna Kea and Mauna Loa (Fig. 1 inset), or