

Groundwater helium anomaly related to the 2024 Noto Peninsula earthquake

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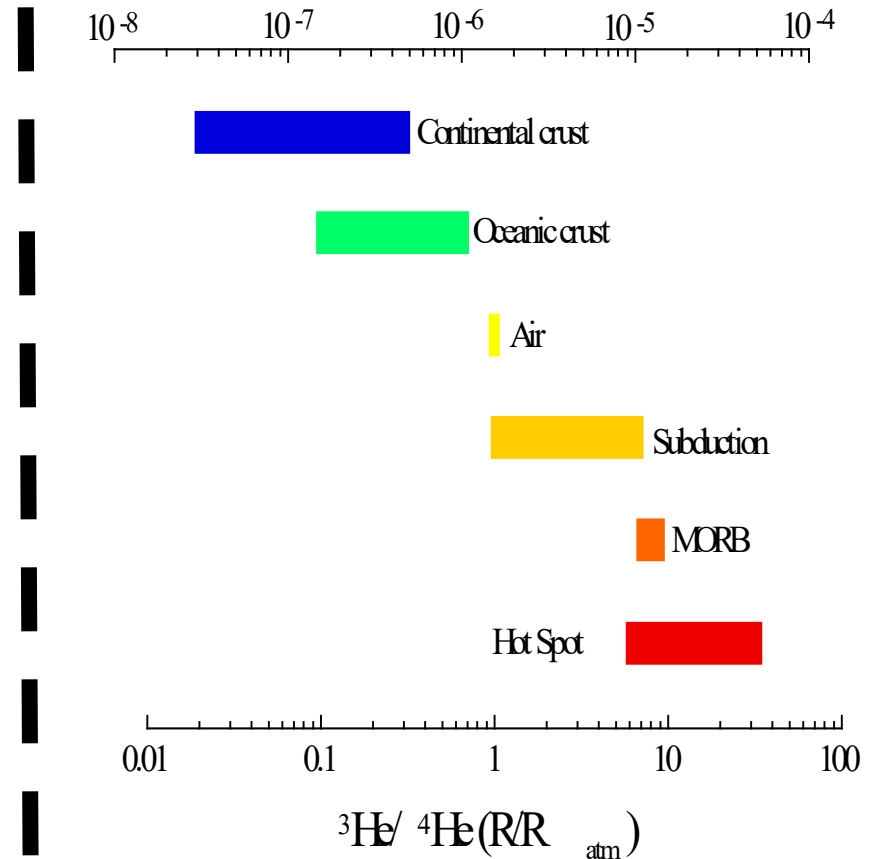
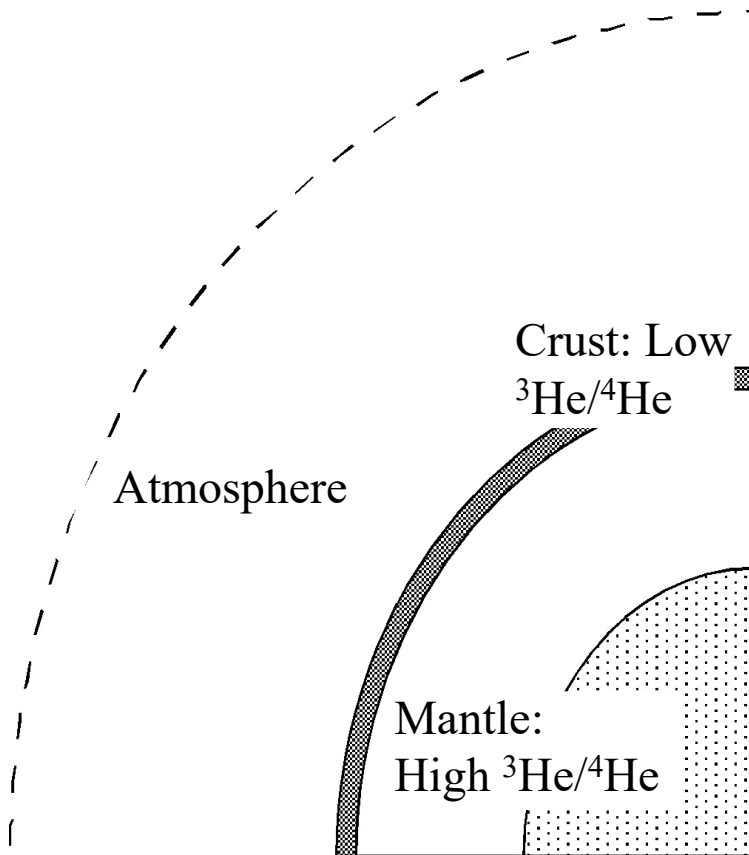
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Terrestrial helium isotopes

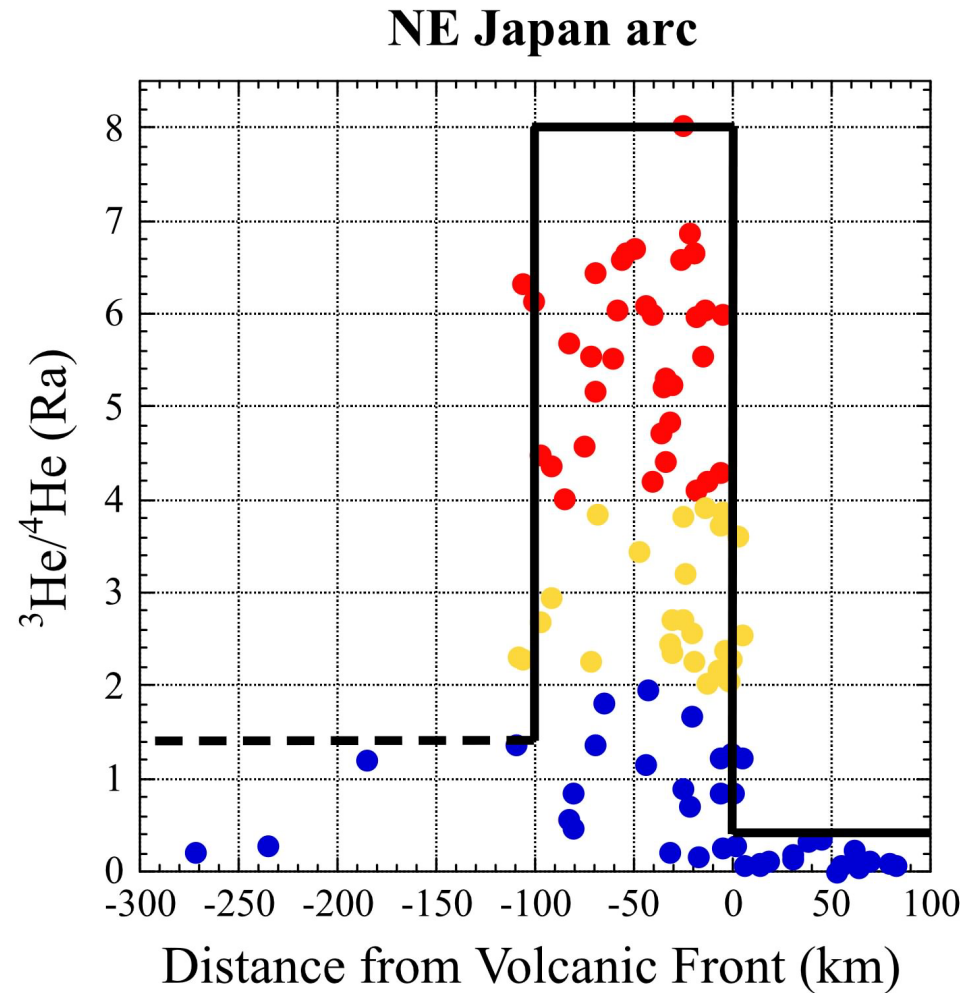
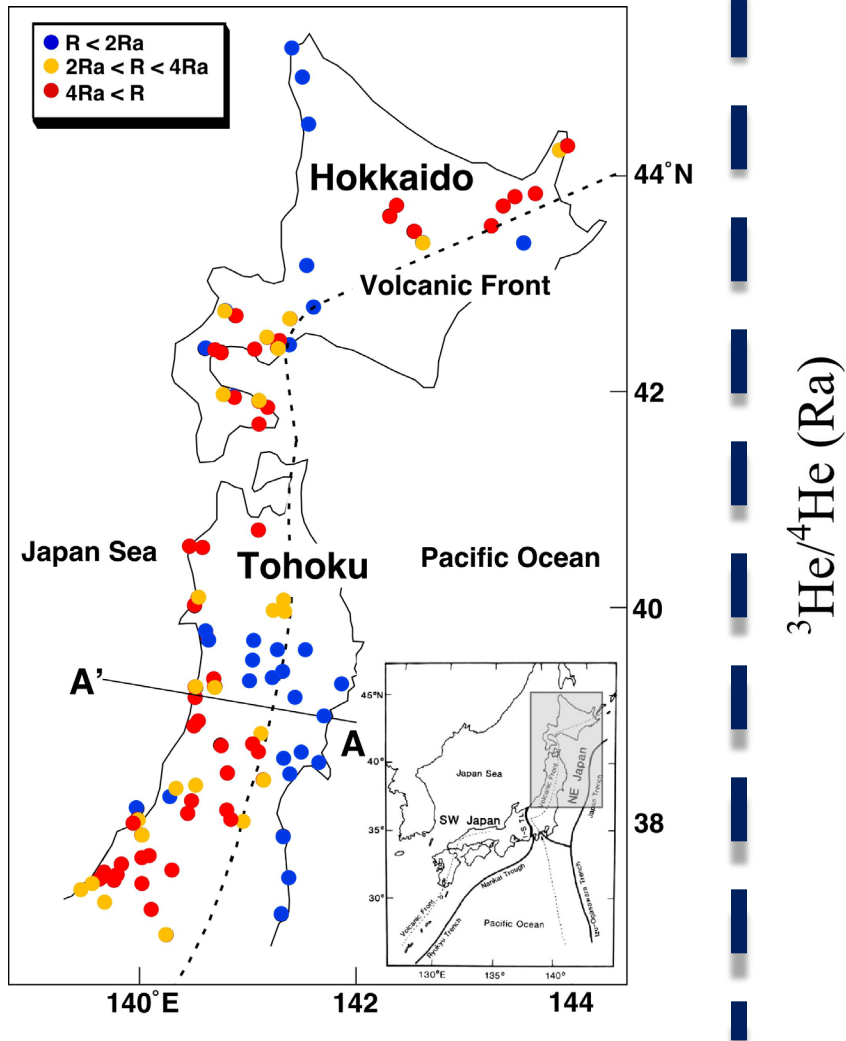
^3He : Primordial

^4He : Radiogenic



$^3\text{He}/^4\text{He}$ ratios are expressed as relative one to the air (1.39×10^{-6}). There is a relationship between the $^3\text{He}/^4\text{He}$ ratio and global geotectonic setting.

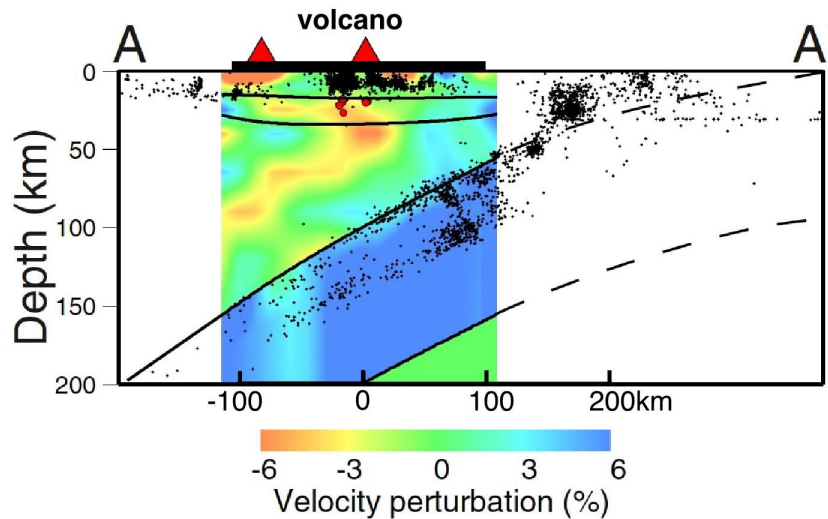
$^3\text{He}/^4\text{He}$ ratios in Northeast Japan



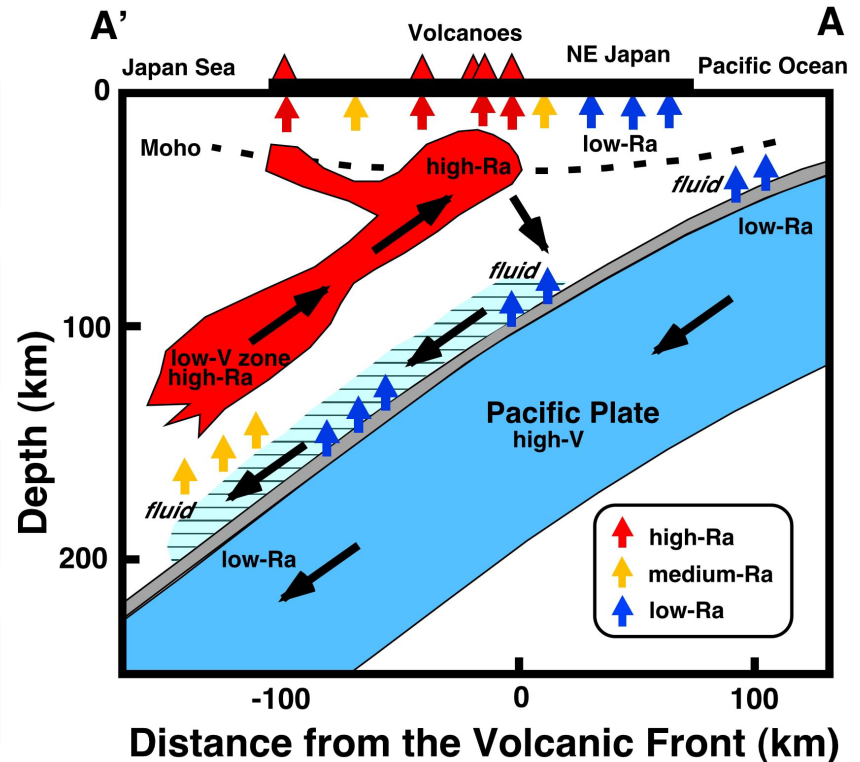
Helium isotopes are low in fore-arc and high in volcanic arc.
Sano and Wakita (1985), Umeda et al. (2007), Horiguchi et al. (2010)

Tectonic implication for NE Japan

Seismic tomography

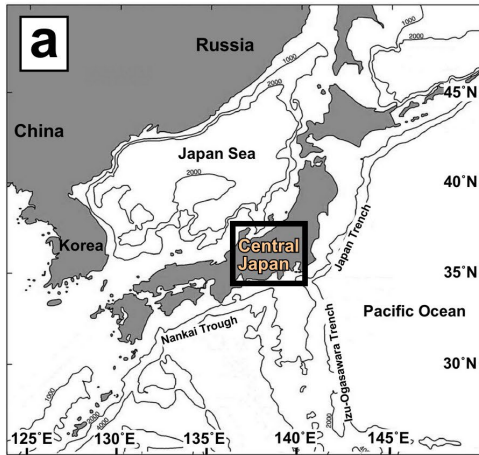


Vertical cross section of S-wave velocity perturbations across the NE Japan arc (Hasegawa and Nakajima, 2004). Partial melting zones are located in sub-parallel to the subduction slab, which is the source of arc magma.



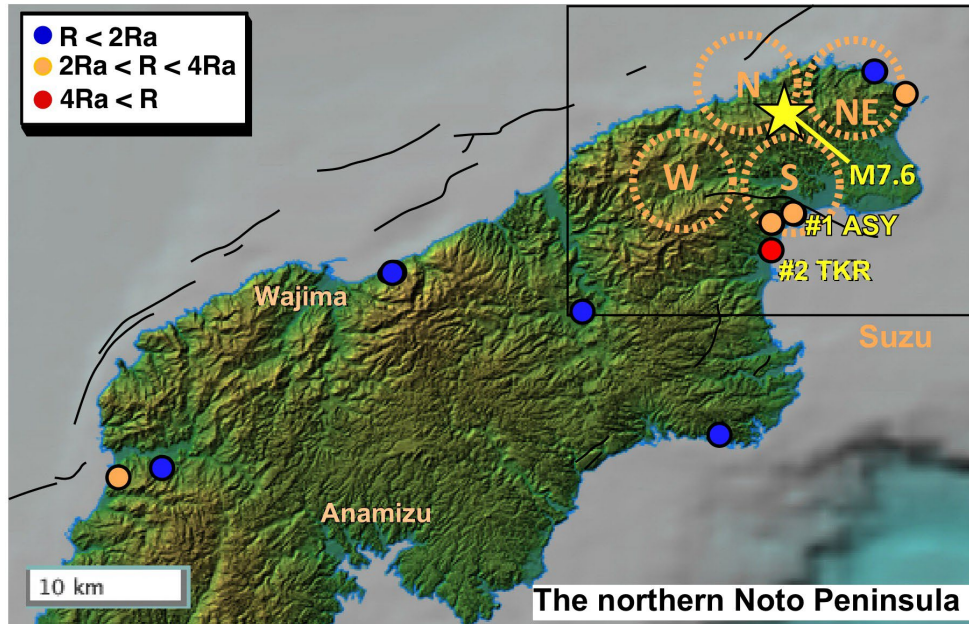
Subsurface region of fore-arc are affected by radiogenic He due to U and Th in crustal and sedimentary rocks. Main carrier of He-3 is a magma uprising (Sano and Nakajima, 2008).

$^3\text{He}/^4\text{He}$ ratios in Noto Peninsula



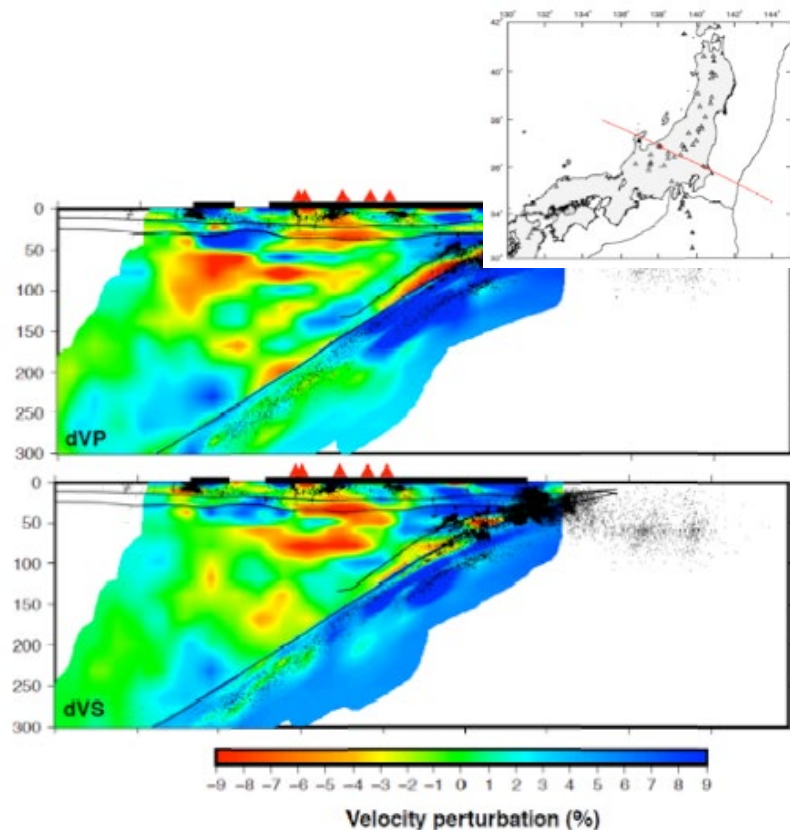
There is no evidence of volcanism in the Noto Peninsula since the late Miocene. Geographical distribution of $^3\text{He}/^4\text{He}$ ratios in the region indicated an insignificant contribution of mantle-derived volatiles (Umeda et al., 2009).

We found very high $^3\text{He}/^4\text{He}$ ratios, up to $5R_a$ in the area close to city hall, the south border of swarm cluster S (This work). A pathway is required for helium to migrate from the mantle to the Earth's surface.

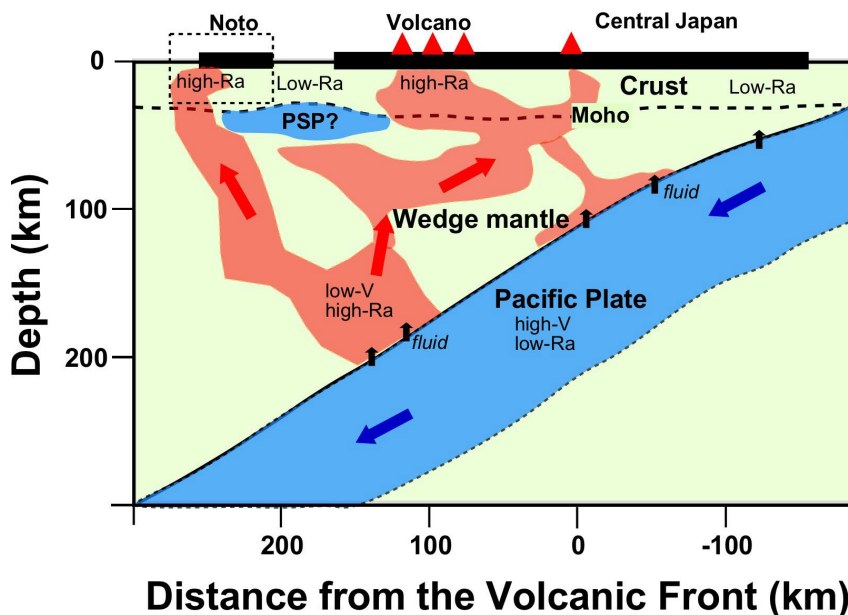


Basalt magma aging: $3R_a$ at 15Ma.

Deep structure

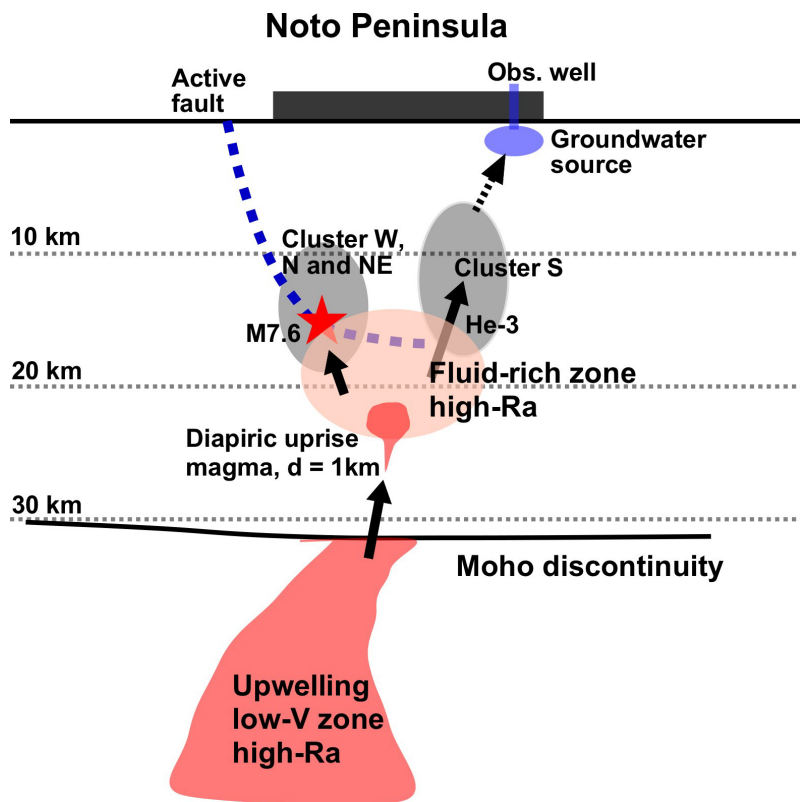


Vertical cross section of S- and P-wave velocity perturbations across the central Japan (This work). Partial melting zones are the source of arc magma.



Fluids generated by degassing of the Pacific plate cause partial melting of mantle materials at about 200 km below the surface. Mantle upwelling flows head down the Noto Peninsula, but are blocked by the high-velocity zone below the Moho surface. The upwelling bypasses the zone and reaches the Moho surface beneath the crust in the Noto Peninsula.

Shallow structure

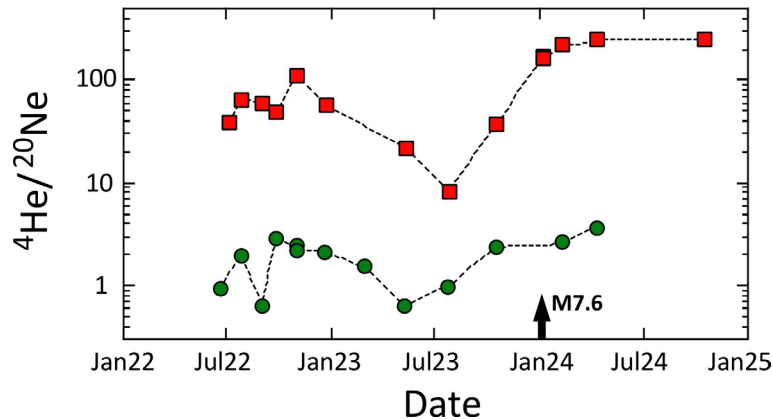
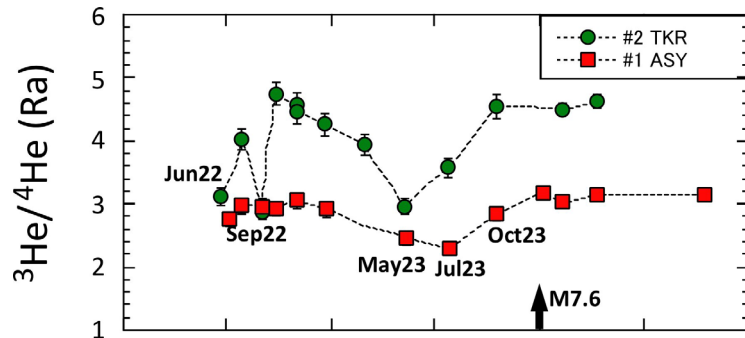
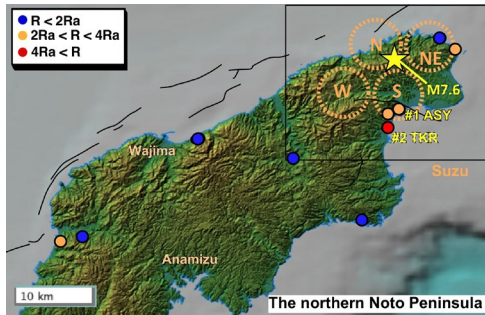


Modified from Nishimura et al. (2023)

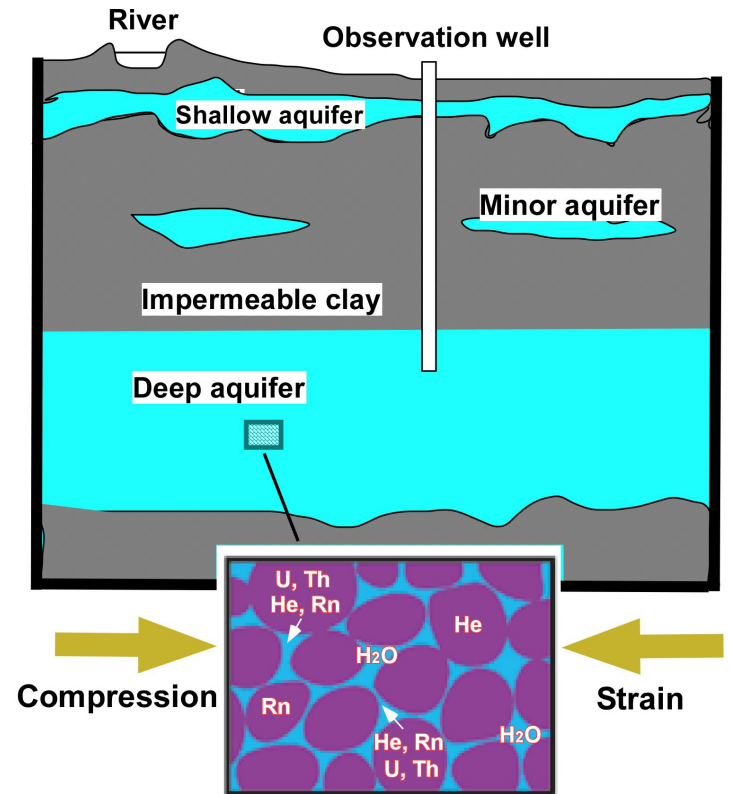
Diapiric magma, an ellipsoid about 1 km in diameter, separated from the mantle material below the Moho, is uprising to about 20 km deep and releases a large amount of fluid as the temperature decreases and crystallization of silicate occurs. This fluid further rises and diffuses through a pre-existing fault zone at 15 km below the surface, probably triggered swarm earthquakes. Some of this fluid may have risen further and reached the aquifer with a $^3\text{He}/^4\text{He}$ ratio $5R_a$. This observation is similar to the case of the Matsushiro warm earthquake in 1960s (Wakita et al., 1978).

About 1 km sphere magma $1.6 \times 10^{15} \text{g}$, if contains 2% water $\rightarrow 3 \times 10^{13} \text{g}$ water
Nishimura et al. (2023) suggested a large volumetric increase of $2.92 \times 10^7 \text{m}^3$.

Secular variation



Record: Jun 2022 ~ Oct 2024



Observed $^3\text{He}/^4\text{He}$ and $^4\text{He}/^{20}\text{Ne}$ ratios in deep groundwater are explained by three component mixing of helium; atmospheric origin, groundwater (mantle + crust) and that from aquifer rock.

Strain change and helium degasing

A laboratory experiment (Honda et al. 1982) showed a positive correlation between the degassed helium and the volumetric change ($\Delta V/V$) as follows:

$$1 - R = k_2 \times (\Delta V/V)^{2/3}$$

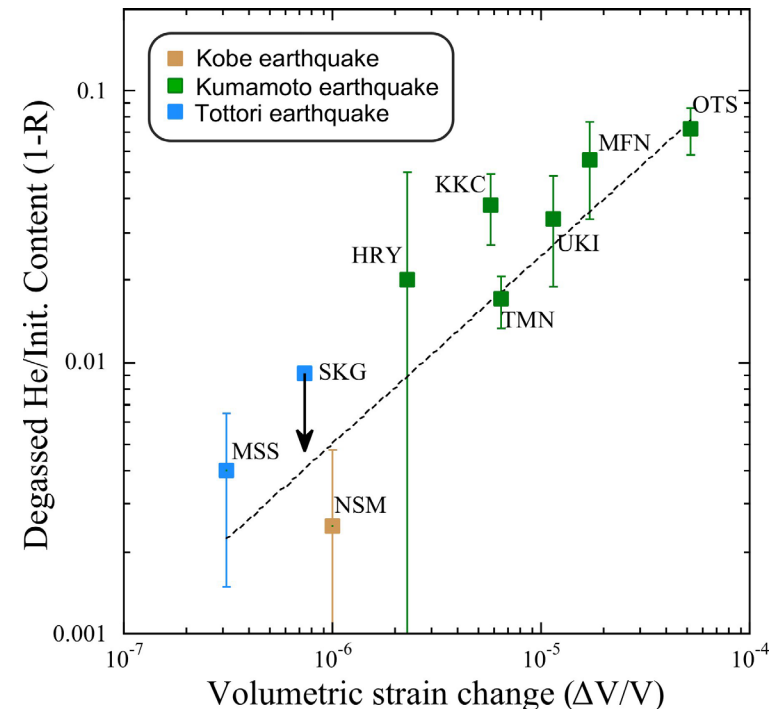
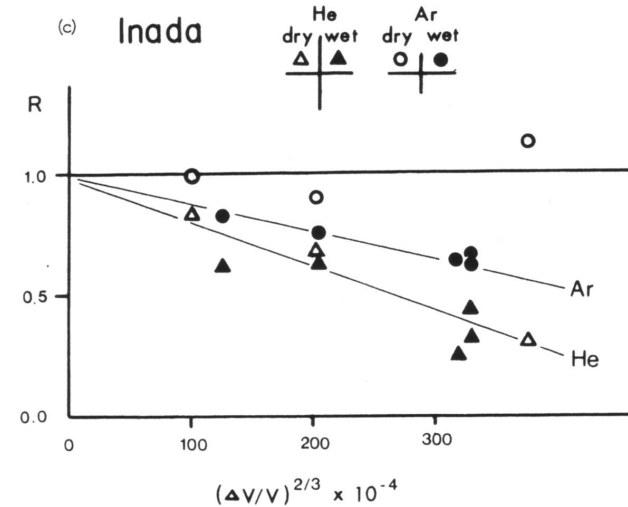
where R and k_2 are retention and constant.

We plot all helium data (Kobe, Kumamoto, and Tottori) against volumetric strain change estimated by a fault model.

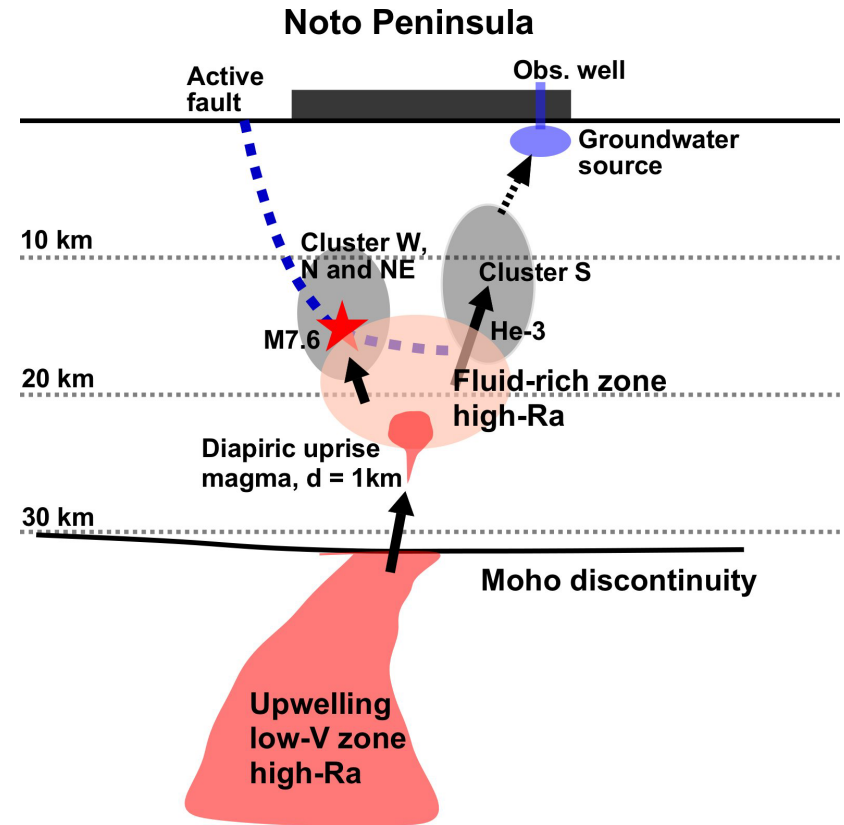
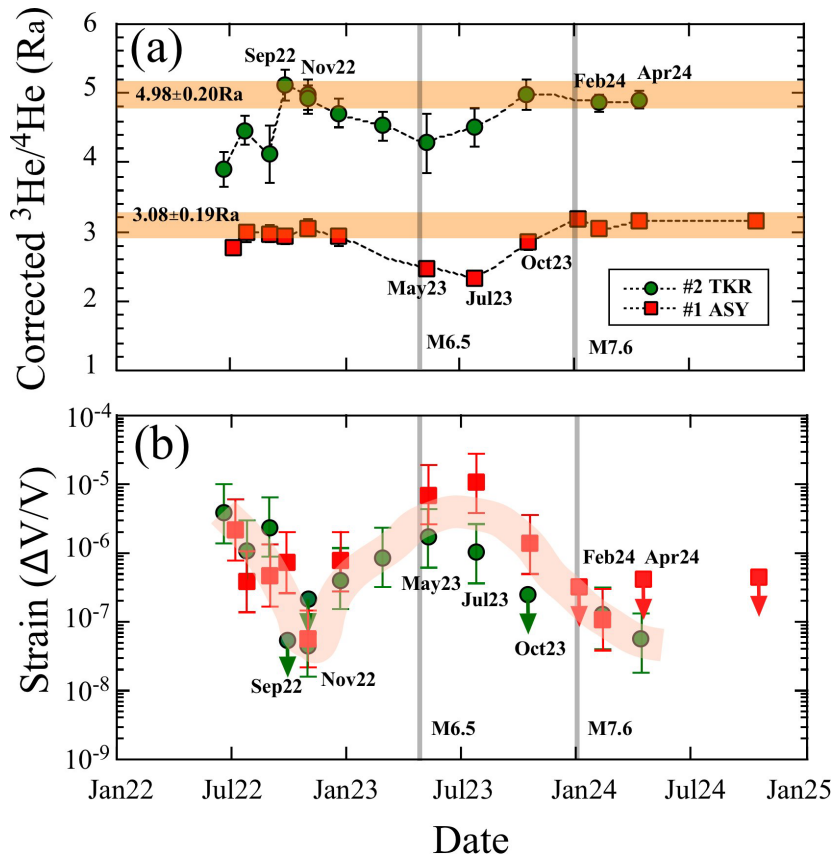
Fitting of function $(1-R) = k_2 \times (\Delta V/V)^a$ is made by a least square method, where “ k_2 ” and “ a ” are unknown constants. Best fit provides that $k_2 = 71 \pm 38$ and $a = 0.69 \pm 0.05$ (1σ) with $r=0.93$ and $MSWD=1.2$.

In a laboratory, $k_2=25 \pm 15$ and $a = 2/3$, they are consistent with the best fit data.

Groundwater helium is considered as an effective strain gauge. (Sano et al., 2016)



Helium anomaly and strain change



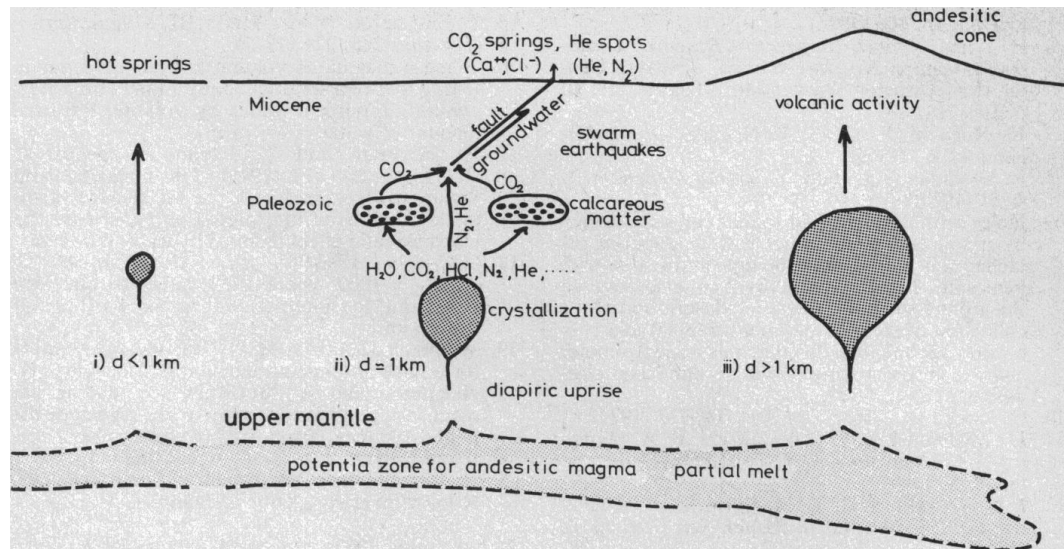
When the $^4\text{He}/^{20}\text{Ne}$ ratio is used to correct for air contamination, the $^3\text{He}/^4\text{He}$ ratios at the both sites, are lower in May23 and Jul23 than the trend. We can calculate the volumetric strain from a laboratory experiment. We estimate a precursory strain change reaching 1×10^{-5} before the M7.6 earthquake.

Summary

- We report data obtained by periodical groundwater sampling and helium isotope measurements in the epicenter area of the Noto Peninsula in central Japan starting July 2022.
- The maximum $^3\text{He}/^4\text{He}$ ratio of 5Ra together with seismic tomography data indicates that the earthquake swarm was caused by fluids rising from the mantle.
- Precursor-like variations in $^3\text{He}/^4\text{He}$ ratios were observed at two stations (ASY and TKR) 8-10 km from the epicenter. This variation may be due to reflecting strain changes in the aquifer rock.

Matsushiro earthquake swarm

The Matsushiro earthquake swarm occurred during the period 1965 to 1967, at and around Matsushiro area in Nagano city, central Japan. Initially the depths of the foci were about 4 to 5 km, but they moved upward with the pregression of seismic activities. Various phenomena, including changes in gravity, magnetic field and ground upheaval, tilting and groundwater gushing were observed.



Based on the high $^3\text{He}/^4\text{He}$ ratio of $6.4R_a$ in CO_2 springs, Wakita et al. (1978) reported that the occurrence of the swarm was interpreted as the results of a diapiric uprise of a magma approximately 1 km in diameter.