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Outstanding Student & PhD candidate Presentation contest

Distinguishing source effects from physical processes using the full suite of noble gas systematics across geothermal systems in Afar (Ethiopia)

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Abstract's QR code :)

Introduction to the East African Rift System

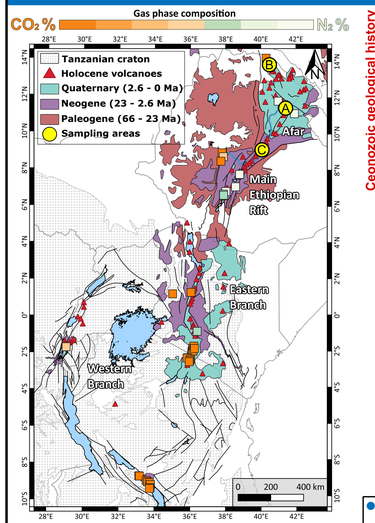
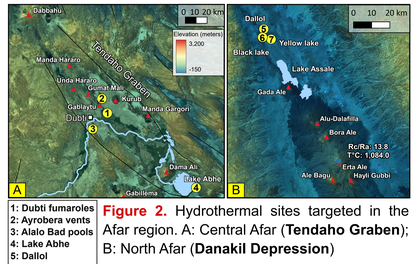


Figure 1. Map of the East African Rift System (EARS) showing geothermal gas composition (CO_2–N_2%), Cenozoic volcanism, and major faults, together with the Tanzanian Craton (grey dotted area).

Ceonozoic geological history

1. Late-Eocene **plume impingement**
2. Lithosphere thinning and widespread regional uplift
3. *Traps Series* implacement ~ 30 Ma
4. Mio-Pliocene Main Ethiopian Rift (MER) development
5. Pleistocene: sub-segmentation and **localization of extension accomodated by magma injection** (e.g., *Stratoid series*)



1: Dubti fumaroles
2: Ayrobera vents
3: Alalo Bad pools
4: Lake Abhe
5: Dallol
6: Black Lake
7: Yellow Lake

Figure 2. Hydrothermal sites targeted in the Afar region. A: Central Afar (**Tendaho Graben**); B: North Afar (**Danakil Depression**)

Aims of the study

- Distinguishing **source effects** from **physical processes** in hydrothermal systems of the Ethiopian Rift and Afar
- Determine whether these processes can concentrate **economically valuable strategic volatiles**
- Identify potential sources of strategic volatiles (i.e., He, H_2) in the study regions to inform future feasibility assessments of their **co-exploitation with geothermal energy**

Noble gases and their use: geochemical tracers and more

4 He	.**Inert nature, highly volatile and incompatible in melts**
20 Ne	.Powerful geochemical tracers of **source effects (mantle vs crust)** and **physical processes** (degassing, diffusion, solubility)
40 Ar	⟹ **Proxies for elemental and isotopic fractionation**
84 Kr	.But, their low concentrations turn into analytical challenges
132 Xe	

Helium and Xenon systematics example

- **Primordial isotopes**: entrapped in the core and mantle during **Earth's accretion**, thus **source tracers.**
- **Secondary isotopes**: i.e., produced by **nuclear reactions.**

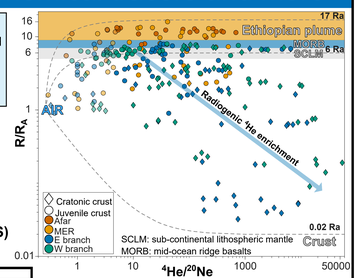


Figure 3. Example of Helium-Neon systematics.
R = ^{3}He/^{4}He measured; R_A = ^{3}He/^{4}He of air (1.39x10^{-6})
.**Continental crust**: R/R_A ~ 0.02
.**Upper mantle**: R/R_A 8 ± 1 (MORB)
.**Mantle plume**: R/R_A > 10-52

Static Mass Spectrometry (SMS) Only | **Dynamic Mass Spectrometry (DMS) + SMS**

^{3}He ^{4}He | ^{124}Xe ^{126}Xe ^{128}Xe ^{129}Xe ^{130}Xe ^{131}Xe ^{132}Xe ^{134}Xe ^{136}Xe

- Xenon combines **primordial** and **secondary** isotopes from extinct and extant radionuclides. Usually, only **secondary isotopes** can be used to track physical processes (Bekaert et al., 2023).

Sampling and analytical methods

Figure 4. Scheme of volcanic gas sampling at hydrothermal springs (Bekaert et al., 2023); Photo on the left shows Giggenbach bottles collecting gases.

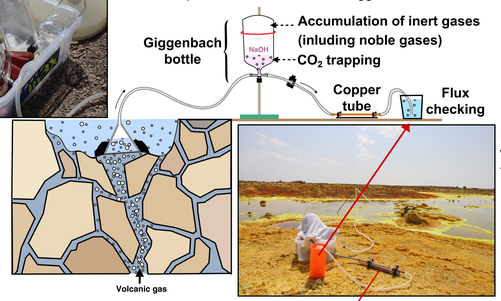


Figure 5. Sampling train with a copper tube ready to collect gases in Dallol.

- Pre-evacuated big (1.5L) Giggenbach bottles with NaOH solution:
  ⟹ **Dynamic Mass Spectrometry (DMS)** analysis of Ar, Kr and Xe isotopic compositions (Seltzer and Bekaert, 2022) WOODS HOLE OCEANOGRAPHIC INSTITUTION
- Copper tubes: for ^{3}He/^{4}He and ^{4}He/^{20}Ne analysis via **Static Mass Spectrometry (SMS)**
- Pre-evacuated small (0.35L) Giggenbach bottles **with NaOH** solution: for **Neon isotopic compositions**
- Pre-evacuated **NaOH-free** Giggenbach bottles : **bulk-gas** chemical composition via **micro-Gas Cromatography**

Light noble gas: source tracers

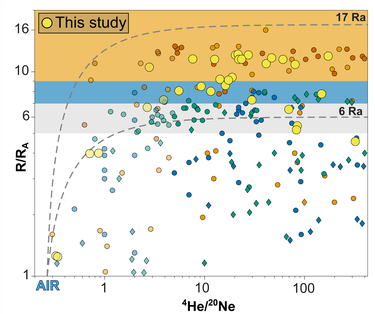


Figure 6. R/R_A vs. ^{4}He/^{20}Ne for this study and literature data across the EARS. Circles are "Juvenile crust" whereas diamonds Cratonic areas.

- **R/R_A values range from 4.56 to 12.19, indicating variable mantle-derived ^{3}He input.**
- **Our samples define a binary mixing array between the Ethiopian plume end-member and the air component.**

- **Correction for air contamination:**
  $R_C/R_A = [(R/R_A \times X) - 1] / (X - 1)$
  X-value (gas) = (^{4}He/^{20}Ne)measured / (^{4}He/^{20}Ne)air.
- **He exploitation threshold (300 vs 3000ppm) depends on:**
  .Reservoir-type, "He stand alone" vs. He + natural gas (e.g., CH_4)
  .Extraction and separation methods
  .Local use vs. transportation

For more info check **45-8 energy** website

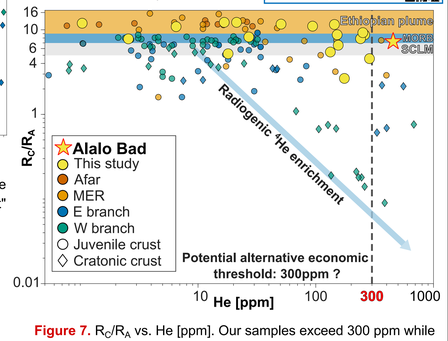


Figure 7. R_C/R_A vs. He [ppm]. Our samples exceed 300 ppm while retaining high R_C/R_A values, unlike cratonic data.

Heavy noble gas: physical process tracers

DTF = Diffusive transport fractionation (mass-dependent process)
$\delta R = (R_{SAMPLE} / R_{ATMOSPHERE} - 1) \times 1000$

$\overline{X}_W$ $^{i/130}$**Xe DTF-corr.** : Raw-data correction using the error weighted average DTF % derived from **each Xe-isotopic pair** DTF % (i.e., ^{128}Xe/^{130}Xe, ^{129}Xe/^{130}Xe, etc.).

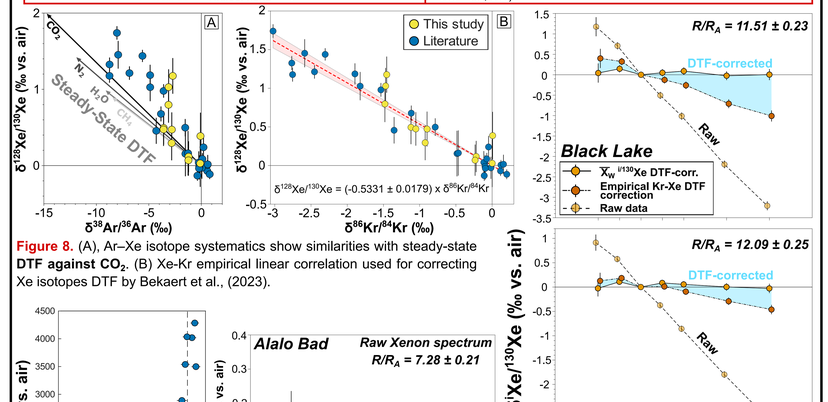


Figure 8. (A), Ar–Xe isotope systematics show similarities with steady-state **DTF against CO_2.** (B) Xe-Kr empirical linear correlation used for correcting Xe isotopes DTF by Bekaert et al., (2023).

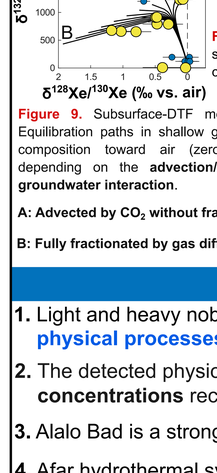


Figure 9. Subsurface-DTF model (Bekaert et al., 2023). Equilibration paths in shallow groundwater evolve from initial composition toward air (zero), with fractionation extent depending on the **advection/diffusion ratio** and shallow **groundwater interaction**.

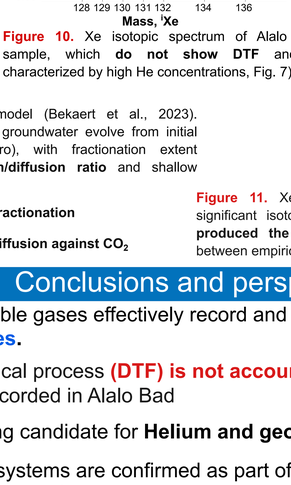
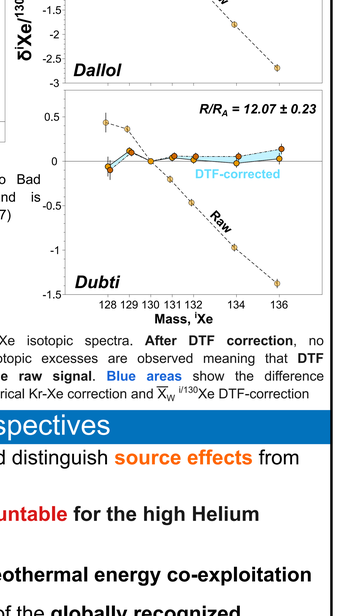


Figure 10. Xe isotopic spectrum of Alalo Bad sample, which **do not show DTF** and is characterized by high He concentrations, Fig. 7)



A: Advected by CO_2 without fractionation

B: Fully fractionated by gas diffusion against CO_2

Figure 11. Xe isotopic spectra. **After DTF correction**, no significant isotopic excesses are observed meaning that **DTF produced the raw signal**. **Blue areas** show the difference between empirical Kr-Xe correction and $\overline{X}_W$ $^{i/130}$Xe DTF-correction

Conclusions and perspectives

1. Light and heavy noble gases effectively record and distinguish **source effects** from **physical processes.**
2. The detected physical process **(DTF) is not accountable for the high Helium concentrations** recorded in Alalo Bad
3. Alalo Bad is a strong candidate for **Helium and geothermal energy co-exploitation**
4. Afar hydrothermal systems are confirmed as part of the **globally recognized subsurface DTF-driven fractionation systems.**

References: Craig, 1977; Darling et al., 1995; Marty et al., 1996; Pik et al., 2006; Fischer et al., 2009; Tedesco et al., 2010; Darrah et al., 2013; Barry et al., 2013; Thiéblemont, 2016; Muirhead et al., 2016; Kraml et al., 2016; Boucher et al., 2017; Minissale et al., 2017; Lee et al., 2017; Muirhead et al., 2020; Kimani et al., 2021; Hutchison et al., 2023; Cardoso thesis 2023; Contamine unpublished; Danabalan et al., 2022; Gluyas et al., 2024; Melaku et al., 2026