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Review of Conventional System and EGS Exploration Approaches and Success Drivers

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INTRODUCTION

Traditional exploration for conventional systems considers:

- Surface mapping of **Heat Anomalies**; the most obvious being evidence of surface thermal activity (hot springs, steam vents, fumaroles, sinter).
- **Geology** mapping including regional and local structural setting.
- **Geochemistry** assuming there are surface thermal features to sample.
- **Geophysics** to seek deeper signals for presence of thermal fluids and hydrothermal alteration; resistivity, magnetics, gravity and InSAR.
- Geophysics to interpret the heat source; deep resistivity, gravity, seismic (melts).
- **Exploration Well Drilling** to refine the system conceptual model.

Blind/Hidden conventional system exploration using Play Fairway Analysis (PFA):

- PFA for geothermal is adapted from original use for O&G exploration.
- Based on the favorable intersection of heat, (sufficiently high) permeability, seal (cap) and fluid characteristics.
- Not as applicable to low temperature geothermal or EGS according to NREL (2023).
- Exploration well drilling to then refine the system conceptual model.

Exploration for EGS considers:

- EGS also requires the intersection of heat, (sufficiently low) permeability, seal/cap and fluid characteristics (groundwater) .
- Many of the same exploration approaches still apply, although their relative importance shifts.
- Ground truthing with exploration well drilling also still required.

REVIEW

Exploration Aspect	Exploration Approach	Conventional Success Drivers	EGS Success Drivers
Heat / Thermal Anomaly	**Regional heat flow maps** **Surface feature mapping** e.g., hot springs, steam vents, fumaroles, sinters. **Evidence for recent volcanic activity** **Elevated groundwater temperatures**	Presence indicates subsurface high heat flow and fluid bearing formations or fault structures. Provides opportunity to determine resource potential geometry, assess temperature of fluid origin and likely reservoir chemistry.	Background heat flow alone is not currently sufficient to allow economic development of EGS. Therefore, there is a need, like hydrothermal systems, for high heat flow to allow EGS development at economic drilling depths. Conductive heat flow is desired. Evidence of surface features are seen as red flag within EGS developments as they suggest existing high permeability pathways for fluid movement. Convective systems are not desired in EGS, although proximity to convective systems may deliver required temperature at economically drilled depths. Most EGS developments to date have been executed adjacent to identified hydrothermal systems e.g. Blundell and FORGE/Cape. Elevated groundwater temperatures still useful if they show conductive heating.
Geology	**Field Mapping and Structural Analysis** Geology mapping including outcrops, fault interpretation, preliminary stress regime assessment, and conceptual model to support initial development of geological model development	Facilitates indications for permeability associated with fault complexes and lithologies with primary permeability at sufficient burial depths to overlap with heat anomalies. Preference for evidence of high natural fracture density, primary permeability and porosity. Typically developed in extensional and strike/slip stress regimes. Although special aquifers in sedimentary basins can offer lower temperature development opportunity.	Facilitates indications for low permeability formation targets and areas with low degree of faulting. Preference for evidence of low-medium natural fracture density to support fracture network development control. Stress regime is also an important consideration for EGS as this will determine the effectiveness of fracture network development. Avoid compressional stress regimes i.e., thrust. Determination of natural fracture orientations and Smax and SHmin to optimize well lateral orientations (Figure 1).
Geochemistry	**Fluid and gas sampling** of surface features where possible followed by exploration well sampling if a drilling campaign proceeds. **Groundwater sampling**	Fluid chemistry is important to further refine the nature of the resource (indications for upflow and outflow areas, mixing with groundwater) and to help consider the management of scaling risks and surface equipment maintenance. Neutral pH, benign chemistry preferred. Many management applications for scaling are industry proven. Groundwater chemistry analysis will support interpretation of the integrity of system cap (i.e., background reservoir fluid leakage), and inform system management strategy to avoid premature cooling, or environmental impacts.	Typically, will not see fluid sampling from the reservoir due to low permeability and deeper system. However, proximity to known hydrothermal systems may be important to find EGS temperatures at economic depths. In addition, groundwater chemistry can be important if it will be used during drilling, stimulation and testing activities as water source requires assessment. Preference for low calcium to avoid deposition during injection, and low silica for plant operations. Core samples from drilling are recommended to enable water-rock lab testing to help understand reservoir scaling risks ahead of system equilibrium.
Geophysics	**Non-invasive geophysics** survey techniques to enhance the conceptual understanding around fluid movement and system architecture.	Resistivity (MT) surveys to indicate presence of fluids, alteration, top of reservoir, deep surveys to interpret heat source (i.e. magma chamber). Magnetics survey as support to alteration indications. Gravity, by looking at density contrasts, to provide insights around reservoir lithology and basement, and any major intrusives for heat source. Seismic, not as common due to the high degree of structural complexity in faulted systems which limits the effectiveness of picking lithologies and structures but can indicate melts due to lower velocities.	Resistivity useful to help delineate basement and overlying sediments. Important when considering preference in EGS for thick overburden as insulating package above target resource. Depth to basement important when considering exploration and development well designs . Gravity for EGS plays similar role to hydrothermal system exploration – basement definition and constraining fault locations (Figure 2). Seismic plays a key role in basin analysis (more typical targets for EGS) where long coherent seismic reflections are more readily interpreted to inform lithology and combined with gravity to constrain fault locations.

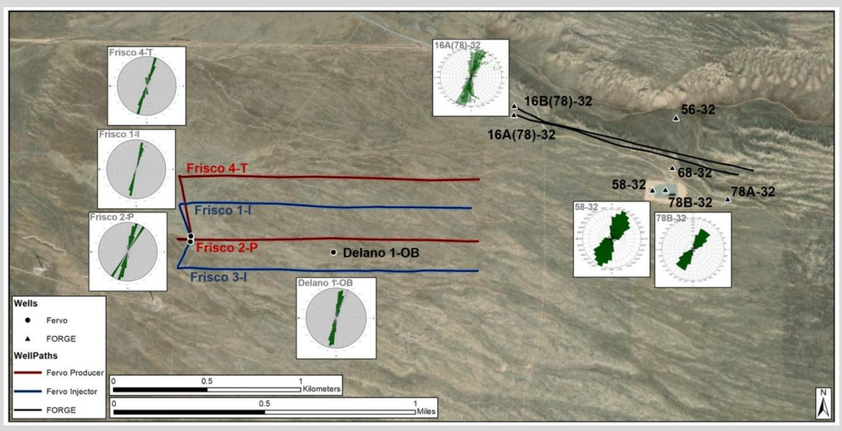


Figure 1. EGS well orientations based on natural fractures (Fercho et al., 2024)

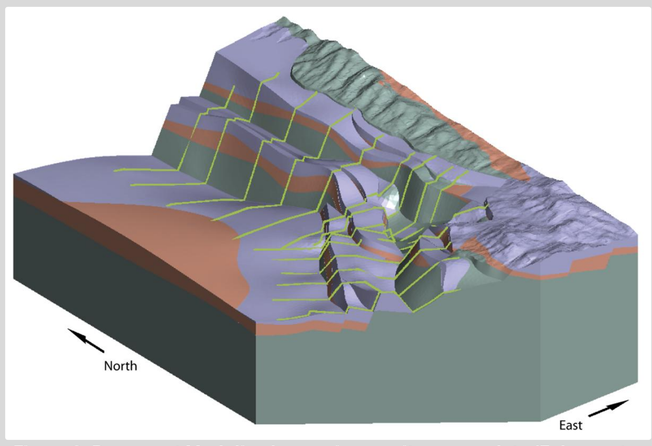


Figure 2. Basement Modeling leveraging gravity survey data (Folsom et al. 2020)

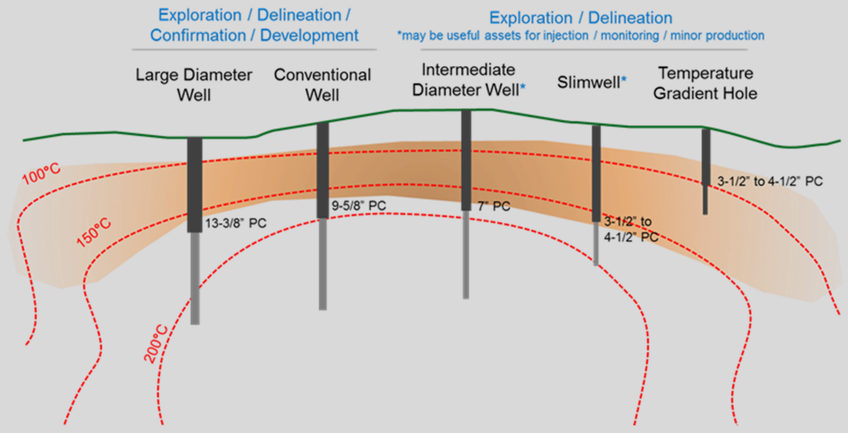


Figure 3. Exploration Well Drilling Options

Exploration Aspect	Exploration Approach	Conventional Success Drivers	EGS Success Drivers
Exploration Well Drilling	**Execute a drilling campaign to prove the conceptual model and test resource size development uncertainty** **Ground truthing of permeability, stress, geomechanics, temperature and chemistry** **Choice of well type:** • Temperature Gradient Hole • Slimhole/Corehole • Intermediate Diameter • Conventional Well • Large Diameter Well	Temperature gradient holes are useful to test shallow thermal anomaly and geophysics interpretations relating to clay caps. More suited to convective resources (Figure 3). Slimholes are a lower cost option designed to intercept the top of the reservoir providing more detailed assessment of conceptual model and can allow resource sampling (cores and fluid/gas) and injectivity/productivity analysis. Their long-term use is typically in the form of monitoring wells or occasionally low-level injection/production. Intermediate, conventional and large diameter wells while carrying greater cost, are often chosen as they offer more opportunity if successful to remain as operating assets. There is often more opportunity for contingency planning like sidetracks and deepening with larger diameter exploration wells. Hydrothermal system exploration well drilling may need more are coverage to derisk the development opportunity – therefore more wells may be needed across the prospect area.	Temperature gradient holes are useful to test shallow thermal anomaly and geophysics interpretations relating to clay caps. Less suited to conductive resources. Slimholes/cored holes are a lower cost option affording EGS projects to test most key development criteria, such depth to target development temperature, lithology, stress regime, rock chemistry (and potential fluid interactions), fracture density, other geomechanical properties. These wells can be valuable as monitoring wells, especially for monitoring stimulation effectiveness and induced seismicity, but won't offer injection or production. As shown with the example of Cape Phase 1 (Figure 4), a smaller resource area may be required compared to an equivalent size hydrothermal system, at least at temperatures of ~200°C. This means resource derisking in EGS could be achieved with fewer exploration wells and smaller diameter given there is no need for flow testing.

EXPLORATION AREA USING POWER DENSITY

Compare Wilmarth (2021) power density (net) and considering production area only with Cape Phase 1

Cape Phase 1 ~80 MWe net (assuming 20% parasitic losses on 100 MWe name plate) covering ~4 km^2 but across 2 benches provides a total of 8 km^2 if using Wilmarth.

=> ~10 MWe / km^2 at ~200°C

But in terms of resource area for 50 MWe project @ 200°C:

- Conventional (Production area only) : ~ 6.5 km^2
- EGS (Cape): ~ 4 km^2

Conventional still needs injection area so this land area could be 50% larger => **direct impact on exploration drilling requirements**

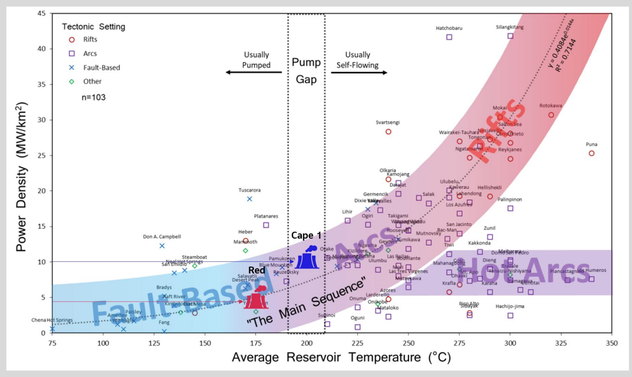


Figure 4. Power Density Cape Phase 1 (adapted from Wilmarth, 2021)

CONCLUSIONS

- Conventional and EGS resource exploration approaches share many similar focus areas and disciplines.
- Critical to understand success drivers of each to determine relative importance and key factor.
- Adjacency of EGS projects to conventional projects is an important consideration when looking for heat anomalies but in basinal settings away from fault structures.
- Exploration drilling programs for conventional geothermal resource likely to require larger areal coverage (Figure 4) to account for lower overall system productivity and reflects the inferred higher power density delivered through EGS projects in the current development temperature range.

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