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Similarities and Differences between Hydrocarbon and Geothermal Resources from a Subsurface Perspective

Introduction

Geothermal energy is heat provided from the Earth. Geothermal resources are commonly reservoirs of hot water or hot rock that exist at varying temperatures and depths below the Earth's surface due to either solar radiation ("shallow geothermal") or heat resulting from the decay of radioactive elements in the Earth's crust, transferred by conduction and / or convection of pore fluids ("deep geothermal").

Geothermal fluids, such as formation water, are mostly present as a liquid phase. However, depending on the depth and temperature, fluids may also consist of a saturated, liquid vapour mix or superheated steam vapour phase. Wells can be drilled to tap into this heated fluid which is then brought to the surface for use in a variety of applications, including electricity generation, and direct heating.

This article discusses how the techniques and methods required for the exploration and development of geothermal resources are similar to those already in use in the E&P sector, and that by transferring data and knowledge from the petroleum industry to the geothermal industry, projects will be optimised.

Status of Geothermal Exploitation

Geothermal resources can be found throughout the world, and are currently utilised in more than 80 countries but are not evenly distributed; geothermal resources (especially high temperature systems which facilitate generation of electricity) tend to be concentrated at geological plate boundaries or mantle hot spots, with certain locations making it easier to access geothermal resources.

In Europe, there were 145 geothermal electricity plants operating at the end of 2021, with a generation capacity of some 3.4 GWe (GigaWatt equivalent)[1], along with 36 projects under development and a further 124 in the planning phase[2].

To access and exploit geothermal resources requires a combination of water, heat and rock permeability in order to be able to extract hot water, or steam to drive turbines that generate electricity. Geothermal systems can occur in diverse geologic settings, sometimes without clear surface manifestations of the underlying resource. Geothermal resource types are often classified by their reservoir temperatures, into low, medium or high enthalpy-types, however, there is no strict classification of how to define a geothermal resource with arbitrary temperature ranges often used (Lee, 1996).

However, the most commonly used (and easily accessed) geothermal resources are hydrothermal (for example, Iceland). This type of resource is geographically limited to areas of recent and dormant volcanic activity and plate boundaries. In essence, these can be exploited using techniques that are considered normal oilfield processes, such as horizontal drilling, hydraulic fracturing etc. But recent advances in both drilling and logging technology have meant that data acquisition from wells with bottom-hole temperatures in excess of 300°C are now possible. As highlighted in a case study from 2020, Baker Hughes drilled the deepest, hottest geothermal well in Iceland. The well reached a total depth of 4,659 m, with the highest temperatures measured reaching 426°C. Key technologies of the new roller cone bit employed at these extreme conditions include all-metal cone seals, all-metal bellows for grease pressure compensator, and a new grease that maintains lubricity at high temperatures. In order to protect the MWD equipment, engineers developed an active, high-temperature downhole cooling system. Continuous pumping of fresh sea water also helped to significantly lower the downhole temperatures while drilling.

The advance of technology over recent years has led to other types of geothermal resources, namely Enhanced or Engineered Geothermal Systems (EGS)[3] and advanced geothermal systems. The EGS concept extracts heat from deep geothermal systems by encountering and / or creating a subsurface fracture system in hot rocks into which water can be injected and recovered by other wells. Advanced geothermal systems use a closed-loop system to extract heat from the subsurface, using single or multiple connected wells, which utilise geothermal energy without the need for continued access to local water resources. Again, standard oilfield practices can be used with fracturing and horizontal drilling utilised in support of such advanced systems.

Hot aqueous fluids are commonly a by-product of many oil and gas wells. Generally, this stream is an inconvenience and a disposal issue, however there is early-stage evaluation for such fluids to be used as a heat resource to produce electricity for field use or be sold off to the grid[4]. As reported in May 2022, Petrofac New Energy Services are going to support deep geothermal specialist, CeraPhi Energy, in a first of its kind trial to repurpose oil and gas wells in the North Sea for geothermal energy. A closed loop technology will be fitted into old wells at EnQuest's Magnus Platform to extract heat from the subsurface by a downhole heat exchanger. Pending the outcome, the heat could provide a direct power source and/or heating and cooling utilities amongst other services. Going forward, this may allow existing petroleum infrastructure to be repurposed as a geothermal project once the oil or gas field has reached the end of its economic life.

Exploration for geothermal resources is one of the key costs in geothermal developments. The exploration phase, similarly to the oil and gas industry requires a multi disciplinary subsurface approach, involving geological, geophysical, petrophysical, and geochemical techniques. Many of which are commonly used in the oil and gas industry, and can easily be transferred to geothermal projects.

[1] *European Geothermal Energy Council.*
[2] *Sedimentary basins are expected to be the dominant in the locations of CCS projects.*
[3] *U.S. Department of Energy – Geothermal Technologies Office.*
[4] *There are "demonstration projects" e.g. Wyoming (Rocky Mountain Oilfield Testing Centre) utilising co-produced fluids (water as by-product of O&G wells) for geothermal power generation.*

Geothermal Resource Settings

In hydrocarbon exploration, a play-based approach is commonly used, where basin evaluation allows an understanding of petroleum systems to be developed, and consolidates leads, prospects, and already discovered hydrocarbon accumulations into plays. Play evaluation improves the understanding of prospect risk and in-place volumes of hydrocarbons. In recent years, authors (for example Moeck 2014, Moeck & Beardsmore 2014, Moeck et al. 2020) have proposed a similar approach in exploration for geothermal resources. This article likewise highlights similarities and differences between the play-based approach for quantifying and risking of hydrocarbon and geothermal resources, and reporting thereof.

As context for the respective plays, petroleum and geothermal systems can be similarly defined with regards to tectonic setting. A description of sedimentary basins based on tectonic settings assists in understanding petroleum and geothermal prospectivity. There are many parallels between basins that are prospective for hydrocarbons and geothermal resources. Table 1 provides a summary of the main tectonic settings and their importance for geothermal and hydrocarbon exploration activities.

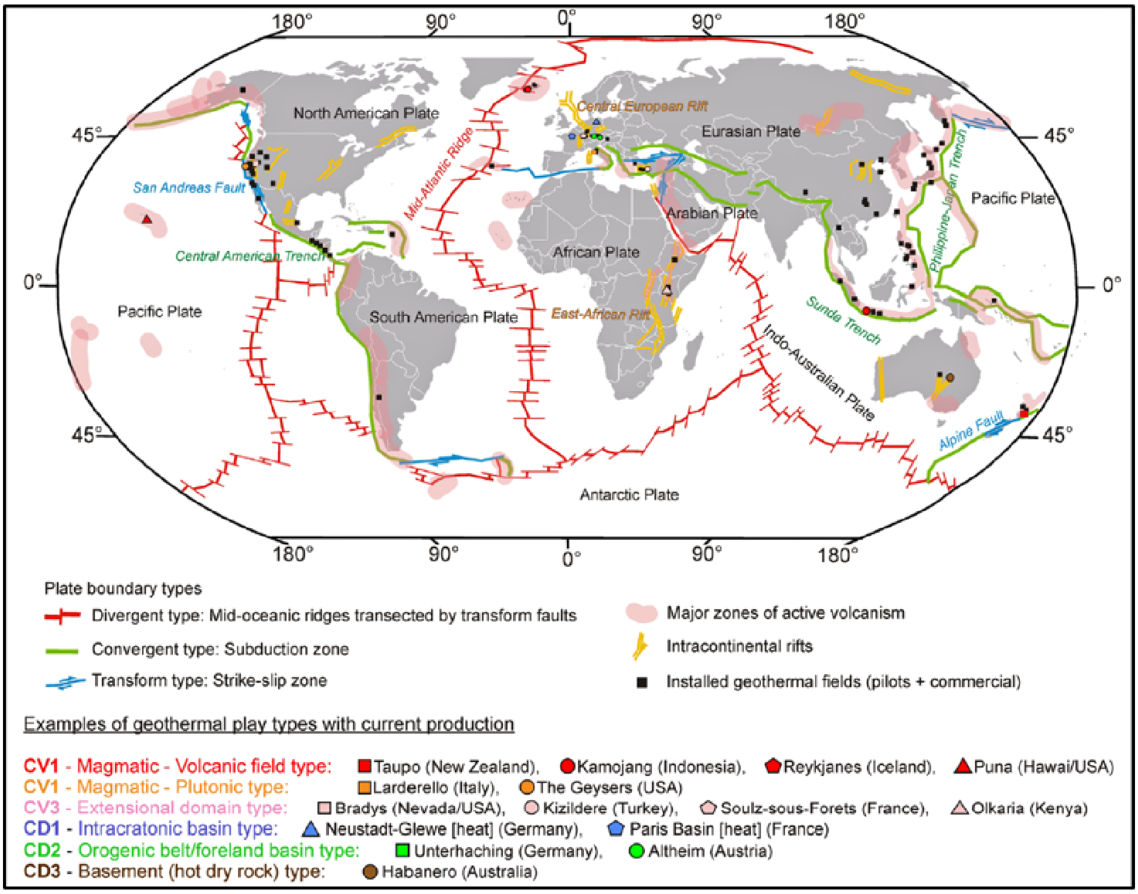
Table 1: Comparison of Different Tectonic Settings and Their Prospectivity

Sedimentary	Hydrocarbons	Geothermal	Prospectivity
Intra-Cratonic Sag	Small oil and gas fields; Generally not a major hydrocarbon province, with exceptions such as for example Williston and Illizi Basin	Geothermal developments for heat production, such as for example Paris Basin (France)	Moderate for both hydrocarbons and geothermal resources
Rift Basins, including failed rift basin (aulacogen)	Excellent; examples include Gulf of Suez (Egypt), Gulf of Thailand	Conduction or convection dominated; low to high enthalpy developments, such as North German Basin	Excellent for hydrocarbons; good for geothermal resources
Epicratonic Embayments	Giant oil and gas fields; examples are Mississippi and Niger Deltas, Sirte embayment	No known geothermal developments; there are trials using existing oil/gas wells to recover geothermal energy	Excellent for hydrocarbons; no standalone geothermal projects known at time of writing
Orogenic Belts (fold and thrust belts, foreland basins…)	Prolific oil and gas fields, e.g. Zagros Basin	Conduction dominated; moderate enthalpy developments, for example Molasse Basin (South Germany)	Good prospectivity for hydrocarbons; geothermal focus due to new developments in EGS technologies
Back-Arc Basin	Significant hydrocarbon basins, e.g. back-arc basins formed on Sunda Shelf, SE Asia	Convection dominated; high enthalpy developments, such as Sunda Arc (Indonesia) or Philippine-Japan Arc	Good prospectivity for hydrocarbons; excellent for geothermal resources
Fore-Arc Basin	Negligible	Convection dominated; low to high enthalpy developments, such as Kamojang (Indonesia)	Poor prospectivity for hydrocarbons; good prospectivity for geothermal resources
Transtensional (pull-apart) Basins	Important basin type, e.g. West African Transform Margin, Pannonian Basin	Convection dominated; moderate to high enthalpy developments, such as in Western Turkey	Good prospectivity for hydrocarbons and geothermal resources

Source: after Allen & Allen 2005, Moeck 2014, Sorkhabi 2019

In general, we can see potential in all basin types for both hydrocarbons and geothermal resources; one exception are Volcanic Arc (especially Fore-Arc Basins) regions which are excellent areas for geothermal resources but display very poor potential for hydrocarbons. There is a focus for the former on areas with high intrinsic heat flow and active faulting that promotes convective movement of heat. Figure 1 shows examples of geothermal basin types with current production according to plate tectonic setting, showing the predominance of schemes at active plate boundaries.

Figure 1: Geothermal Fields According to Plate Tectonic Setting



Source: Moeck 2014, reproduced under Creative Commons Licence

Play Elements

The different basin types dictate overall prospectivity. For a hydrocarbon play to be prospective all the critical elements such as source, reservoir, seal, trap, migration and favourable timing need to be in place to permit generation and storage of hydrocarbons. Geothermal resources require some of the same factors, but some are distinctly different. Table 2 presents a simplified list of the most common play elements in hydrocarbon and geothermal exploration.

Reservoir and seal (cap rock) mostly share the same characteristics for petroleum and geothermal systems, with reservoirs often characterised by high porosity and/or permeability, and cap rocks by low permeability, associated with low conductivity and barriers to convection.

A main difference between hydrocarbon and geothermal systems is the source. Petroleum source rocks are specific, local organic-rich rocks, but the “heat charge” represents a widespread resource which is focussed to create areas of high geothermal gradient. Both hydrocarbon and geothermal resource assessments require similar temperature information: hydrocarbon basin modelling assessments consider if and when the source rock entered a certain temperature window to generate hydrocarbons, but from a geothermal perspective, it is only the current heat charge that is crucial.

Another main difference is that geothermal systems do not require a trap – a specific reservoir seal geometry controlling the extent of the resource.

Table 2: Comparison of Petroleum and Geothermal System Elements

	Petroleum	Geothermal
Source	Rock that is capable of generating or that has generated movable quantities of hydrocarbons, such as rock rich in organic matter.	Heat charge system, consisting of the heat source and heat transport.
Reservoir	Rock that has the ability to store hydrocarbons in its pores and yield them to the wellbore at commercial rates.	The reservoir unit has to be porous or fractured enough to store thermal fluids and yield them to the wellbore at commercial rates. Enhanced Geothermal Systems (EGS) rely on the reservoir units capability for stimulation treatments, such as fracturing or acidizing.
Seal	Rock that impedes the escape of hydrocarbons from the reservoir rock.	Low permeability or low thermal conductivity unit or fault, trapping thermal fluids or inhibiting conduction and convection. Not always applicable.
Trap	A trap consists of a geometric arrangement between reservoir and seal, allowing hydrocarbons to accumulate.	-
Timing	Timely relationship of the other elements so that, for example, traps are available at the time of charge.	Of minor importance other than to provide succession of reservoir and cap rock.

Source: after Allen & Allen 2005, Moeck & Beardsmore 2014

Petrophysical Properties

The petrophysical properties of the rocks are equally as important in geothermal exploration / exploitation as they are in the oil and gas industry. Common deliverables for both geothermal and hydrocarbon exploration include lithology / mineralogy, porosity, permeability, transmissivity and fracture properties, including intensity, orientation, porosity, dip angle and aperture, all of which can be calculated from well logs. This is significance in both low-enthalpy systems (sedimentary basins, for example, the Paris Basin, France) and high-enthalpy systems (volcanic provinces, for example Iceland and Italy). The required petrophysical output can differ between the two, with more emphasis on matrix properties, such as porosity, permeability and transmissivity, as well as geomechanical properties in low-enthalpy systems, whereas the definition and understanding of fracture networks is more critical in high-enthalpy systems.

Time lapse temperature logging is also required to estimate stabilised geothermal well temperatures. During drilling, temperatures are disturbed by circulation of drilling fluid and cold water injection, temperature profiles can provide insight on aquifer location (feed zones) and their relative size (indicator of permeability). Geomechanical aspects include the stress regime and elastic moduli, as well as borehole shape and stability. Cased-hole logging acquisition is equally as important in order to assess the well casing and cement integrity to ensure safe and permanent well completions.

One critical difference is the availability of well/log data between traditional oil and gas wells and geothermal wells (Janszen, 2022). Data acquisition is often limited compared to that of a typical oil/gas well and therefore uncertainty of the reservoir characterisation can be relatively high compared to oil and gas wells. Optimisation of data acquisition by way of some obligation of acquiring basic datasets may help alleviate any errors in interpretations and aid post-well analyses, whether successful or not. However, low-enthalpy geothermal systems co-exist with areas of hydrocarbon exploration and therefore data from these wells can be used as analogues (or may even be of interest to geothermal exploitation themselves, if the well proved unattractive for hydrocarbon exploitation). More use of legacy oil and gas datasets may open up further opportunities in geothermal exploitation.

Once the petrophysical properties have been estimated, geothermal specific properties such as heat capacity, thermal conductivity, enthalpy change from reservoir to surface, and thermal diffusivity can be derived from empirical curve fitting. These results, along with the reservoir volume ("stored heat"), can then be used to provide an overall assessment of a geothermal prospect's potential as an economic energy source. The techniques applied here are similar to the development of a hydrocarbon reservoir volume.

Geophysical Interpretation

Geothermal systems can be broadly classed as convection or conduction dominated, or 'active' and 'passive', with a further distinction between fault controlled and sedimentary hosted systems, as well as EGS systems, which rely on reservoir stimulation. Consequently, geophysical exploration methods are mainly used to identify fault zones, or thick intervals of porous/permeable sediments. In areas with past exploration for hydrocarbons, legacy data, such as well data and seismic surveys, provide valuable information, with the main features of the basin and basin fill already known. Seismic interpretation together with attribute analysis provides insights into the subsurface away from well control. Coherency analyses highlight areas of potential fault and fracture zones. Acoustic (compressional and shear wave) properties can be investigated with a view towards rock physics and rock deformational properties. High resolution 3D or 4D surveys are likely to provide information on enhanced or potentially enhanced permeability zones within a reservoir. Velocity analysis aids in the identification of porosity, fracturing, changes in lithology, and subsurface pressure regimes. These types of information gathered from seismic allow delineation of the most productive areas for geothermal projects.

Interpretation of gravity and resistivity (magneto-tellurics or electromagnetics) data provides additional input. Variations in the electrical resistivity distribution may indicate high temperature geothermal systems, where for example low resistivity structures are interpreted as hydrothermal alteration zones above a higher resistivity zone, corresponding to rocks at higher temperatures. Electromagnetic methods are also capable of directly measuring the fluid movement in the pore space due to resulting resistivity variations. Whilst non-seismic geophysical methods have the advantage of lower associated costs and establishing a direct relationship with porosity, they are best used in combination with seismic data to enable a more detailed interpretation of the subsurface.

All of the methods mentioned above are commonly used in hydrocarbon exploration and development to describe geological, compositional, and hydraulic conditions.

Geomechanics

High temperatures, large amounts of fluid, and suitable permeability are required to make a site suitable for exploitation of geothermal resources. EGS developments require large fractures to provide sufficient areas for heat exchange. Permeability enhancement cannot be maintained through proppants as solid transport over long distances is difficult. Alternatively, permeability can be increased and maintained by the shear-enhanced self-propping effect, where natural fractures that are already close to sliding are mobilised through the increase in hydraulic pressure and shear zone minerals are removed. As injection-induced deformation occurring at depth can also become perceivable at the surface, it is important to improve the understanding of injection-induced changes to fault stability and to avoid already critically stressed faults during site selection (Vilarrasa et al. 2020). Wei et al. (2019) concluded that induced seismicity is determined by the amount of low permeability faults penetrating the reservoir. For areas where faults are less pervasive, the risk of induced seismicity is reduced.

An understanding of the stress regimes influencing well stability are also key in geothermal exploitation with a concern being the risk of induced seismicity from the injection of cold water into the system. Any induced seismicity is likely to cause major concerns regarding public acceptance and therefore understanding of and correctly calculating rock strength or injection pressures is critical to any geothermal project. Understanding of fault patterns and main stresses is not only important in mitigating surface risks or enhancing reservoir permeability but also plays a major role in drilling. Presence and orientation of fault zones will impact on well planning and directional drilling decisions. Also, as geothermal wells are often drilled as near balanced to minimise formation damage, fracture mechanical studies which integrate core testing and numerical modelling are crucial in securing borehole stability.

Classification

Resource classification is a key element in the characterisation, assessment and development of geothermal energy. There is a need to be able to use and understand consistent terminology, both in the geological nature of a geothermal resource and the practical technological and economic aspects of resource exploitation. Traditional methods, in use since the 1960's, have based the resource estimation on the energy stored in a reservoir and the amount of this energy that can be recovered. More recent, and perhaps advanced methods, base the estimation on an analytical approach, defining the amount of heat transfer between the host rock and the fluid circulating into the reservoir, essentially estimating a "recovery factor". Based on the advances in geothermal technology, the scope of exploitable geothermal resources have developed beyond those used in earlier classifications.

An important consideration is the sustainability of the geothermal resource taking into account the energy stored within the reservoir and the associated thermal and fluid dynamics. From this, reservoir simulation can be considered as an effective method for estimating the sustainable mass flow rate for extraction without compromising the resource base. Franco & Donatini (2017), outline methods for estimating geothermal energy potential depending on data availability (Table 3).

Table 3: Methods for Estimating the Energy Potential of a Geothermal Resource

Methods without Production Data	Methods with Production Data
Heat Flow	Lumped Parameter Models
Areal Analogy	Decline Curve Analysis
Volumetric Methods	Numerical Reservoir Simulation

Source: Franco & Donatini, 2017

In hydrocarbon resource estimation, internationally defined guideline systems are in place for consistent and reliable definition of classification and estimation of resources, an example being the Petroleum Resource Management System (PRMS). Currently, there does not seem to be a similar global system for the geothermal sector, with local or national systems in place at a state or country level. The United Nations have defined a framework classification based on the UNFC-2009 to Geothermal Energy Resources, with three major categories (E, F and G), which appear, at least in part, comparable in approach to that of the PRMS, with the main classification categories related to defined projects. The UNFC framework is geared towards classifying resources for single projects only, therefore for reporting at a national or corporate level, the projects would need to be aggregated.

The lack of a coherent and internationally recognised resource management system, as well as a clearly defined way for the estimation of geothermal resources, makes the comparison of projects worldwide difficult, if not impossible, limiting portfolio ranking and asset valuation within a company.

Conclusion

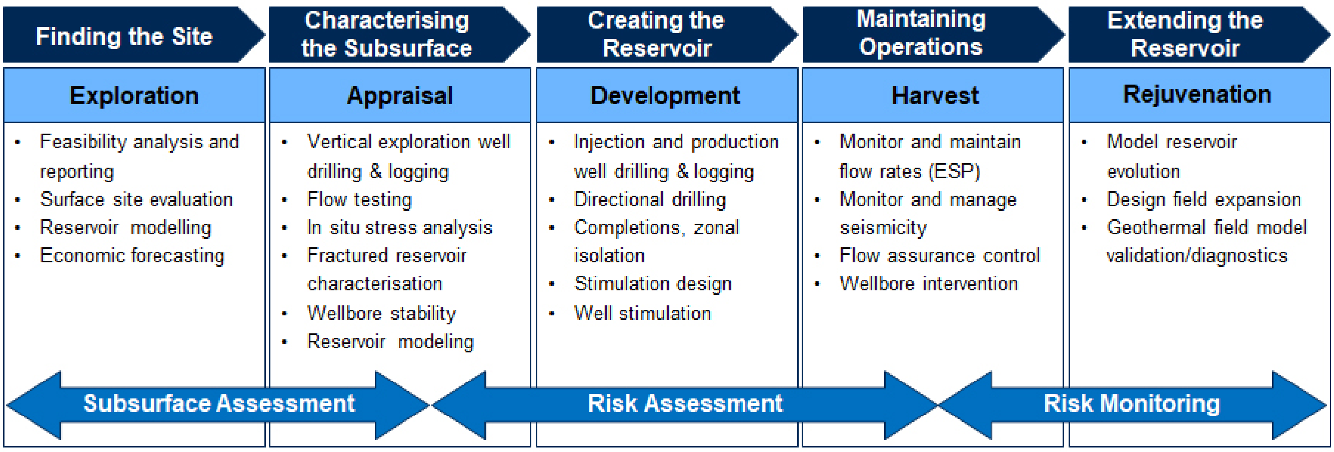
Geothermal and hydrocarbon resources are sufficiently similar to allow analogous subsurface assessment methodologies to be used throughout project maturation, whereby geothermal projects could benefit from transferred experience from the hydrocarbon sector. Geothermal projects are also likely to experience similar challenges related to engineering and project management disciplines as those witnessed in the hydrocarbon sector, thus these skills would also be transferrable to the geothermal industry, whereby transferring knowledge between the two industries can only be beneficial in terms of optimising a project's lifecycle.

The requirement of a multi-disciplinary subsurface team, involving geological, geophysical, geochemical, petrophysical and geomechanical techniques are a key component in both hydrocarbon and geothermal exploration:

- The similarities between basins that are prospective for both hydrocarbons and geothermal resources include the storage and flow capacity of the reservoir(s). Reservoir and seal properties share many of the same characteristics in both hydrocarbon and geothermal systems, whereas the source and trap are areas where there are less synergies. These differences will determine the detail of exploration workflows.
- Geophysical methods to describe geological, compositional and hydraulic components to help define a geothermal resource are methods commonly used in hydrocarbon exploration.
- Minimal log data are generally acquired in geothermal wells, therefore uncertainty in reservoir characterisation is often much higher than in oil/gas wells, with an emphasis of using oil/gas wells as analogues.
- Understanding of the geomechanical aspects of the reservoir is key, influencing wellbore stability and understanding stress regimes and the risk of induced seismicity from cold water injection.

Some of the principles applied in hydrocarbon exploration and development have already been adapted for geothermal resources. However, there is no universally accepted, standardised regulatory framework when it comes to estimating and reporting geothermal resources, similar to the PRMS in the oil and gas industry. As the amount of geothermal projects has been increasing over recent years and with geothermal resources likely to become more important in years to come, formalised reporting and auditing will become inevitable in order to address legal as well as commercial aspects.

GaffneyCline's team of subsurface, surface and commercial professionals are able to perform integrated reservoir characterisation, production and facilities studies in addition to providing commercial and strategic advice to the geothermal sector.



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