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PRELIMINARY RESULTS FROM AN ISOTOPE HYDROLOGY STUDY OF THE KILAUEA VOLCANO AREA, HAWAII

M.A. Scholl[1], C.J. Janik[1], S.E. Ingebritsen[1], J.P. Kauahikaua[2] and F.A. Trusdell[2]

[1]U.S. Geological Survey, Menlo Park, CA
[2]U.S. Geological Survey, Hawaiian Volcano Observatory, HI

ABSTRACT

Deuterium (D) content of groundwater and precipitation, and tritium content of selected groundwater samples are used to infer flowpaths for groundwater in the Kilauea volcano area. The spatial distribution of calculated recharge elevations and residence times for groundwater samples tends to support the idea that Kilauea's rift zones comprise leaky boundaries within the regional groundwater flow system, partly isolating the groundwater in the area bounded by the rift zones and the Pacific Ocean. The southwest rift zone also appears to act as a conduit for groundwater recharged at relatively high elevation. The relation between precipitation δD values and elevation differs between areas receiving frequent rainfall and areas where most rainfall occurs during storm events.

INTRODUCTION

This paper reports preliminary results from an ongoing isotope hydrology study of the Kilauea volcano area. One of the objectives of the study was to determine the role of Kilauea's rift zones in the regional hydrology, using stable isotopes and tritium as tracers for the groundwater flow system. The study was designed to identify probable recharge areas and residence times for groundwater discharging from Kilauea's rift zones, as well as ground water in the area bounded by the rift zones and the Pacific Ocean (Fig. 1).

The rift zones contain low-permeability, high-angle dikes that have intruded high-permeability, sub-horizontal basalt flows. Other workers have suggested that the rift zones of Kilauea divert much of the groundwater flowing downslope beneath adjacent parts of Mauna Loa volcano (Takasaki, 1993), or less specifically, that rift zones are barriers to groundwater flow (Davis and Yamanaga, 1973; Druecker and Fan, 1976; McMurtry et al., 1977). In this paper, we present general interpretations based on the isotopic composition of groups of groundwater samples, and consider whether Kilauea's rift zones and summit area appear to be (1) barriers or partial barriers to regional groundwater flow and (or) (2) conduits for high-level, dike-confined groundwater.

Previous studies provide groundwater stable isotope data from about 30 sites in the study area (McMurtry et al., 1977; Tilling and Jones, 1991), tritium data from 7 wells and a spring in the area of the lower east rift zone (ERZ) (Kroopnick et al., 1978), and sparse data on the isotopic composition of rainfall (Friedman and Woodcock, 1957, Tilling and Jones, 1991; Goff et al., 1991). Our ongoing study involves yearly collection of groundwater samples at 42 sites and 6-month-interval precipitation samples at 64 sites.

The hydrologic boundaries of the area that includes Kilauea volcano are defined by the rift zones and summit of Mauna Loa. The northern boundary of our study area, however, extends from Mauna Loa summit north of the rift zone to Hilo (Fig. 1). Kilauea's rift zones and summit area as shown in our figures were delineated on the basis of positive gravity anomalies (Kauahikaua, 1993). The gravity high is assumed to be related to the presence of dikes, and it extends somewhat to the north of the surface expression of the rift zones, and to the south of the summit area.

Groundwater hydrology

The groundwater hydrology of an oceanic island with uniform permeability would be expected to conform to the Ghyben-Herzberg model of a freshwater lens floating on the surrounding seawater. The presence of low-permeability dikes concentrated in the rift zones of Hawaii's volcanoes alters this simple model (Stearns and Clark, 1930; Stearns and Macdonald, 1946; many others). The presence of heat in an active volcanic rift zone may also have an effect on groundwater flow patterns.

In most Hawaiian volcanic rift zones, dikes impound groundwater to higher levels than the surrounding basal water table (Stearns and Macdonald, 1946; Takasaki, 1978). There is geophysical evidence for impounded groundwater in the rift zones and summit area of Kilauea (Jackson and Kauahikaua, 1987, 1990), supported by a water level measurement in the NSF drill hole near Kilauea summit. The geo-electric features were interpreted as a high-level water table underlying the summit area and extending south to the Koa'e fault system and down both the ERZ and the

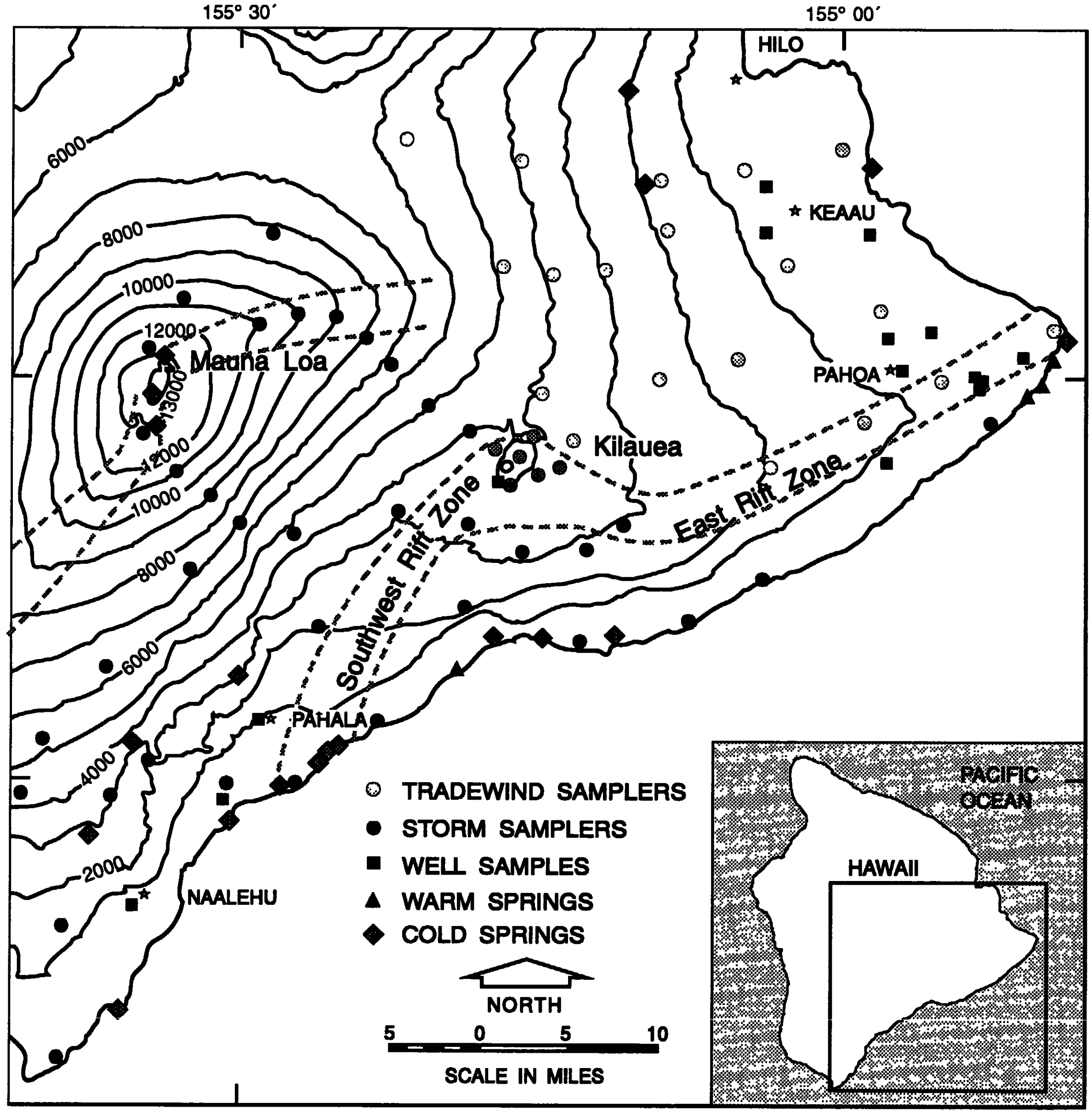

Figure 1: Map of the study area, showing sample sites. Light circles are "tradewind" precipitation collector sites and dark circles are "storm" precipitation collector sites. Dashed lines are approximate rift-zone boundaries. Warm springs are defined as those ≥30°C.

southwest rift zone (SWRZ). In Figure 1, the Koa'e fault system is coincident with the dashed boundary immediately south of Kilauea summit.

Samples of the basal groundwater can be obtained from coastal springs and wells at low elevations (<1000 feet). At higher elevations, the basal water table is far below the land surface and not tapped by wells. Shallow wells and springs at higher elevation are assumed to discharge perched water (Takasaki, 1978, 1993).

Rainfall and groundwater recharge

The rainfall in the study area is highly variable, ranging from a mean of 250 inches per year west of Hilo to less than 20 inches per year near Mauna Loa summit and at Ka Lae (Fig. 2). Several climatic factors affect rainfall in the study area. Moisture-laden tradewinds from the east-northeast undergo orographic lifting on the slopes of Mauna Loa, resulting in frequent rainfall in part of the study area southwest of Hilo. There is also a NE-SW trending zone of

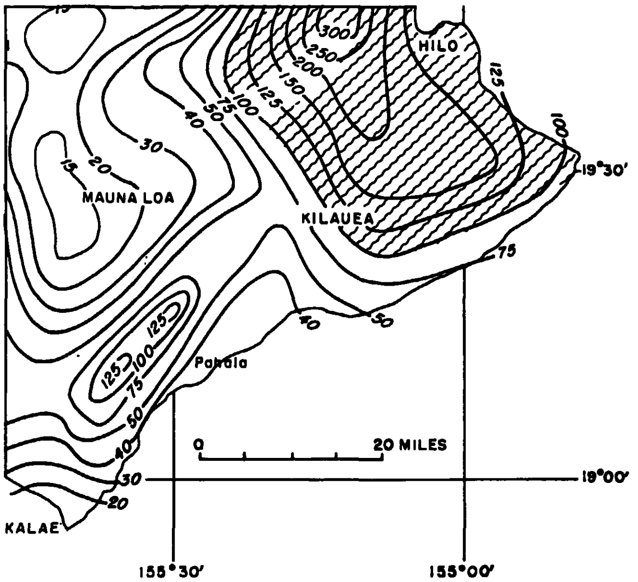

Figure 2: Isohyetal map of the study area, showing mean annual rainfall in inches per year, adapted from Davis and Yamanaga, 1973. Crosshatched area is the "tradewind" rainfall area, as defined in this report.

relatively high rainfall northwest of Pahala (Fig. 2), thought to be caused by prevailing upslope tradewinds augmented by a sea/land air circulation pattern (State of Hawaii Report R34, 1970). The remainder of the study area gets most of its rainfall from large storm systems moving across the island. Groundwater recharge in the study area scales nonlinearly with total rainfall, because evapotranspiration rates vary with the distribution of vegetation (Takasaki, 1993).

METHODS

The rain deuterium data used in this report are 6-month cumulative values from the collection periods September 1991-February 1992 and February 1992-September 1992. At most groundwater sites, samples were collected twice, in September 1991 and September 1992. All sample locations are shown in Figure 1.

Rain collectors used in the study were 3½- or 5-gallon high-density polyethylene (HDPE) buckets with o-ring sealed lids. Funnels of 2-inch, 3-inch or 5½-inch diameter, depending on the rainfall in the area, were set in the lids. The collectors were designed to minimize sample evaporation. Three collector designs have been used: (1) with silicon oil that floats in a layer over the sample, (2) with a polypropylene bag inside the bucket, and (3) with a floating ball in the funnel to cover the opening during dry periods. Design (1) was used for the first sample period; (2) and (3) for the second period, for forested and open-sky sites, respectively.

Samples from coastal springs were taken as close to low tide as possible, to minimize seawater content. Well samples were taken from pumped wells, with the exception of three which were collected with a thief sampler. Wells that are not continuously pumped for water supply were pumped for 15 minutes before sampling.

Estimates of recharge elevation for groundwater samples

Tradewind showers are a near-daily occurrence in the NE part of the study area. We assume that the rain collectors in that area ("tradewind" sites in Fig. 1) contained rain from these frequent showers, together with rain from storm events. Most rain in the remainder of the study area falls during storm events. The Pahala high-rainfall area is a possible exception, but we have not collected enough precipitation data there to draw conclusions.

We previously cited a gradient for precipitation δD values of 17‰ per 1000 m elevation (5‰ per 1000 feet) for the entire study area based on 6 months of data (Scholl et al., 1992). With one year of data, that average gradient

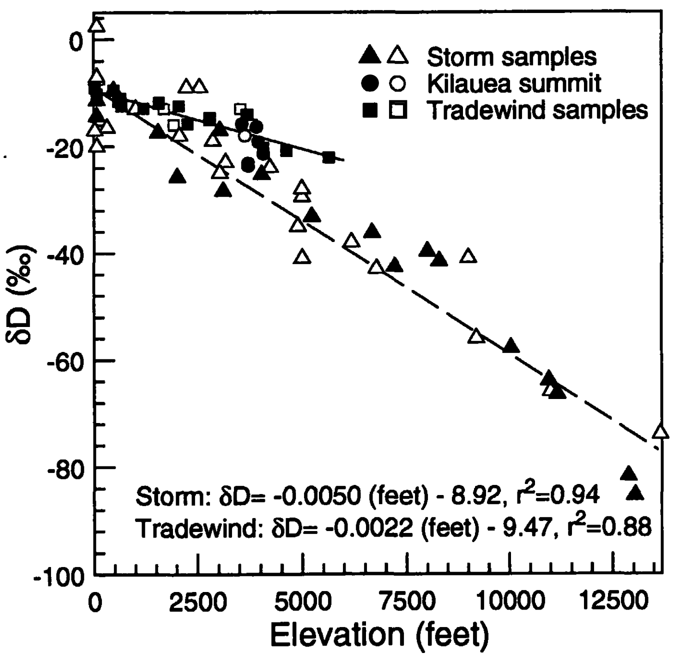

Figure 3: Relation between precipitation δD and elevation. The regressions were calculated using only volume-weighted average δD values from sites for which a complete year of data was available (solid symbols). Data for sites with only one 6-month sample are plotted for comparison (open symbols). Kilauea summit is on the edge of the area that receives tradewind precipitation; these sites were not used in either regression.

remains the same, but the "tradewind" and "storm" areas appear to be characterized by two different δD/elevation relations (Fig. 3). Least-squares regression lines fit to the volume-weighted data from one year's precipitation (September, 1991-September, 1992) are used to calculate recharge elevations for groundwater in wells and coastal springs.

For the purposes of the recharge elevation estimates, the δD values for brackish springs were corrected for seawater content, using the chloride content. Springs contained 2-44% seawater; most had <15%. The seawater correction assumed a seawater composition of 18,900 mg/L chloride and -0.4‰ δD (F. Goff, Los Alamos National Lab., oral comm., 1992), and a groundwater chloride content of 5 mg/L (the average from our non-brackish samples). This correction may not be entirely appropriate for the warm springs (defined as ≥30°C); however, the Br/Cl and B/Cl ratios for those waters were both similar to seawater. The chloride content of thermal waters in the area is highly variable, and we have not yet identified a separate thermal end member in the brackish warm springs.

The average δD value for a groundwater sample is used to calculate a recharge elevation based on either the "tradewind" or the "storm" regression, depending on its probable recharge area. In most cases, the water sampled at a spring or well is likely a mixture of waters recharged at different elevations, so we assume the estimated recharge elevations (Fig. 4) represent a median recharge elevation. The analytical error (1σ) for the δD values is ±1.5‰, which translates to ±700 feet for the "tradewind" recharge elevation estimate, and ±300 feet for the "storm" recharge elevation estimate. More accurate estimates of recharge compositions will require knowledge of year-to-year variability of the isotopic composition of precipitation and groundwater.

Determination of residence times using tritium

Tritium concentrations were measured in groundwater samples from 29 sites; for 12 of those sites, two samples collected one year apart were analyzed. Tritium concentrations for brackish springs were corrected using chloride content and a seawater tritium value of 2.1 tritium units (TU) (F. Goff, Los Alamos National Lab., oral comm., 1992). The correction was significant only for two springs with >20% seawater. Residence times for groundwaters were estimated by comparing tritium concentrations in the samples to the expected concentrations obtained by solving equations for well-mixed reservoir (Eq. 1) and piston-flow (Eq. 2) models (Yurtsever, 1983):

$$C_{out}(t) = \int_0^t C_{in}(t-\tau)\, \frac{1}{\tau_0} e^{(-\frac{t}{\tau_0})}\, e^{(-\lambda t)}\, d\tau \qquad (1)$$

and

$$C_{out}(t) = C_{in}(t-\tau) e^{(-\lambda t)} \qquad (2)$$

where tritium concentration in the spring or well water (C_{out}) depends on the input concentration (C_{in}), the residence time, (τ), and the year in which the sample was taken (t); λ is the decay constant for tritium. The well-mixed model for a steady-state system (Eq. 1) assumes an instantaneously mixed reservoir, and the piston-flow model (Eq. 2) assumes that groundwater recharge traverses the flowpath without mixing with subsequent inputs.

Tritium input to the groundwater system since 1952 was estimated using yearly weighted-average International Atomic Energy Agency (IAEA) precipitation data for Hilo (1962-1969), Midway Island (1962-1984), Ottawa (1952-1961), and a 1991 precipitation value for the Kilauea area (Goff et al., 1991). Atmospheric tritium rose above background levels (<1 TU) when nuclear bomb tests started in 1952, and reached a peak (~200 TU) about 1963. The concentration in the atmosphere and in the rainfall has declined exponentially (on the average) since that time to values near 2.4 TU (Goff et al., 1991). Thus, for groundwaters recharged less than about 30 years ago, a higher tritium content suggests a longer residence time. Waters with a low tritium content (in our study, <1.8 TU) are assumed to have been recharged more than 35 years ago or to be a mixture of older water and recent recharge.

Two residence times (Fig. 5) were obtained for each sample from the end-member models described above. For 11 of the 12 sample sites analyzed twice, similar residence times were obtained for both years' tritium concentration. The groundwaters were divided into three categories according to apparent residence time: recent, with apparent residence time of <10 or <15 years; intermediate, with apparent residence times of 10-18 or 15-20 years; and older, with apparent residence times of >75 to >35 years; the first and second residence-time estimates are from the well-mixed and piston-flow models, respectively. Assigning a residence time to a groundwater sample by this method involves the assumption that there is no mixing of waters from different flowpaths, which is not necessarily the case. Therefore, the observed tritium concentration for a spring or well may indicate a residence time within the range given by the two end-member models, or may result from mixing of waters with different residence times.

RESULTS AND DISCUSSION

Estimated recharge elevations and residence times obtained using the methods summarized above can be used to make some preliminary inferences about the influence of Kilauea's rift zones and summit area on groundwater flow.

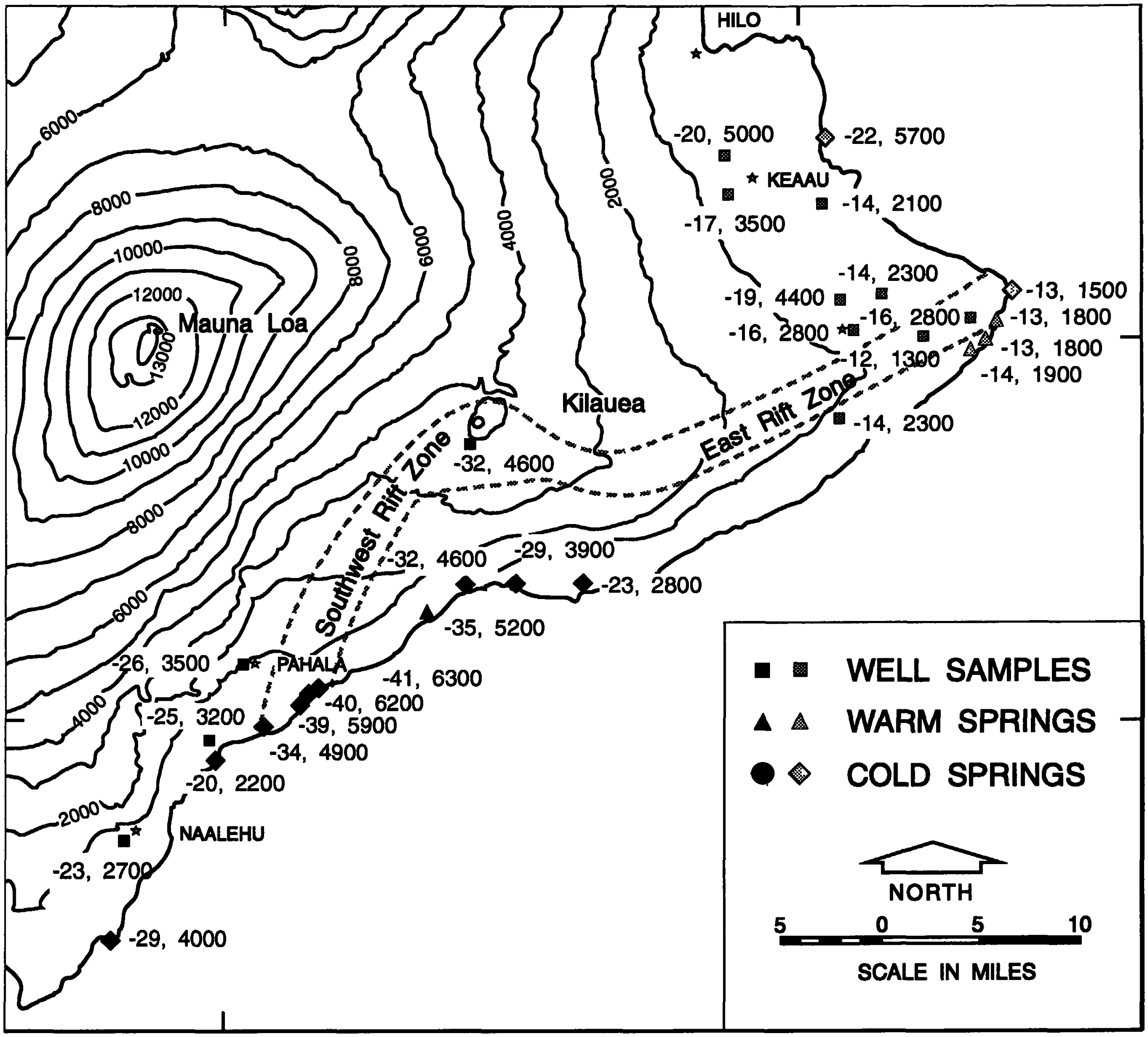

Figure 4: Groundwater sample sites with average δD value from 1991 and 1992 samples and calculated recharge elevation. Coastal springs were adjusted for seawater content and average δD value rounded to nearest whole number (first number); estimated recharge elevation was rounded to the nearest hundred feet (second number). Dark and light symbols represent recharge elevations calculated on the basis of storm and tradewind regressions, respectively. Data are shown only for springs and wells discharging basal or dike-impounded groundwater. Analytical error (1σ) for the δD values is 1.5‰.

Southwest rift zone and area between rift zones

In the southwest part of the study area, a large contrast in calculated recharge elevations can be seen between the springs in the area where the SWRZ intersects the coast (4900-6300 feet) and the springs and wells to the west of the rift zone (2200-4000 feet). The isotopic composition of the coastal springs within the SWRZ suggests recharge from elevations well above the Kilauea summit area and SWRZ, and indicates little mixing with waters discharging to the west.

The four springs along the coast south of Kilauea summit have calculated recharge elevations decreasing from west to east (5200 to 2800 feet). The westernmost spring (δD = -35‰) is warm (38-43°C), which suggests that it issues from the SWRZ. The recharge elevations of the two central springs (δD = -32‰ and -29‰) could represent a mixture of water from the SWRZ and local recharge, or they could be related to the impounded water in the summit area, represented by the NSF drill hole near Kilauea summit (δD = -32‰). Water from the spring farthest east appears to originate around 2800 feet, which can be interpreted in terms of recharge within the rift zone. It is unclear which regression is more appropriate for this location, so the more conservative "storm" regression was used.

The sample from the NSF drill hole is the sole representative of groundwater in the summit area, and its deuterium composition (δD = -32‰) is more depleted than the nearby Kilauea summit precipitation samples (average weighted-mean δD = -22‰). This suggests that at least part of the water sampled in the well originates at an elevation higher than the summit area.

East rift zone

Calculated recharge elevations for the springs and wells north of the ERZ range from 2100 to 5700 feet. The recharge elevations for springs and wells south of and within the rift zone are generally lower, ranging from 1300 to 2800 feet. We did not obtain groundwater samples in much of the area south of the ERZ; recent lava flows have destroyed some existing springs and wells and other historic wells were dry. The wells in the lower ERZ area for which we calculated recharge elevations are shallow wells with low chloride content and relatively low temperatures (≤47°C). The coastal springs and wells south of and within the rift zone, as a group, have some of the highest average δD values in the study area (-12 to -16‰). Mean annual rainfall along the ERZ below 3000 feet is fairly uniform, between 100 to 125 inches per year (Fig. 2), and the isotopic composition of precipitation also seems to be fairly uniform. Our rain collectors along the rift zone gave weighted-average δD values of -9‰ at 30 feet, -13‰ at 1210 feet, and -12‰ at 2060 feet.

The ERZ is in the "tradewind" area, and δD/elevation gradients for the "tradewind" and "storm" areas are 2‰ per 1000 feet and 5‰ per 1000 feet, respectively; thus contrasts in the deuterium composition of groundwater in the ERZ area would be expected to be smaller than in the SWRZ area. Use of the recharge-elevation approach to trace groundwater in the area may require more sample sites or more frequent sampling. The recharge elevations calculated from these samples do not clearly delineate different bodies of groundwater to the north, south and within the ERZ, but as a group, the waters within and south of the rift zone show lower recharge elevations.

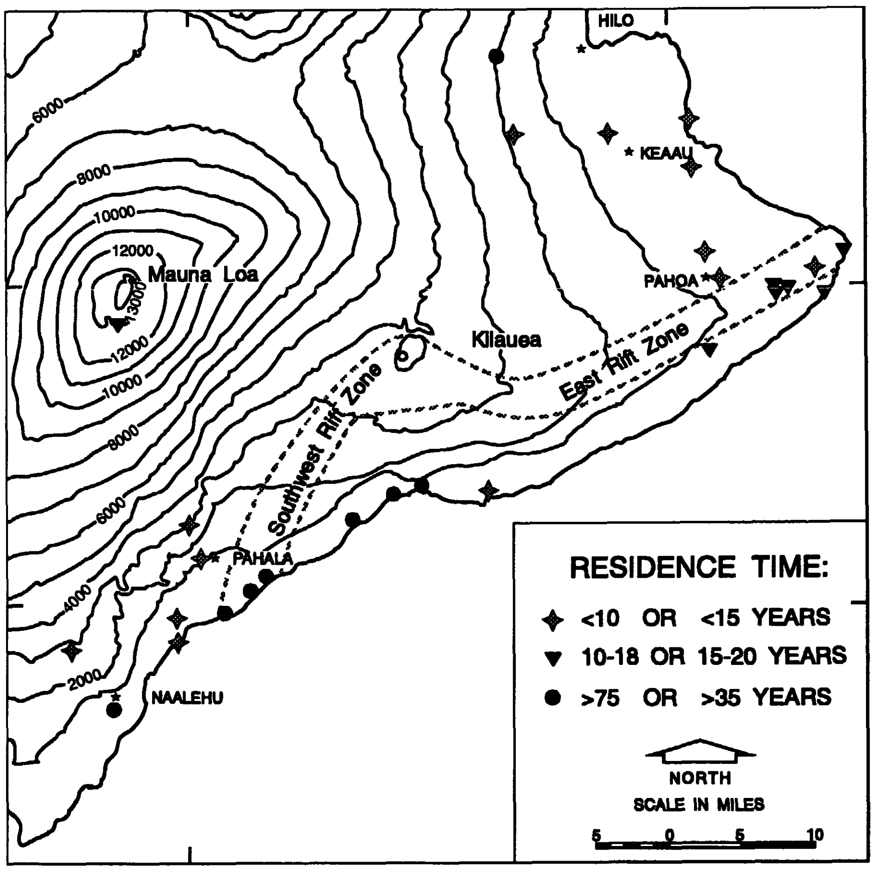

Figure 5: Residence times estimated from tritium content. Stars represent the recently recharged waters, triangles represent intermediate-age waters, and circles represent the older waters. The two age ranges given in the legend are from the well-mixed and piston-flow end-member models, respectively. The analytical error for the tritium measurements was ≤0.4 TU for the 1991 samples and ≤0.25 TU for the 1992 samples.

Residence times

Residence time depends on flowpath length and fluid velocity. For our study area, factors affecting residence time include the distance between the spring or well and the recharge area, the likely recharge rate, and permeability (highly permeable flow basalts or less permeable dike basalts). Most of the springs and wells with the 'youngest' groundwater (tritium concentrations of 2-3.4 TU) are located in or downgradient of the areas with higher rainfall and, by inference, recharge. The shorter residence times indicate that water in these springs and wells flows through the system relatively rapidly.

The samples with the intermediate residence times (tritium concentrations ≥3.5 TU) were mostly from the lower ERZ (Fig. 5). The observation that most of these waters have a slightly longer estimated residence time than waters to the north suggests that some of the rift-zone waters are isolated from the higher-flowrate system to the north.

The 'oldest' groundwaters we sampled (tritium concentrations ≤1.8 TU) were mostly from the SWRZ and south of Kilauea summit. These springs are in a low-rainfall region, and low-permeability dikes occur between the springs and the apparent recharge areas. The easternmost spring in the area south of Kilauea summit is an exception; that water has a much shorter estimated residence time and lower calculated recharge elevation, and appears to have a different, perhaps local, source.

CONCLUSIONS

A major purpose of this study is to assess the influence of Kilauea's rift zones on the hydrology of the southeast portion of the island of Hawaii. Our conclusions based on one year of data are necessarily preliminary, pending additional information on temporal variation in the isotopic composition of groundwater and precipitation. The spring water discharging at the coast end of the SWRZ does not appear to originate from rainfall over the high-elevation part of the rift, but from the higher slopes of Mauna Loa northwest of Kilauea summit. The deuterium and tritium composition of these rift-zone springs contrasts markedly with springs and wells to the west. Three of the four springs sampled in the area south of Kilauea summit have calculated recharge elevations somewhat higher than the summit area, and relatively long residence times. The easternmost spring in that area has water with a lower calculated recharge elevation and a shorter residence time. There is relatively little contrast in groundwater deuterium composition across the lower ERZ, but as a group, springs and wells south of and within the lower ERZ have lower recharge elevations. The residence time for most of the waters within and south of the ERZ appears to be slightly longer than for waters to the north.

The patterns of deuterium and tritium concentrations in groundwater tend to support the idea that the rift zones act as low-permeability, leaky boundaries within the larger groundwater flow system, although they are evidently not complete barriers to flow. There is isotopic evidence that groundwater within and between the rift zones is partly isolated from the regional flow system.

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