

Zeolite Tracers Applied to Flow through Production Well Connections

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ABSTRACT

Reported injection surveys in couplet Enhanced Geothermal System (EGS) injection wells show flow rate variations among several fracture-driven interactions (FDIs). Because the reported cases have all created hydraulic fractures in both injection and production wells, there may be production well fractures through which no flow is occurring. The placement of zeolites in production well fractures can serve to characterize the FDI between wells, thereby assessing how efficiently the system recovers heat and energy.

The proposed approach involves employing commercially available zeolites with particle diameters ranging from 300 to 500 nm to evaluate both the passage and contact between the circulating fluid and the production well fractures. A doublet well configuration—comprising one injection well and one production well—serves as the assessment scenario. We propose to place zeolites in production well fractures in the expectation that flow through the fractures will carry zeolites to the surface.

We propose to detect zeolites through X-ray diffraction (XRD) analysis of samples collected from the production well, leveraging the fact that zeolites are chemically stable and resistant to degradation under high temperature and pressure conditions. In summary, the proposed concept is to assess the contribution of productive fractures to the overall flow, which directly impacts the EGS heat recovery efficiency.

1. INTRODUCTION

(Gringarten et al., 1975) proposed the EHE well pattern shown in Figure 1 involving directional wells and a model consisting of multiple, equally spaced, parallel vertical fractures embedded in a hot dry rock before this technology became common in the petroleum industry. After decades of large unsuccessful efforts to achieve heat extraction from more random fracture networks such as seen in Figure 2 (EERE, 2013), Utah FORGE developed the stacked directional well configuration shown in Figure 3, which also shows a later Fervo Energy development using parallel lateral wells (Horne et al., 2025). The Utah FORGE well is pattern very similar to that proposed in 1975, but has been subjected to deliberate treatment variations including both unpropped and propped hydraulic fractures. Fervo Energy is using this early first pattern for commercial geothermal power generation to begin in 2028.

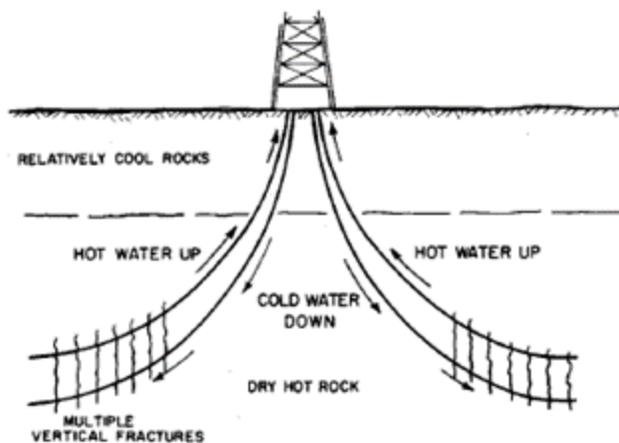


Figure 1: EHE concept from (Gringarten et al., 1975)

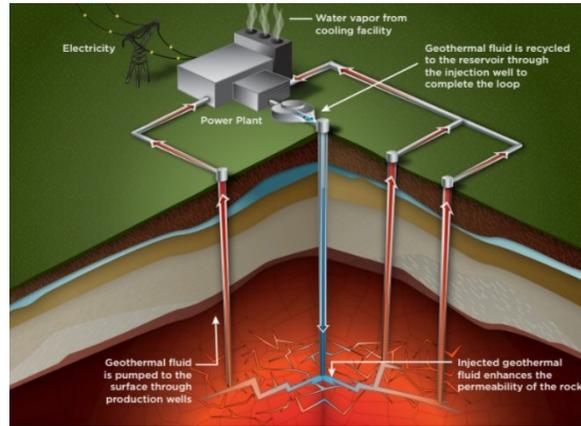


Figure 2: Traditional EHE (EERE, 2013)

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is a field laboratory dedicated to advancing the science and engineering of geothermal systems, with the goal of identifying a replicable and commercially viable pathway for EGS deployment worldwide.

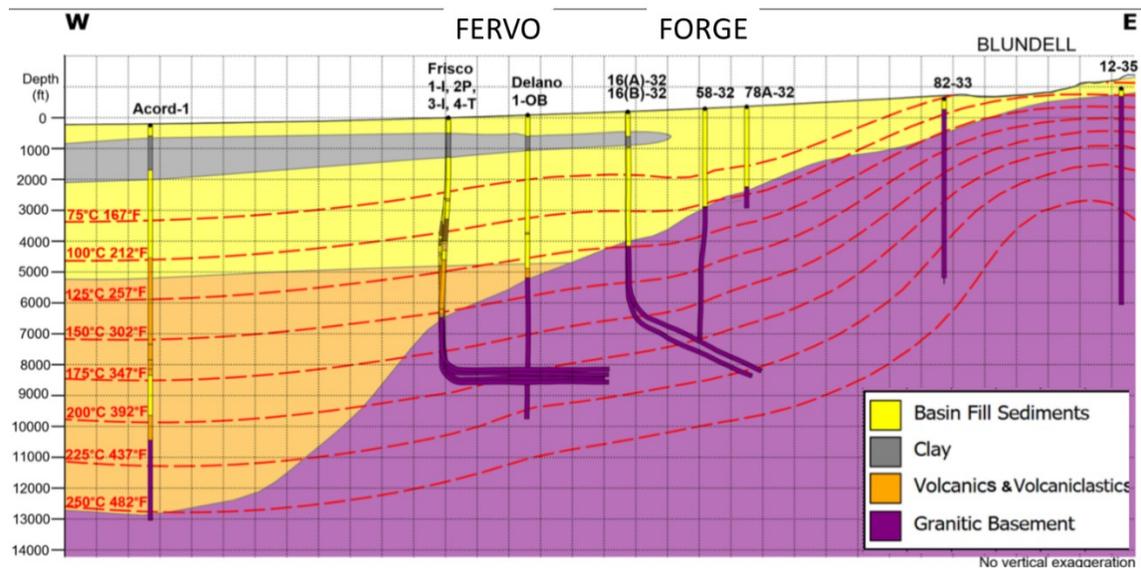


Figure 3: Utah FORGE (stacked slanted wells) and Fervo Energy (parallel lateral wells) EGS well patterns adapted from (Horne et al., 2025)

Utah FORGE first drilled and hydraulically fractured the deeper well. They then drilled the shallower directional well. Sensing that the second well did not connect to all of the hydraulic fractures created in the deeper well, Utah FORGE also fractured the shallower well. They have successfully circulated brine by injecting cold brine into the deeper well and producing hot brine from the shallower well. Fervo Energy also hydraulically fractured both horizontal wells and then injected cold brine into one and produced hot brine from the other.

(Ehlig-Economides & Barros-Galvis, 2025) explain the importance of uniform flow distribution among the fracture driven interactions (FDIs), and (Ehlig-Economides & Barros-Galvis, 2026) offer insights on ways to achieve more uniform FDIs, either by drilling through created fractures, or by fracturing into previously drilled slotted liner wells. Fracturing both injection and production wells leads to considerable variation in the FDI conductivities and uncertainty which fracture created in the injection well connects to which fracture in the production well. This uncertainty directly affects our ability to quantify heat sweep efficiency and optimize resource stimulation strategies. However, because current practice favors fracturing production wells, this paper considers a way to use zeolite nanoparticle tracers to determine which production well fractures are flowing.

2. ZEOLITE TRACER CONCEPT

Zeolites are a class of microporous, crystalline aluminosilicate materials both natural or synthetic crystals. Crystals can be synthesized much smaller than rock pore diameters. Their characterization requires advanced analytical techniques such as X-ray Diffraction (XRD),

Magic-Angle Spinning Nuclear Magnetic Resonance (MAS NMR), Single-particle ICP-MS (spICP-MS), ICP-MS (ICP-MS) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). The unique signature of each zeolite is defined by its specific elemental composition and concentration, which provides a quantifiable and distinguishable signal.

The idea is to use a portable XRD for in-situ applications due to its low cost, portability, and ease of implementation. It is capable of confirming the presence of zeolite in filtered solids, with the only limitation being that it does not quantify dissolved elements or particle size. In other words, zeolites can be deployed in each FDI during hydraulic fracturing.

Frameworks and SEM images of two synthetic zeolites. Zeolite A consists of sodalite cages, while zeolite type P belongs to the gismondine family.

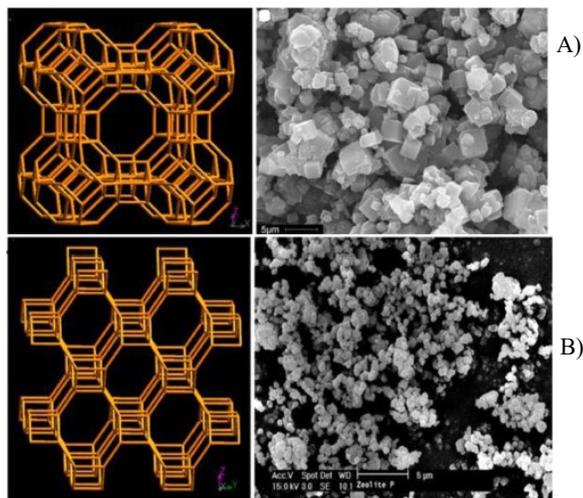


Figure 4: A) Synthetic zeolite with sodalite cages, and B) synthetic zeolite with gismondine family characteristics (Khaleque et al. 2020).

While it is straightforward to acquire an injection flow profile along the injection well, a production flow survey in the production well must be acquired at a temperature that may challenge standard flow logging tools. The OSU led research team currently funded by Utah FORGE Project 9-3709 proposed using zeolite crystal nanoparticles as a tracer capable of withstanding the complex chemical interactions and high temperature EGS flow conditions.

The project supports research to investigate the feasibility of using zeolite crystals with particle diameters ranging from 300 to 500 nm to identify through which FDIs flow is occurring. The concept is to place different zeolite crystals in each FDI during the hydraulic fracturing process. Working fluid flowing through an FDI during circulation transports zeolite crystals from the FDI into the production well to be detected at the surface where mineralogical analysis enables identification of the specific fracture contributing to flow. In other words, an active mobilizes its associated zeolites particles.

Inexpensive commercial engineered zeolites exist as particles containing crystals composed mainly of silica and aluminum. The University of Houston can synthesize particles less than 300 nm in diameter, much smaller than pore diameters found in proppants used for geothermal well hydraulic fractures

3. ZEOLITE TRACER PLACEMENT

A limitation of injection-well tracer deployment is the limited control over tracer placement, temperature stability and transport properties (Spitzmüller et al., 2024). Tracers introduced at the injection well may preferentially follow dominant flow paths, potentially bypassing secondary or weakly conductive fractures and thereby underrepresenting their contribution, and their particles may disperse broadly within the fracture network. For solid tracers, additional uncertainty arises from particle retention or filtration within fractures near the injection well, which can reduce recovery efficiency and complicate quantitative interpretation and detection.

To maximize the likelihood that the geothermal working fluid will transport zeolite particles from a given FDI into the horizontal well, the nanoparticles should be placed as near the production well as possible. This minimizes the distance the particles must flow through a porous medium. Evidence shows that flow from propped injection well hydraulic fracture(s) likely passes through an unpropped natural fracture network before reaching propped production well fracture(s). Zeolite nanoparticles placed in an injection well fracture would have to flow through a complex unpropped fracture network to reach production well fractures. Therefore, zeolite particles should only be placed in production well fractures.

The model by (Zhang et al., 2017) considers a tail-in process to refill the proppant free zone caused by overflushing (McLennan et al., 2025) in the hydraulic fracture treatment. They advocate injection large diameter proppant during the tail-in process, which remains mainly near the horizontal well. **Error! Reference source not found.** (b) and (d) shows the location of tail-in proppant when injected after overflushing. Mixing zeolite markers with the tail-in proppant could increase the likelihood of their placement near the production well.

Tail-in proppant sized at 0.8 mm (20/40 mesh), as modeled by (Zhang et al., 2017), has much larger size than zeolite particles with size ~ 0.3 mm, much smaller than typical formation fines. Assuming 30% porosity, a proppant free zone radius of 10 m would require ~ 1200 kg (88,000 lbm) tail-in proppant for a fracture width of 0.0254 m (0.1 in). As an example, mixing 1 % by weight zeolite would require 1.2 kg of zeolite.

Interestingly, (Hendricks et al., 2025) have shown successful detection of nanoparticle tracers placed in perforations. They do not indicate what nanoparticle substances were used and do not indicate the detection analysis mechanism, but they do mention that their nanoparticle tracer applications include EGS wells. We initially evaluated the possibility of deploying zeolite within the hydraulic fracture itself by injecting them the tail-in proppant stage. The idea was to allow zeolite to occupy the void space left after overflushing. These studies encourage continued work with engineered zeolites as nanoparticle tracers and that placing zeolites in injection well perforations could enable their detection to indicate through which fracture stages flow occurs.

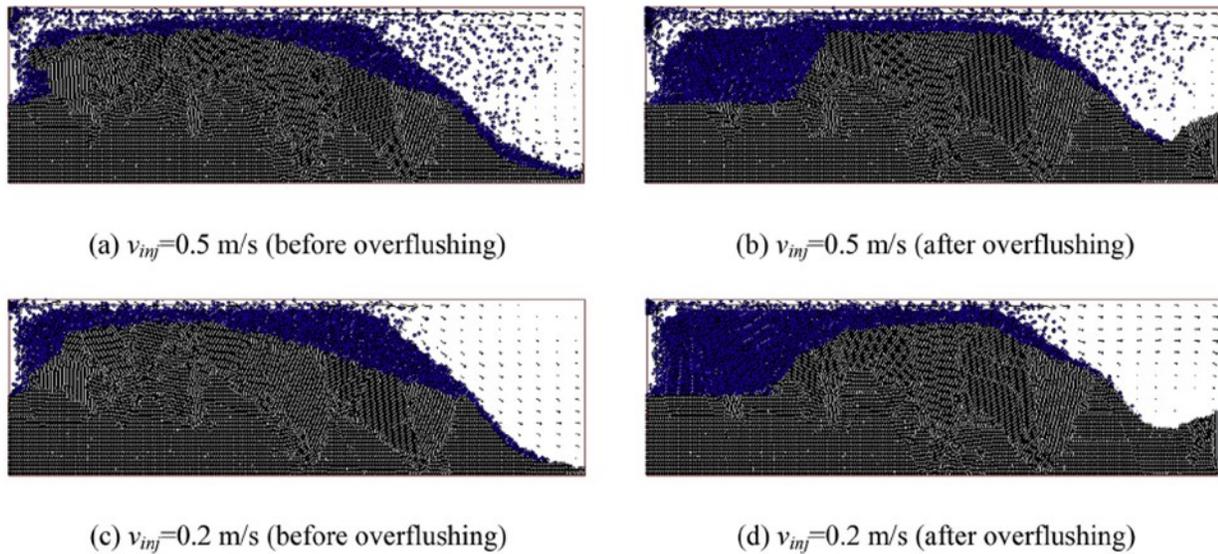


Figure 5: Simulation of tail-in proppant placement in a hydraulic fracture from a horizontal well (Zhang et al., 2017)

4. ZEOLITE NANOPARTICLE TRANSPORT

The work by (Hendricks et al., 2025) strongly suggests trying their approach to place nanoparticle tracers in perforations. They report detecting and distinguishing nanoparticle tracers from multiple stages at concentrations as low as 0.04 parts per billion (ppb) from fracture flowback fluids that continued to be detectable for some days even after formation fluid production starts. Results are best for installing nanoparticle tracers in a 3D-printed charge ring installed in the perforation. In contrast to 0.25 g per charge incorporated into perforating charge liners, the 3D-printed charge rings contain 1.3 g per charge. Their reported results indicate that nanoparticle tracers placed in perforations are workable for the EGS application. There are several technologies related to placing nanoparticle tracers into perforation tunnels (Shokavov et al., 2025; Chen et al., 2022).

During flowback from a hydraulic fracture created in a productive reservoir, the formation closes on the hydraulic fracture as the fracturing fluid expands while the pressure drops from fracture propagation to a pressure governed by the column of flowing fluid in the well. Operators may continue to flow a production well until all or most of the injected fracturing fluid flows to the surface. The fraction of injected fracturing fluid that flows back to the surface is called load recovery.

Flowback in EGS wells will not include significant production of formation fluid because there is negligible producible formation fluid in a hot dry rock formation. Instead, (Jones et al., 2023) observed that the production rate during flowback from fractures in the Utah FORGE production well declined exponentially from a maximum rate of nearly 200 gpm (1080 bpd) as increasing concentrations of Na, K, Ca, Mg, B, SiO₂, Cl, SO₄, and HCO₃ increase over time (Simmons et al., 2025). Following flowback circulated working fluid reached a production rate of ~ 10 bph (240 bpd).

By way of comparison, (Hendricks et al., 2025) reported an initial flowback rate of 1000 bpd in one field test and 1300 bpd in a second field test. They concluded that placing more nanoparticles in the charge resulted in greater tracer recovery. The reported field test wells with many more stages with 8 or more perforation clusters per stage were much like wells being developed for EGS by Fervo Energy than like the Utah FORGE project wells.

4. ZEOLITE TRACER DETECTION

Eight commercial zeolites suitable for the envisioned tracers include MFI (ZSM-5), MOR (mordenite), BEA (beta), FER (ferrierite), CHA (SSZ-13), FAU (13X), LTA (zeolite A), and LTL (zeolite L). Four zeolites that are straightforward and cost effective to synthesize include EMT, GIS, MER, ANA, and others. Each of these zeolites are easily detected using XRD, and they have easily distinguishable XRD signatures. Therefore, X-ray Diffraction analysis of a sample acquired at the surface from produced working fluid will enable their detection.

Figure 6 illustrates the signature of the synthesized sodalite nanozeolite, highlighting its characteristic peaks and crystal structure. The Scanning Electron Microscopy (SEM) image of the crystalline phase reveals the morphology of the obtained crystals, while XRD analysis provides the corresponding powder diffraction pattern.

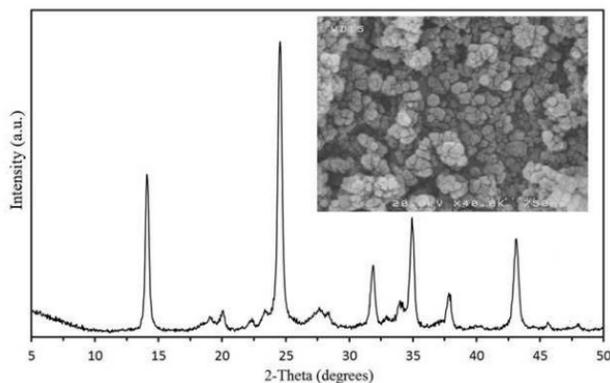


Figure 6. Distinct XRD signature of the synthesized sodalite nanozeolite. (Hassaninejad-Darzi and Yousefi, 2015)

All of these engineered zeolites are known to be stable at higher temperature and pressure than encountered in geothermal well applications in hydrocarbon mixtures. However, because typical uses for the listed zeolites do not involve water, it is important to consider their stability in water. These zeolites are subject to dealumination, but typically neither dealumination nor temperature significantly alters their crystalline structure because the Al exits spaces in the crystal and not the crystal lattice. At acidic conditions with pH below 4-5, crystal framework Al may leach out and alter the crystalline structure. Likewise, strongly alkaline conditions with pH more than 12-13 can result in desilication that alters the zeolite crystalline structure.

Constituents reported by (Simmons et al., 2025) in produced water circulated in the Utah FORGE well include Na, K, Ca, Mg, B, SiO₂, Cl, SO₄, and HCO₃. They also report the pH of the produced water, which ranges from 5.99 to 7.83 when including also flowback data. This pH range should not alter the crystalline structure of the zeolites.

(Jones et al., 2024) observed minerals including actinolite, epidote, albite, quartz, carbonate, anhydrite, illite, chlorite, kaolinite, SiO₂, and halite in cuttings and core from drilling of Utah Forge. Possibly produced water could contain formation rock or proppant particles. However, zeolite XRD signatures are clearly distinct from any of these minerals. In particular, all of the zeolite crystals show many, closely spaced, symmetrical peaks reflecting their large cages and channels.

Produced fluid sampling for XRD detection of zeolite nanoparticles offers special challenges. Their low likely concentration in produced fluid (Hendricks et al., 2025) will require careful sample processing to collect produced solids, which may include proppant and formation fragments. To be detectable with XRD, a given zeolite tracer must comprise at least 3-5% by mass of the resulting produced solids, and the total produced mass to be analyzed should be several milligrams, which would require a more than 10,000-liter (> 60 bbl) production sample.

Mass spectroscopy is an alternative approach to zeolite detection that might be achieved without taking samples of the produced fluid. However, a different set of zeolites containing metals would be needed for this approach. Metals in zeolite crystals are lodged in spaces within the crystal framework and typically are not part of the crystal lattice, and many metals could work for this purpose. However, because they are not part of the crystal framework, they are subject to ion exchange mechanisms that would introduce considerable detection uncertainty.

The idea to use zeolites as producible tracers is novel and shows considerable promise. This allows us to move from bulk connectivity assessment to fracture-level flow discrimination. In essence, each fracture is given its own fingerprint. In particular, the ICP-MS analysis would be required to detect engineered zeolite nanoparticle tracers at the low concentrations reported by (Hendricks et al., 2025) that make XRD detection infeasible. However, applicable zeolite tracers are limited due to constraints such as degradation, sorption and/or retention of the tracer molecules. There is a need for new zeolites types to overcome these issues. Fortunately, 253 unique zeolite frameworks have been identified and officially recognized by the International Zeolite Association (IZA) Structure Commission (IZA-SC), providing a broad structural foundation for the development of advanced zeolitic materials.

5. CONCLUSIONS

Successful field demonstrations of nanoparticle tracers do not specify the tracer material used. Engineered zeolites offer a wide variety of commercially available nanoparticle substances that are known to be stable under high temperature and pressure applications common in chemical processing and that are easily detected in sufficient quantities using XRD analysis. Their stability in brine at high temperature and pressure is critical to EGS using brine as a circulating fluid.

Addressing these limitations does not necessarily require the development of entirely new zeolite types, but rather a systematic assessment of existing frameworks. The 253 unique zeolite structures officially recognized by the International Zeolite Association (IZA) Structure Commission (IZA-SC) represent a valuable platform for evaluating characteristic values and properties associated with zeolite tracers degradation, retention, and sorption.

This work concludes that some engineered zeolites may be workable as nanoparticle tracers in EGS applications, but their concentrations in produced fluids will be too low to enable XRD analysis. However, a key practical limitation is detection sensitivity: XRD requires a high mass concentration, and this limitation reinforces the need for controlled tracer placement at the wellbore rather than within the fracture network. We recommend placing the zeolite tracers in 3D-printed perforation charge rings in production wells provided they are cost effective compared to other proven nanoparticle tracer options.

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