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From Seep to Storage: Constraining CO_2 Leakage Flux and Early Geochemical Indicators Within the Eifel Natural Analogue

MOHAMMED ALSHAREEF[1], REBECCA TYNE[2], DARREN HILLEGONDS[3], DAVID V BEKAERT[4], ALAN M. SELTZER[5], MICHAEL W. BROADLEY[6], FAHAD SOUID[1], OLIVER WARR[7] AND CHRIS J. BALLENTINE[3]

[1]Dept Earth Sciences, University of Oxford, UK
[2]The University of Manchester
[3]University of Oxford
[4]Université de Lorraine, CRPG, CNRS
[5]University College Dublin
[6]University of Manchester
[7]University of Ottawa

Natural CO_2 seepage systems provide rare opportunities to test leakage monitoring concepts under real-world complexity. We present a tracer-led framework that links CO_2 flux quantification with multi-isotope and noble-gas fingerprints to identify early-warning indicators of upward CO_2 migration that are transferable to engineered carbon storage sites.

Our field focus is the Eifel region (Germany), where CO_2-rich mofettes, mineral springs, and geysers offer contrasting expressions of degassing along short spatial scales. We sample gases and waters across 11 sites spanning these seep types, pairing surface flux observations with co-located geochemical measurements. Carbon sources and near-surface overprinting are assessed using $\delta^{13}C–CO_2$ alongside major gas species and complementary water isotopes ($\delta^{18}O$, δD) and dissolved-ion chemistry to characterise fluid–rock interaction and groundwater mixing. Where available, radioisotopes (^3H and ^{14}C) gauge the influence of modern recharge on CO_2-bearing fluids and help separate recent atmospheric inputs from longer-residence groundwater components. Volatile provenance and transport are constrained using noble gases, systematics to separate mantle, crustal, and atmospheric components and to evaluate dilution during ascent. Initial results show R/Ra values of 1.1–5.4 and $\delta^{13}C–CO_2$ values of −1.9 to −9.06‰, consistent with a significant mantle contribution combined with variable mixing and near-surface modification.

Bubble-mediated transport provides a mechanistic link between geochemistry and measurable leakage signals in the Eifel system. Variations in bubble size, ascent rate, and residence time in water can modulate gas–water exchange, leading to selective dissolution and diffusive fractionation that attenuate or reshape noble-gas signatures during migration. As a result, diagnostic ratios may evolve between depth and the surface. We use different processes considerations to interpret observed tracer variability in terms of partitioning between free-phase and dissolved CO_2 and to evaluate how rapidly noble-gas and CO_2 signals can be modified by dissolution and groundwater mixing.