

## **Stable isotopic composition of groundwater from Mt. Yatsugatake and Mt. Fuji, Japan**

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**Abstract** Mt. Yatsugatake and Mt. Fuji are dormant volcanoes in central Japan having elevations of 2899 and 3776 m, respectively. For Mt. Yatsugatake, groundwaters on the west slope, which is on the leeward side of the mountain, are more isotopically depleted in  $\delta D$  by about 10‰ than those of comparable elevations on the east slope. A similar situation exists for Mt. Fuji, for which groundwaters on the north slope (leeward side) are more isotopically depleted in  $\delta D$  by >10‰ than those of the other slopes (windward side). Hydrologic analysis indicates that the differences are attributed to different processes for the respective volcanoes. For Mt. Yatsugatake, isotopic difference of groundwater on the leeward and windward slopes is due to evaporation rate, which is lowest on the leeward west slope. For Mt. Fuji, isotopic difference of groundwater on the leeward and windward slopes is due to depleted precipitation on the leeward north slope, caused by a rain-shadowing effect of the mountain.

### **INTRODUCTION**

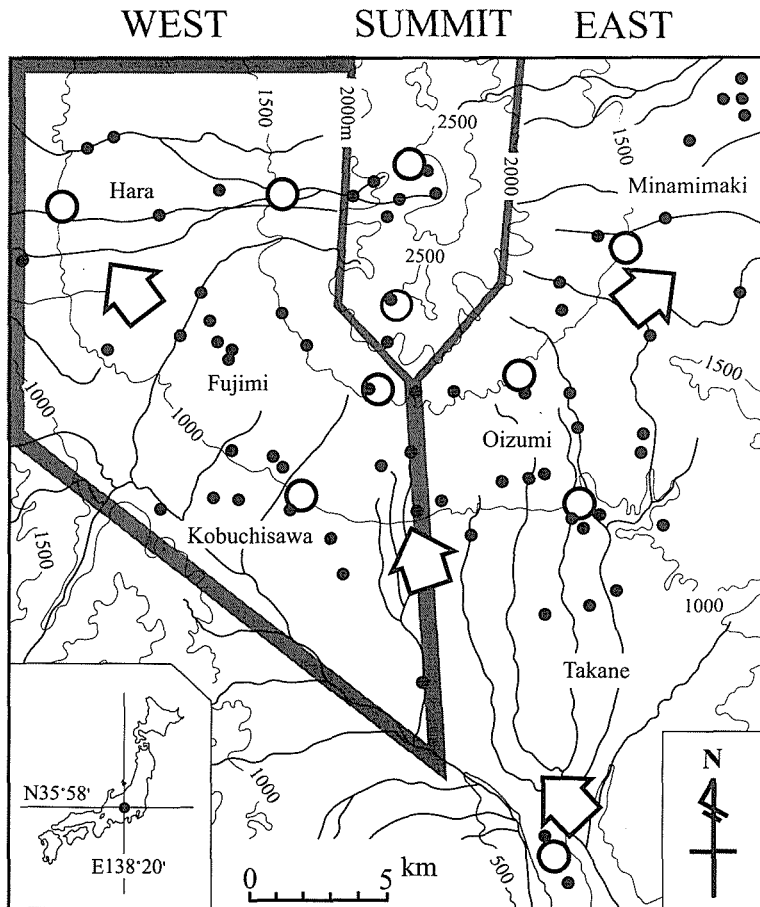
Many studies indicate that the average isotopic composition of precipitation and/or groundwater tends to have more negative values as distance from the ocean coast increases (e.g., Rozanski, 1985). The explanation for this "continental effect" lies in the history of the precipitation air masses.

In contrast, differences in isotopic composition of precipitation and/or groundwater, comparable on a small scale with a continental effect, occurs between slopes for a mountain range (e.g., Friedman & Smith, 1970; Gonfiantini *et al.*, 1976; Siegenthaler & Oeschger, 1980). Our previous studies also pointed out that there is a remarkable difference in isotopic composition of groundwaters between the slopes of Mt. Yatsugatake (Yasuhara *et al.*, 1993) and of Mt. Fuji (Yasuhara *et al.*, 1995). This paper focuses on the processes causing the isotopic differences of groundwaters between the slopes of these two mountains.

### **STUDY AREAS**

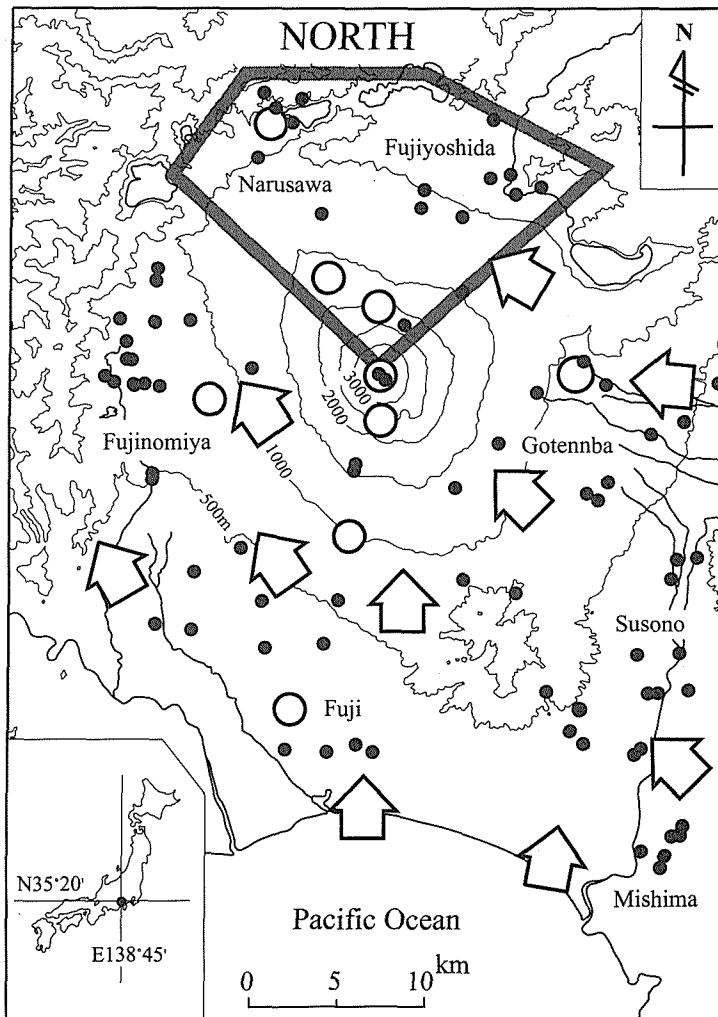
Mt. Yatsugatake and Mt. Fuji are dormant stratovolcanoes in central Japan and are 2899 and 3776 m high, respectively, (Figs. 1 and 2). The volcanoes experience wet summers and dry winters. Summer precipitation occurs between May and October and primarily consists of rains due to the so-called Baiu in June and July and typhoons in September

and October. Winter precipitation, which is less in amount and isotopically more depleted than summer precipitation (Kazahaya & Yasuhara, 1994), generally occurs as snow from December to March. Average annual precipitation of Mt. Yatsugatake is 1317, 1153 and 1453 mm at Hara (1017 m a.m.s.l.), Oizumi (867 m a.m.s.l.) and Minamimaki (1350 m a.m.s.l.), respectively (Japan Meteorological Agency, 1993). Annual precipitation of Mt. Fuji is elevation dependent, but generally ranges from more than 2750 mm on the wettest east slope to 1500 mm on the north slope (Kizawa *et al.*, 1969).



**Fig. 1** Locations of the groundwater (dots) and precipitation (circles) sampling on Mt. Yatsugatake. Also shown are the dominant wind directions (arrows) when intensive groundwater recharge occurs during summer. Mt. Yatsugatake is divided into three physiographic areas: summit above 2000 m a.m.s.l., and the east and west slopes separated by a north-south ridge.

Groundwater recharge to these volcanoes occurs during summer. Kizawa *et al.* (1969) concluded that for Mt. Fuji precipitation greater than or equal to 20 mm d<sup>-1</sup> primarily occurs during May to October, when most of the moisture supply is derived from the Pacific Ocean through southeasterlies and/or southerlies (Fig. 2). As a result, precipitation on the north slope, which is on the leeward side with respect to precipitation air mass trajectories, is less than on the other slopes. After passing Mt. Fuji, the air mass proceeds further inland bringing summer precipitation to Mt. Yatsugatake, the east and west slopes of the mountain being on the windward and leeward sides with respect to the dominant southeasterlies, respectively (Fig. 1).



**Fig. 2** Locations of the groundwater (dots) and precipitation (circles) sampling on Mt. Fuji. Also shown are the dominant wind directions (arrows) when intensive groundwater recharge occurs during summer.

## SAMPLE COLLECTION AND ANALYSIS

Precipitation was collected monthly at 10 sites on Mt. Yatsugatake between May 1992 and April 1993 (Fig. 1) and at nine sites on Mt. Fuji from August 1993 to July 1994 (Fig. 2). For Mt. Yatsugatake, two collectors were on the summit and four collectors were on each of the slopes. For Mt. Fuji, one collector was on the summit, three on the north slope, and five on the other slopes. Precipitation samples were collected by a device that sealed the mouth of the bottle after a precipitation event, protecting the water sample from evaporation and associated isotopic enrichment (for details, see Kazahaya & Yasuhara, 1994). The volume of the collected water was recorded at the time of sample collection.

For Mt. Yatsugatake, 50 groundwater samples were collected from the low-temperature, perennial springs in August 1988 and January 1989, and for Mt. Fuji, 60 samples were collected in August 1993 and July 1994. Groundwater dripping in some caverns (lava caves) and in shallow wells also were collected during the same period. In addition, some isotope analyses by Tsuchi (1992) and Yoshioka *et al.* (1993) were quoted for discussion. These sampled sites are shown in Figs 1 and 2.

Water samples were analyzed for hydrogen isotopic composition. Hydrogen isotopic composition,  $\delta D$ , is expressed as per mille (‰) difference relative to standard mean ocean water (SMOW). Water samples were converted to hydrogen gas by zinc oxidation. Hydrogen gas was then analyzed for hydrogen isotopic content using a Finnigan-matt 251 mass spectrometer. Reproducibility of the  $\delta D$  is <1.5‰.

## RESULTS AND DISCUSSION

### Mt. Yatsugatake study

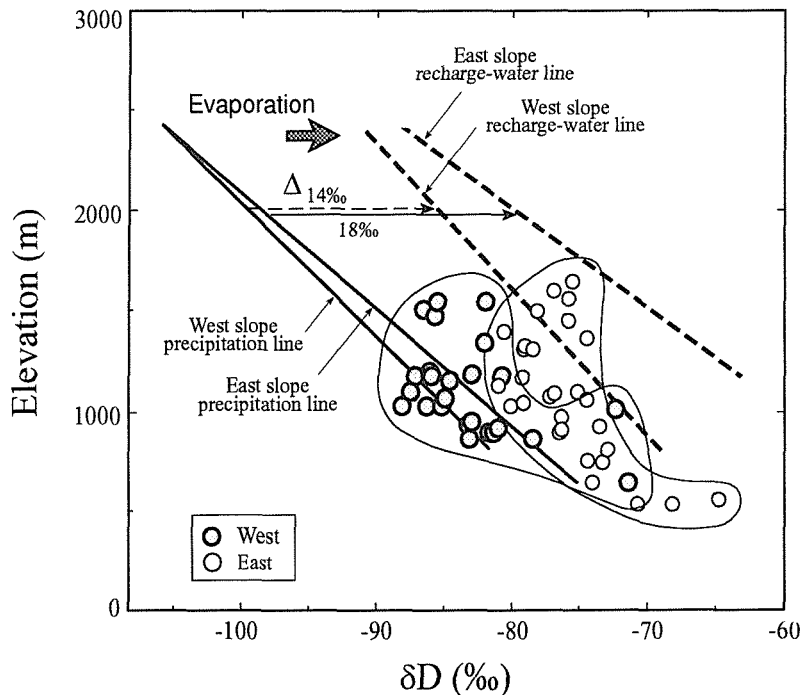
The relation between  $\delta D$  and elevation for groundwaters sampled in August 1988 is shown in Fig. 3. A comparison of samples at the same elevation indicate that  $\delta D$  of groundwaters on the leeward west slope are more isotopically depleted and about 10‰ less than those from the windward east slope, which also is observed for groundwaters sampled in January 1989 (Yasuhara *et al.*, 1993).

A possible explanation is the rain-shadowing effect of Mt. Yatsugatake causes precipitation to be isotopically different between the slopes, reflecting the different physiographic locations of the slopes relative to the dominant southeasterlies. To verify this hypothesis, annual volume-weighted mean  $\delta D$  of precipitation for each slope was compared (Fig. 3). Each slope has a different relation between  $\delta D$  and elevation: -1.7‰ per 100 m for the windward east slope and -1.5‰ per 100 m for the leeward west slope. Although the leeward west slope precipitation is somewhat depleted relative to the windward east slope, an off-set between the two precipitation lines is too small to account for the isotopic difference of groundwaters. Consequently, a rain-shadowing effect by the mountain is not a major factor responsible for the difference between the  $\delta D$  of the east and west slope groundwaters.

The recharge-water lines in Fig. 3 were calibrated using samples from 12 springs of local origin having well-defined recharge area (for details of the recharge-water line, see Kazahaya & Yasuhara, 1994). Clearly, the east and west slopes have different recharge-water lines (Fig. 3). The recharge-water line for the west slope is more

isotopically depleted (ranging from 4 to 12‰ in  $\delta D$ ) than for the east slope. We conclude that this isotopic difference in recharge water is responsible for the heavy isotope depletion in the west slope groundwaters, because the isotopic composition of groundwaters on the slope is totally dependent on the associated recharge-water line.

We consider why the recharge-water lines are distinctly above the precipitation lines (Fig. 3) and a large discrepancy occurs between east and west slope recharge-water lines. The difference  $\Delta$  (Fig. 3) in  $\delta D$  between the precipitation and recharge-water lines probably results from isotopic enrichment caused by evaporation during infiltration in recharge areas. Thus, the larger the evaporation is, the larger the difference  $\Delta$ . Differences in evaporation rates between the east and west slopes cause the difference in the recharge-water line.



**Fig. 3** Relation between  $\delta D$  and elevation for groundwaters on the windward east and leeward west slopes of Mt. Yatsugatake (August 1988). Also shown are the precipitation and recharge-water lines for the respective slopes.  $\Delta$  is the difference in  $\delta D$  between the precipitation and recharge-water lines at a given elevation. As an example, at an elevation of 2000 m,  $\Delta$  is 18 and 14‰ for the east and west slopes, respectively.

In the elevation range 1000-2500 m a.m.s.l.,  $\Delta$  ranges from 16 to 21‰ for the east slope and from 14 to 16‰ for the west slope (Fig. 3). Based on these  $\Delta$  values, the altitude distribution of annual evaporation rate (% of annual precipitation),  $E$ , on the east and west slopes was calculated using the Rayleigh-type equation as follows:

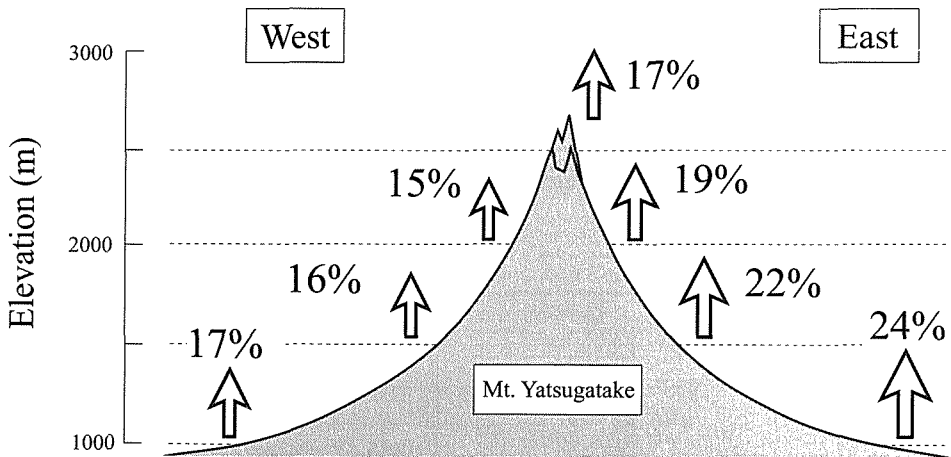
$$1 - 10^{-3} \nabla = F^{\alpha-1} \quad (1)$$

where  $F$  is the residual fraction of precipitation and  $\alpha$  the equilibrium hydrogen isotope fractionation factor. The evaporation rate,  $E$ , is obtained by:

$$E = (1 - F) \times 100 \quad (2)$$

The equation of Kakiuchi & Matsuo (1979) provides the equilibrium hydrogen isotope fractionation factor  $\alpha$  between liquid and vapor phases at a given air temperature. Mean annual air temperature necessary for the calculation of  $\alpha$  was estimated by extrapolating the Japan Meteorological Agency (JMA) weather station data to the respective elevations.

As per deuterium enrichment, the kinetic effect is known to be 10% or less compared to an equivalent equilibrium process (Gat, 1980). Moreover, Mt. Yatsugatake is very humid having average relative humidities in excess of 70-80% (JMA, 1972). Therefore, the evaporation rate calculated from equations (1) and (2), which take into account the equilibrium fractionation factor  $\alpha$  alone, is assumed to be representative and reasonably accurate.



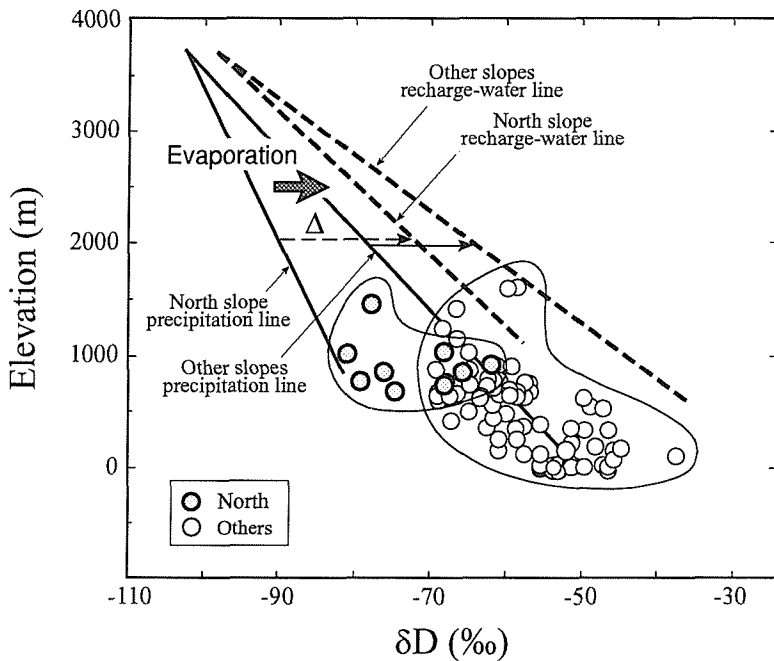
**Fig. 4** Isotopically determined evaporation rate (% of annual precipitation) from the windward east and leeward west slopes of Mt. Yatsugatake.

The isotopically determined evaporation rate for Mt. Yatsugatake is shown in Fig. 4. Generally, the higher the elevation is, the lower the evaporation rate. Evaporation rate ranges from 19 to 24% and from 15 to 17% of the annual precipitation for the east and west slopes, respectively, and the differences indicate that evaporation at a given elevation on the west slope is 4 to 7% less than that on the east slope. Consequently, groundwater recharge on the west slope is more isotopically depleted than on the east slope. It is most likely that this difference in the evaporation rate between the east and

west slopes produces the distinctly different recharge-water lines for Mt. Yatsugatake, and consequently, leads to the marked off-set of isotopic composition of groundwaters between the slopes.

### Mt. Fuji study

The relation between  $\delta D$  of groundwater samples and elevation are shown in Fig. 5 for Mt. Fuji. Groundwaters on the north slope are isotopically more depleted by at least 10‰ for  $\delta D$  than those at comparable elevations on the other slopes (that is, on the south, east and west slopes).



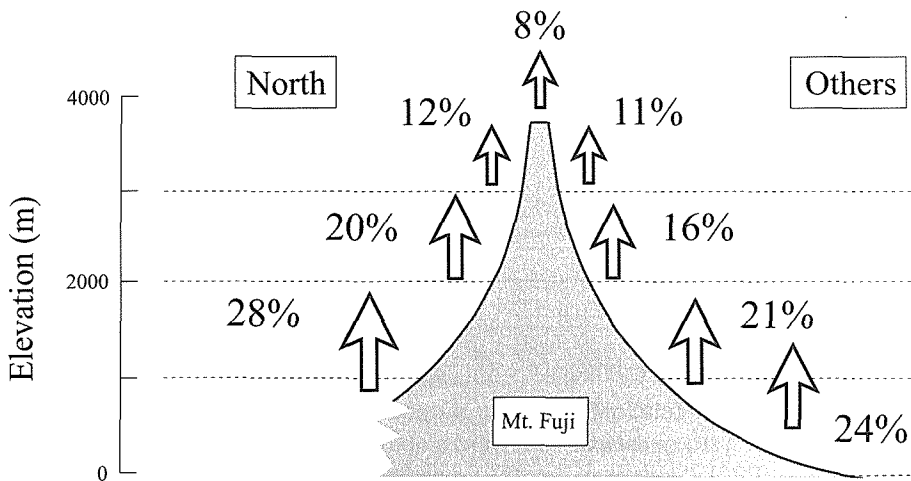
**Fig. 5** Relation between  $\delta D$  and elevation for groundwaters on the leeward north and windward slopes of Mt. Fuji (August 1993 and July 1994). Also shown are the precipitation and recharge-water lines for the respective slopes.  $\Delta$  is the difference in  $\delta D$  between the precipitation and recharge-water lines at a given elevation.

The relation between annual volume-weighted mean  $\delta D$  of precipitation and elevation also are shown in (Fig. 5). The  $\delta D$  variations of precipitation with elevation yield different precipitation lines for the north and other slopes:  $-0.8\text{‰}$  per 100 m for the north slope and  $-1.4\text{‰}$  per 100 m for the other slopes. The leeward north slope precipitation is more depleted than that on the windward slopes and the difference in  $\delta D$  between the two precipitation lines is 17, 10 and  $5\text{‰}$  at 1000, 2000 and 3000

m.a.m.s.l., respectively. Compared with Mt. Yatsugatake, isotope differences of precipitation for Mt. Fuji are 5 times higher for any given elevation. The substantial isotope depletion of north slope precipitation is attributed to the prominent rain-shadowing effect of Mt. Fuji.

The recharge-water lines in Fig. 5 are calibrated by the spring and cavern waters of local origin (Yasuhara *et al.*, 1995). There is a marked off-set in  $\delta D$  between the precipitation and recharge-water lines at a given elevation for each of the slopes for which  $\Delta$  ranges from 10 at 3000 m a.m.s.l. to 26‰ at 1000 m a.m.s.l. for the leeward north slope and from 8 at 3000 m a.m.s.l. to 23‰ at 500 m a.m.s.l. for the windward slopes. As observed for Mt. Yatsugatake, differences in  $\Delta$  are attributed to isotopic enrichment caused by evaporation during infiltration.

In the same manner as determined for Mt. Yatsugatake, we calculated evaporation losses (evaporation rate,  $E$ ) as a function of elevation (Fig. 6) based on the annual mean air temperature (Ito, 1964). The evaporation rate ranges from 12 to 28% of the annual precipitation for the leeward north slope and from 11 to 24% for the windward slopes. At a given elevation, evaporation from the leeward north slope is 1 to 7% more than that from the windward slopes, and is attributed to a longer duration of sunshine and lower humidity on the leeward north slope (Kizawa *et al.*, 1969) than on the windward slopes.



**Fig. 6** Isotopically determined evaporation rate (% of annual precipitation) from the leeward north and windward slopes of Mt. Fuji.

Although higher evaporation from the leeward north slope causes a reduction in the isotopic difference of precipitation between the leeward north and windward slopes, this process is not sufficient to completely mask the original isotopic difference in precipitation. The result is that the two recharge-water lines show an off-set (Fig. 5), i.e., for a given elevation, the recharge-water line for the leeward north slope is more

isotopically depleted by 3 to 12‰ in  $\delta D$  compared with that for the windward slopes. Difference in  $\delta D$  between the groundwaters on the leeward north and windward slopes is attributed to differences in recharge-water lines.

Therefore, we can conclude that for Mt. Fuji, the prominent rain-shadowing effect produced by the mountain is primarily responsible for isotopic differences of groundwaters between the leeward north and windward slopes.

## SUMMARY

Differences in  $\delta D$  of groundwaters between the slopes on each of Mt. Yatsugatake and Mt. Fuji can be attributed to different processes for the respective volcanoes. For Mt. Yatsugatake, less evaporation on the leeward west slope results in isotopically ( $\delta D$ ) depleted groundwaters on the leeward west slope. In contrast, isotopically depleted precipitation on the leeward north slope of Mt. Fuji, which is caused by the rain-shadowing effect of the mountain, is most responsible for isotopically depleted groundwaters on the same slope.

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