

Integrating eDNA, Noble Gases, and Isotopic Tracers to Unravel Groundwater Origins in Volcanic Island Aquifers: The Example of Mt. Fuji watershed in Japan

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Mount Fuji, Japan's most iconic volcano, hosts one of the country's most complex and dynamic volcanic aquifer systems, supplying freshwater to millions of people. Despite its importance, groundwater flow paths, residence times, and mixing processes within the catchment remain insufficiently understood, particularly in relation to tectonic activity and deep groundwater circulation.

In this study, we integrated a suite of classic and unconventional hydrogeological tracers to shed new light on the volcanic aquifer's spatial and temporal groundwater mixing patterns. Alongside the classic major ion and stable water isotope tracers, we employed (i) an unusually broad range of radioactive noble gas (⁸⁵Kr, ³⁹Ar, ⁸¹Kr, ³H/³He) and radiocarbon (¹⁴C) tracers, allowing us to date groundwater across the full range of expected residence times within Mt. Fuji, (ii) isotopic and trace element analyses (e.g., vanadium, fluoride, d¹³C-DIC, d¹⁵N-N₂), and (iii) novel microbial DNA sequencing and online flow cytometry analyses, applied here as hydrogeological tracers. To not only analyze a single snapshot in time but also capture transient variations, we furthermore installed a continuous monitoring station in a municipal drinking well intersecting an active fault zone, tracking noble and reactive gas concentrations, electrical conductivity, pressure, and temperature in real-time.

Our findings revealed a deep groundwater component that was previously unknown to reach such shallow depths across the Mt. Fuji watershed. This deep water is helium- and trace-element-enriched and hosts extremophile Archaea adapted to high-temperature and high-pressure subsurface conditions, typically found only at great depths within the volcanic system.

Surprisingly, these microbial signatures were consistent throughout the watershed, suggesting their potential as a novel tracer for groundwater origins and connectivity between shallow and deep layers. Continuous monitoring data further highlighted the strong influence of seismic and meteorological events on groundwater mixing, demonstrating the high sensitivity of volcanic aquifer systems to such perturbations.

The combined geochemical, isotopic, and biological tracers have proven to be a powerful toolset for providing new insights into volcanic aquifer systems dynamics and thus enable sustainable and resilient groundwater management, particularly in the face of climate change and seismic activity.