Introduction to this special section: Geophysical applications to geothermal exploration and development

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The three geothermal papers included in this issue's special section present research on microseismic monitoring technologies that have been identified as critical to the development of enhanced geothermal systems (EGS). Recent investments in EGS projects in the U.S. Basin and Range (B&R) geologic province have adapted plug-and-perf stimulation and proppant technology developed in the oil industry to produce hot water from low-permeability metamorphic and granitic rocks where temperatures greater than 200°C can be found at less than 3000 m depth adjacent to existing conventional permeable geothermal reservoirs.

Figure 1. A view of the Utah FORGE geothermal site and operations during groundbreaking April 2024 EGS stimulation and circulation. Photo courtesy of Utah FORGE and Eric Larson (Flash Point SLC).

To support the production rates of hot water needed to economically generate electricity from the 130°C to 230°C reservoirs found in the B&R, conventional geothermal systems require very high natural permeability associated with complex fault geometry. Hot water production from a single commercial geothermal well typically ranges from 40 to 160 l/s (30,000 to 120,000 bpd) to support electricity generation of 2 to 12 MWe. Unlike the rapid harmonic decline expected in oil production over a couple of years, decline in hot water production from a B&R geothermal well is expected to be small over 30 years, although decline in temperature will be significant. Because sites with such extraordinary permeability and capacity are rare, extending geothermal production to low-permeability rocks using EGS greatly increases opportunities for geothermal development.

Since 2022, the U.S. Department of Energy's (DOE's) FORGE EGS research project (Figure 1) and Fervo's Cape Modern EGS commercial project, both adjacent to the conventional Blundell Geothermal Field in Utah, have demonstrated a significant reduction in the cost of drilling and stimulation in impermeable granitic rocks. The initial extended well test at Cape Modern in August 2024 indicated a stable production rate of 110 l/s (80,000 bpd) at 195°C, capable of supporting about 9 MWe generation.

For decades, microseismic monitoring has been a routine best practice at many conventional geothermal reservoirs to manage the injection of the cooled produced water (and sometimes supplementary water) that supports reservoir pressure. Microseismic data are used to characterize the base of the reservoir where cold injected water is heated, detect short-circuiting of cold injection directly to production wells, and mitigate nuisance seismicity. Microseismic monitoring has similar long-term applications in EGS, but it has a more immediate role during the stimulation phase of EGS when patterns of microseismic locations and strain detected by downhole geophones and distributed acoustic sensing (DAS) systems define the initial reservoir geometry. Long-term microseismic monitoring is expected to validate the thermoelastic modeling that predicts how thermally induced stress and strain will dynamically change the EGS reservoir volume, permeability, and fluid flow paths through the 30-year expected life of the reservoir.

McLennan at al. summarize the geophysical components of the DOE FORGE project directed at advancing the technologies required for EGS. In addition to investigating drilling, stimulation, and production optimization, the DOE has sponsored tests of geophysics methods with a focus on surface geophone and nodal arrays and downhole geophone and DAS arrays. Although the downhole DAS arrays will provide the initial

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constraints on reservoir geometry, the surface and shallow geophone and nodal arrays are likely to become increasingly important to long-term reservoir performance monitoring because, at expected EGS temperatures of 150°C to 230°C, current DAS borehole systems have a predicted service life much shorter than the planned 30-year duration of the geothermal production and injection wells.

Park et al. describe velocity analyses from the surface to the reservoir zone that will be especially relevant to characterizing microseismic patterns based on surface and shallow borehole geophone arrays. In this study, successive updates of an initial seismic velocity model are completed, first using 3D traveltime tomography from first arrival picks of 3D surface seismic data, then with 2D traveltime tomography of downhole DAS vertical seismic profiling (VSP) data acquired in wells at the FORGE EGS project, and finally with 2D acoustic full-waveform inversion (FWI) using the same DAS VSP data. This shows that FWI should be considered as a potential option to supplement the conventional traveltime tomography analyses routinely used to derive seismic velocity models for microseismic monitoring of geothermal developments.

Nakata et al. review machine learning (ML) methods potentially applicable to the various stages of microseismic monitoring. The first application focuses on using a Swin transformer to fill the gaps in data of a closely spaced square array of seismometers at the FORGE EGS project. A conditional generative modeling approach is applied to a similar waveform analysis of more widely spaced but lower noise seismic stations at the Geysers geothermal field. ML phase pickers perform well for regional earthquake monitoring systems but have been less consistent for local arrays. Thus, a new ML approach to phase picking using an encoder-decoder approach has been implemented on the surface nodal array of closely spaced seismometers at the Cape Modern EGS project. Finally, a clustering analysis based on power spectral densities of more than 2500 well-located seismic events recorded at the FORGE EGS project is directed at differentiating shear, mixed, compressive, and tensile fracture mechanisms. This broad range of potential applications is a snapshot of opportunities for addressing the needs of the rapidly evolving EGS industry using rapidly evolving ML technology.

Geothermal energy is entering a new phase of development roughly analogous to the oil and gas transition to perf-and-prop technology two decades ago. However, the more demanding geothermal requirements for performance and longevity require extended and new geophysical tools to identify and optimize the new reservoirs to provide sustained energy generation to the world. TLE