Subsurface Characterization for Evaluating Geothermal Resource Potential from Existing Oil and Gas Wells in Tuttle, Oklahoma

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Hyunjun Oh,[1] Sertac Akar,[1] Estefanny Davalos Elizondo,[1]
Cesar Vivas,[2] and Saeed Salehi[2]

1 National Renewable Energy Laboratory
2 University of Oklahoma

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National Renewable Energy Laboratory
15013 Denver West Parkway
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Subsurface Characterization for Evaluating Geothermal Resource Potential from Existing Oil and Gas Wells in Tuttle, Oklahoma

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[1]National Renewable Energy Laboratory, Golden, Colorado

[2]Mewbourne School of Petroleum and Geological Engineering, University of Oklahoma

Keywords

Geothermal energy, subsurface characterization, geothermal resource assessment, hydro geochemistry, geothermometer, repurposing oil and gas wells

ABSTRACT

Oil and gas (O&G) wells often encounter co-produced hot water, possibly suitable for geothermal direct-use applications. The City of Tuttle is located on the eastern part of the Anadarko sedimentary basin in Oklahoma with high heat-in-place potential and recovery capability at depth. This study aims at demonstrating the potential of geothermal energy production for direct-use applications in two public schools and 250 nearby houses in Tuttle via repurposing existing O&G wells. In this scope, geochemistry, geology, and borehole log data were collected and incorporated into a 3D conceptual subsurface model. A digital elevation model (DEM) was used to represent the study area topography with four O&G wells. In addition, hydrogeochemical characteristics of the geothermal fluid and scaling potential were analyzed using ternary diagrams and chemical ratios to develop mixing models. The subsurface geology model indicated that the study area primarily consists of Permian to Mississippian Sandstone and Limestone formations, implying a porosity ranging between 12% and 22%, and a permeability up to 3.90E-14 m^2 in certain reservoir levels. The reservoir temperature is expected to be ranging between 80°C to 95°C around 3 km depth with an average temperature gradient of 22.8 °C/km. Chemical geothermometers also estimated the reservoir temperature as 90°C. Findings of the chemical model demonstrated that the geothermal fluid is Sodium-Potassium-Chloride-Sulfate type and possibly mixed with shallow groundwater resulting in higher Ca and Mg concentrations and lower Na/K ratio implying lower calcite scaling. These results comprehensively characterize the potential of geothermal resources in the study area and imply that geothermal energy production by repurposing existing O&G wells is suitable for low-temperature direct-use applications.

1. Introduction

According to the U.S. Energy Information Administration (EIA), the Oklahoma hydrocarbon field, including the Anadarko basin, has been exploited for over a century to produce oil and gas (O&G), and Oklahoma was the nation's fifth-largest producer of marketed natural gas and the sixth-largest producer of crude oil in 2021 (EIA, 2022). The EIA also reported about 40,000 natural gas producing wells in Oklahoma in 2020. In addition to the EIA's report, O&G Conservation at

Oklahoma Corporation Commission (OCC) identified that Oklahoma has more than 443,000 O&G wells, including plugged, temporarily abandoned, and terminated wells, at a broad range of depths. Due to the Earth's internal heat (e.g., heat generated from decay of naturally occurring radioactive elements, magma chamber, and latent heat from crystallization of molten outer core) and crustal heat flow, ground temperature increases with depth, and thus the O&G wells often encounter co-produced hot water possibly suitable for various geothermal direct-use applications, such as heating and cooling in residential and commercial buildings, schools, and greenhouses. Previous studies (e.g., Bu et al., 2012; Caulk and Tomac, 2017; Nian and Cheng, 2018; Kurnia et al., 2021) described that repurposing of existing O&G wells for geothermal energy production is feasible, without drillings, at lower cost and seismic risk than conventional enhanced geothermal system (EGS) and borehole heat exchanger (BHE). Particularly, deep sedimentary layers at depths of 2.5 km to 4 km with normal geothermal temperature gradients (e.g., 30 °C/km) can be exploited for low-temperature energy conversion systems without hydraulic fracturing (DiPippo, 2012).

As O&G wells have been drilled, regardless of the subsurface temperature, mostly into sedimentary basins where geothermal resources may be limited (e.g., hot rocks at accessible depths), certain conditions are needed to convert existing O&G wells to geothermal wells. For example, the Department of Energy (DOE)'s *GeoVision* study described that the geothermal reservoir requires a large volume with distributed fractures for the geothermal energy production over long periods (i.e., relatively lower energy density of hot water), while the O&G reservoir volume is limited around the boreholes for O&G production in relatively shorter periods (i.e., high energy density of hydrocarbons) (DOE, 2019). In addition, the wellbores repurposed for geothermal energy production should have sufficient depths, specifically with a minimum depth of 2.4 km to 3 km depending on the geothermal gradient and geological formations (Bu et al., 2012; Cheng et al., 2014). To ensure high outlet temperature from the O&G wells for heating applications, additional top boiler and insulations are also suggested by Kujawa et al. (2005) and Gharibi et al. (2018), respectively. Furthermore, the repurposed geothermal wells should be close to the end users to minimize heat losses from the distribution pipes (Kurnia et al., 2021).

The OCC Oil and Gas Conservation demonstrated that there are more than 100 O&G wells in Tuttle, Oklahoma, with bottomhole depths approximately from 1 km to 3.5 km. In other words, the O&G wells in the Tuttle area may have the potential of geothermal energy production from relatively deeper bottomhole depths to possible end-users at a close distance, as well as economic benefits from 'no drilling'. In this study, subsurface geochemistry, formation, and temperature distribution in southern Tuttle were characterized to demonstrate the feasibility of geothermal energy production from existing O&G wells for direct-use applications in nearby primary and secondary schools and 250 houses. Four wells with bottomhole depths from about 3.3 km to 3.6 km and a close distance approximately one mile away from the elementary school were selected for this study (Figure 1).

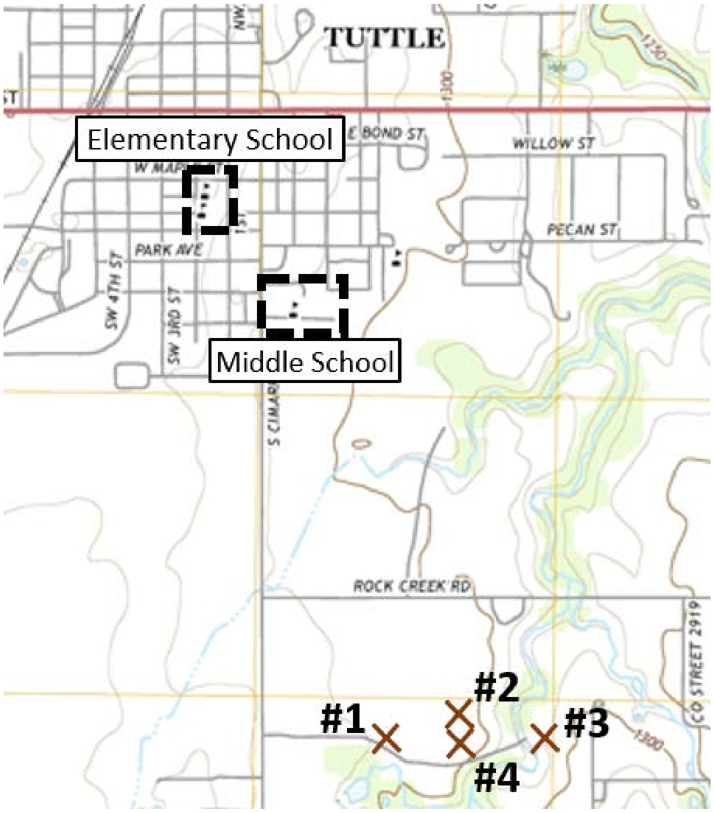
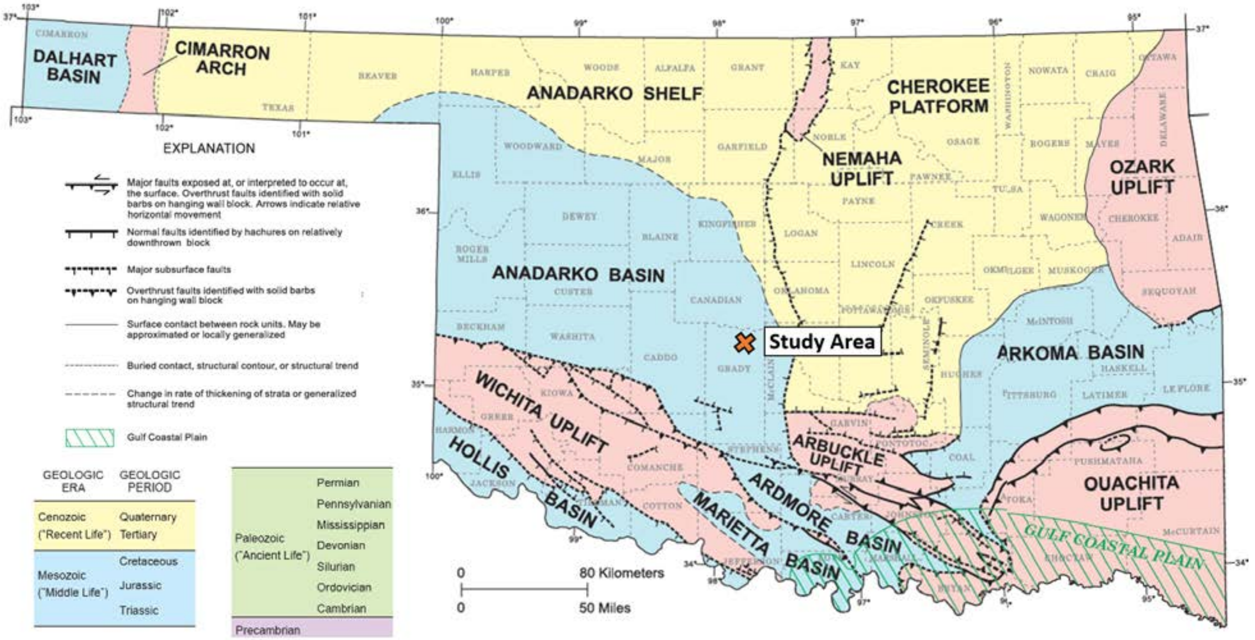


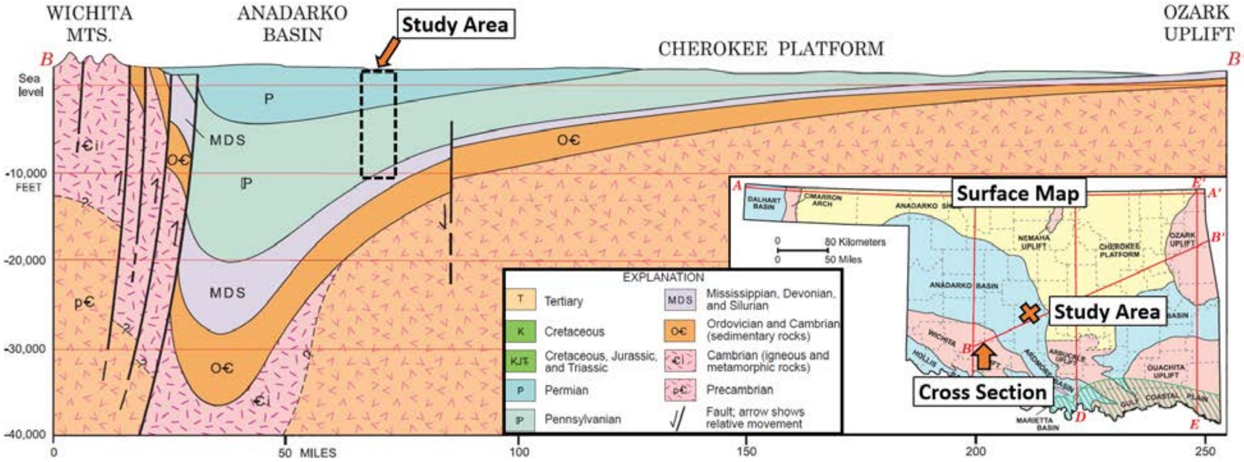
Figure 1. Study area with four oil and gas wells and two schools (modified from USGS topography map)

2. Literature Review for Subsurface Geology and Temperature in the Study Area

The study area, including the targeted four wells, two schools, and houses, is in the eastern part of the Anadarko basin (Figure 2). Anadarko basin is a sedimentary basin, which extends along Oklahoma, Texas, Kansas, and Colorado. Geological formations in the study area specifically include Permian red shales and sandstones that are relatively younger formations around 1 km to 1.5 km depth and Pennsylvanian and Mississippian sandstones and limestones that are relatively older formations around 1.5 km to 3 km depth and below 3 km, respectively. Crystalline basement is expected below 5 km depth (Johnson and Luza 2008; Clement 1991). According to Clement (1991), most of the oil and gas wells in the Anadarko basin had penetrated Lower Pennsylvanian Springer or the underlying Mississippian Chester. Similarly, borehole logs obtained from the four targeted wells demonstrated a wide range of formations from Tonkawa sandstone around 2 km in depth to Hunton limestone around 3.5 km in depth where oil and gas have been mainly produced.


DALHART BASIN
CIMARRON ARCH
ANADARKO SHELF
CHEROKEE PLATFORM
NEMAHA UPLIFT
OZARK UPLIFT
ANADARKO BASIN
Study Area
ARKOMA BASIN
WICHITA UPLIFT
HOLLIS BASIN
ARBUCKLE UPLIFT
ARDMORE BASIN
MARIETTA BASIN
OUACHITA UPLIFT
GULF COASTAL PLAIN
EXPLANATION
Major faults exposed at, or interpreted to occur at, the surface. Overthrust faults identified with solid barbs on hanging wall block. Arrows indicate relative horizontal movement
Normal faults identified by hachures on relatively downthrown block
Major subsurface faults
Overthrust faults identified with solid barbs on hanging wall block
Surface contact between rock units. May be approximated or locally generalized
Buried contact, structural contour, or structural trend
Change in rate of thickening of strata or generalized structural trend
Gulf Coastal Plain
GEOLOGIC ERA
GEOLOGIC PERIOD
Cenozoic ("Recent Life")
Quaternary
Tertiary
Mesozoic ("Middle Life")
Cretaceous
Jurassic
Triassic
Paleozoic ("Ancient Life")
Permian
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
Precambrian
0 80 Kilometers
0 50 Miles

(a)


WICHITA MTS.
ANADARKO BASIN
Study Area
CHEROKEE PLATFORM
OZARK UPLIFT
B
B'
Sea level
-10,000 FEET
-20,000
-30,000
-40,000
P
MDS
O€
€i
p€
0
50 MILES
100
150
200
250
EXPLANATION
T Tertiary
K Cretaceous
KJ₸ Cretaceous, Jurassic, and Triassic
P Permian
₱ Pennsylvanian
MDS Mississippian, Devonian, and Silurian
O€ Ordovician and Cambrian (sedimentary rocks)
€i Cambrian (igneous and metamorphic rocks)
p€ Precambrian
Fault; arrow shows relative movement
Surface Map
Study Area
Cross Section
80 Kilometers
50 Miles

(b)

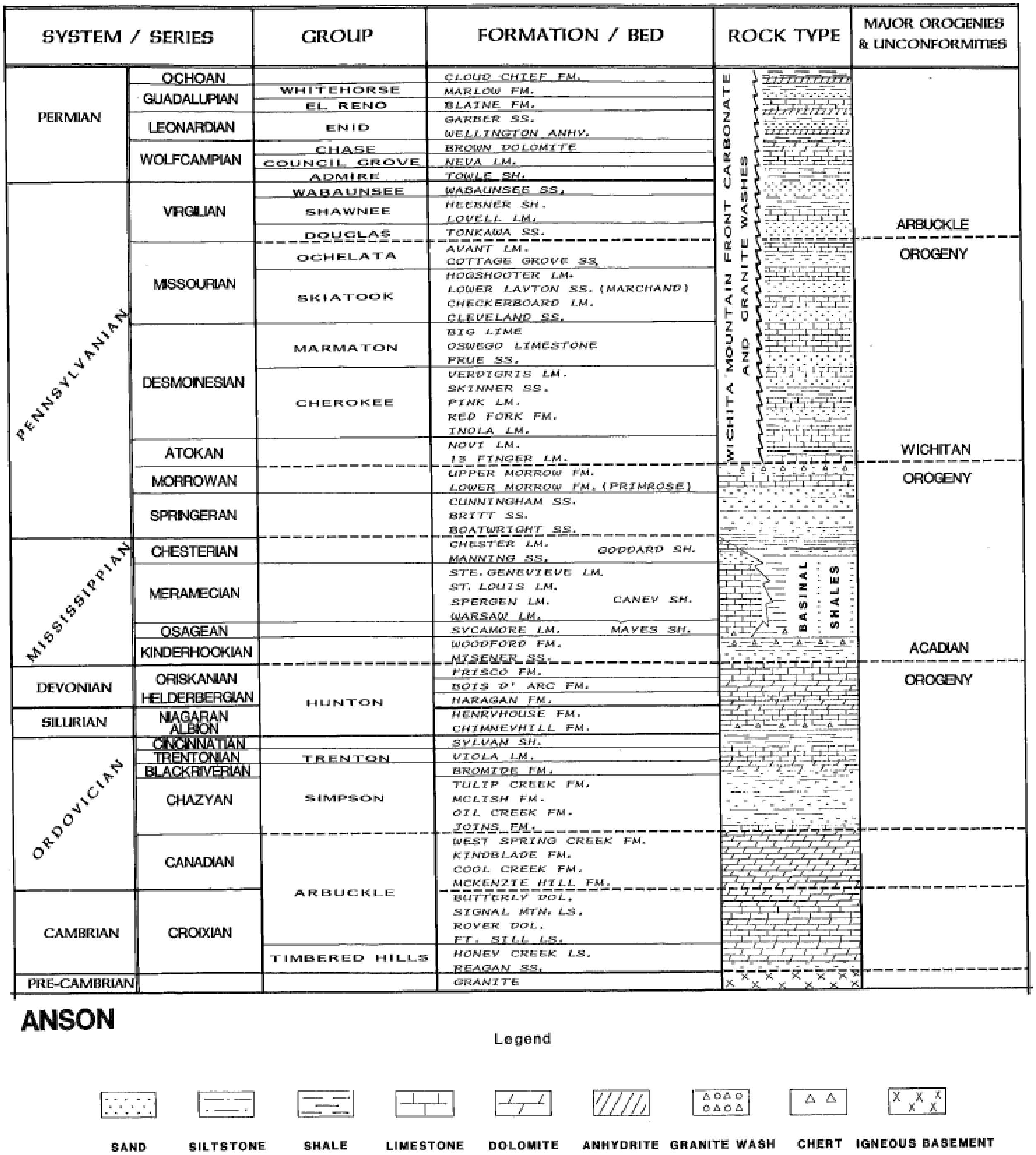
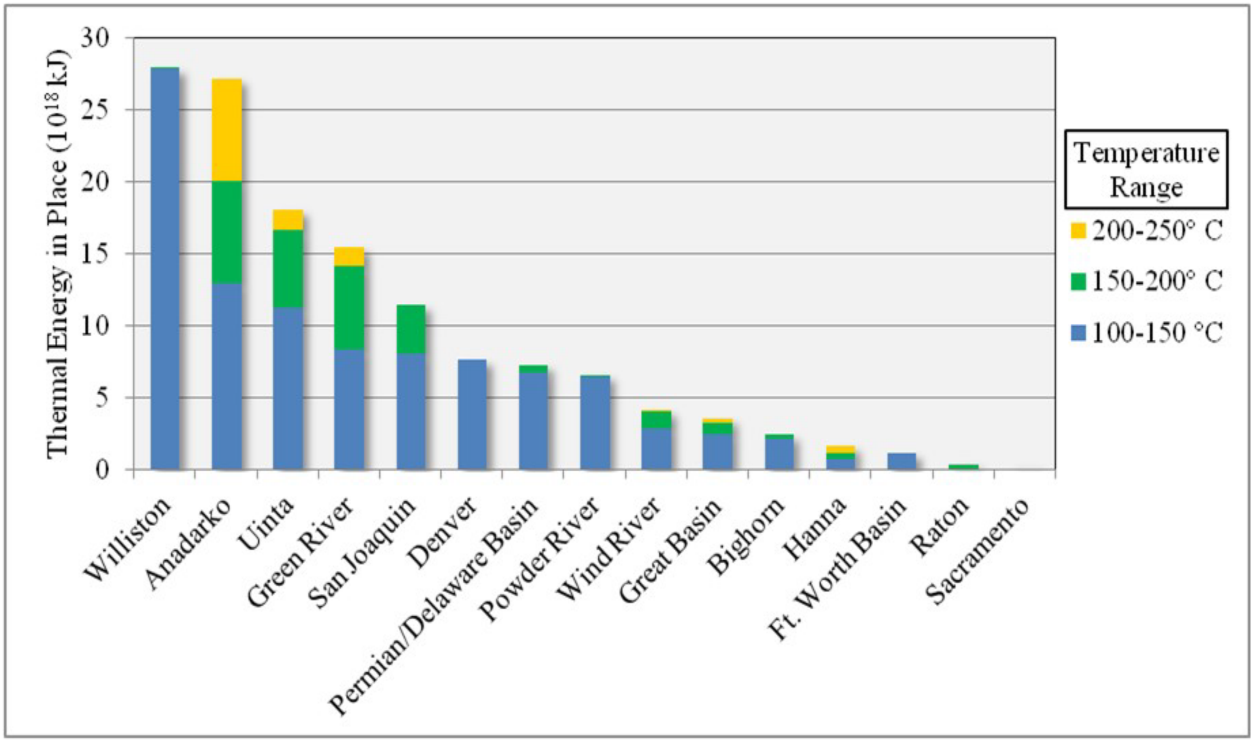
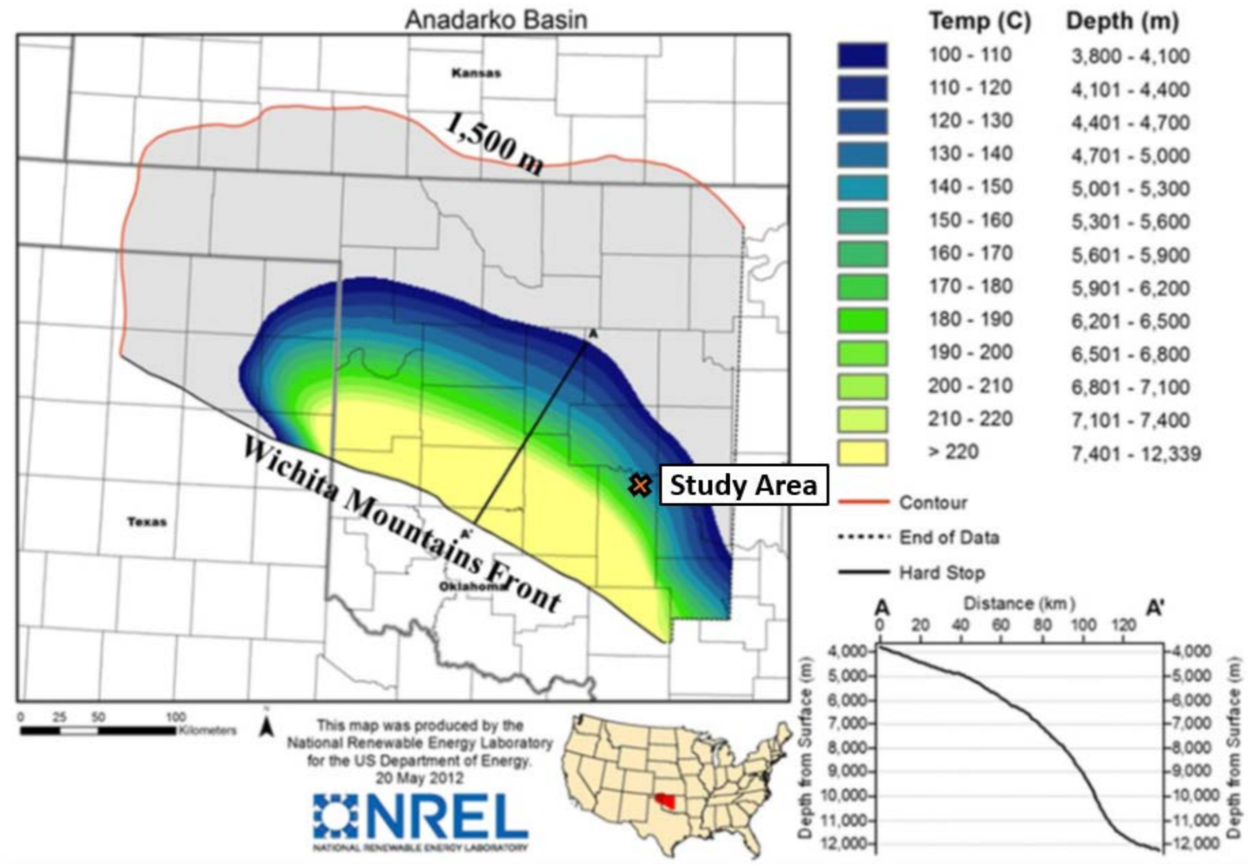


Figure 2. Geological characteristics in the study area: (a) geological map, (b) Anadarko basin cross-section (modified from Johnson and Luza 2008), and (c) generalized stratigraphic column and producing fields of Anadarko basin (Clement 1991). The depths of 1) Permian, 2) Pennsylvanian, 3) Mississippian, Devonian, and Silurian, 4) Ordovician and Cambrian, and 5) pre-Cambrian systems in the study area are approximately 3,000 ft (914.4 m), 10,000 ft (3,048 m), 13,000 ft (3962.4 m), and 17,000 ft (5181.6 m), respectively.

Porro et al. (2012) estimated geothermal resources in 15 major sedimentary basins in the United States, including the Anadarko basin, based on the volume of rocks for each 10 °C temperature interval. The analysis results demonstrated that the Anadarko basin has a strong hydrothermal recharge rate directly addressing the recovery capability of geothermal resources and has the second highest total heat among the 15 sedimentary basins with a large rock volume of more than 20,000 km^3. Moreover, Anadarko basin contains geothermal energy potential at temperatures greater than 220 °C, while most of the sedimentary basins have relatively low thermal energy at temperatures between 100 °C to 150 °C (Figure 3(a)). With a geothermal gradient of 34 °C/km, Tuttle area is expected to have geothermal energy resources ranging from 150 °C to 200 °C temperature around 5 km to 6 km below the ground surface (Figure 3(b)).



(a)



(b)

Figure 3. Estimated geothermal energy resource in Anadarko basin (modified from Porro et al. 2012): (a) total heat in place for 15 major sedimentary basins in the United States and (b) Anadarko basin map where ground temperatures are greater than 100 °C

Similarly, bottom hole temperatures (BHTs) can be used with ambient temperature to estimate the geothermal gradient and subsurface temperature at depth. Southern Methodist University (SMU) Geothermal Lab collected national-scale BHT database, and the database included 19 BHTs approximately 2 to 4 miles (3 km to 6 km) away from Tuttle. The 19 BHTs were obtained at the depth ranging from 3.75 km to 4.18 km (4.03 km on average) and the BHTs ranged from 72.8 °C to 102.2 °C (92.5 °C on average), which is approximately aligned with Porro et al. (2012). The corresponding geothermal gradient with an average ambient temperature of 15 °C ranged from 15.4 °C/km to 20.9 °C/km (19.2 °C/km on average).

3. Hydrogeochemical Characteristics of Geothermal Fluid

Geochemistry is important in the exploration, development, and utilization of geothermal resources. In the exploration phase, for example, the geothermal reservoir temperature is estimated using a chemical geothermometer characterizing chemical equilibrium, which is a function of temperature (Ármannsson and Fridriksson, 2009; Flóvenz et al., 2012). The chemistry of geothermal fluid (e.g., hot springs, fumaroles) is also analyzed to predict operational issues including scaling of different components, by comparing the water chemistry to empirical database for mineral solubility. In this section, the reservoir temperature and scaling potential in the study area were evaluated through chemical geothermometer and piper diagram analysis, respectively.

The produced water chemistry was collected from USGS National produced waters geochemical database (v2.3) and groundwater chemistry data was collected from Oklahoma Geological Survey. Water chemistry in the targeted four wells was also incorporated in the analysis using the data obtained from the operator, Blue Cedar Energy LLC.

Various geothermometers have been developed by previous researchers and particularly silica and cation geothermometers have been widely used to estimate the reservoir temperature. Silica geothermometers (e.g., quartz) are based on experimental measurements for silica solubility (e.g., Fournier, 1991) and relatively quickly respond to interactions between rock types and reservoir conditions (Harvey, 2014). Similarly, cation geothermometers characterize cation ratios (e.g., Na-K) at a chemical equilibrium between the geothermal solution and geochemistry as a function of temperature. While the silica geothermometers can be invalidated due to mixing and dilution with groundwater (near surface non-geothermal water), cation geothermometers are less affected by the dilution (Harvey, 2014). The relatively slow equilibrium of cation geothermometers also can be used as an indication of the cooling or heating history of the geothermal fluid (Flóvenz et al., 2012). Fournier (1979), Giggenbach (1988) and Nieva and Nieva (1987) are some examples of the well-known cation geothermometers. Another commonly used cation geothermometer is the Na-K-Ca geothermometer of Fournier and Truesdell (1973), which is widely used and has frequently provided excellent agreement with measured reservoir temperatures. The charts and geothermometer equations for calculating reservoir temperature are based on the spreadsheet which is described in Powell and Cumming (2010). The cation concentrations are in parts per million (ppm).

Table 1 summarizes cation geothermometer results for three produced water samples (PW-1, PW-2, and PW-3) in Grady County where Tuttle city is located and one water sample from the Tuttle well. The geothermometer results showed that the reservoir temperature ranges from 61 °C to 109 °C with an average of 85 °C. The results also indicated that produced water samples from south Grady County wells have much higher reservoir temperatures, up to 162°C with an average of 117 °C.

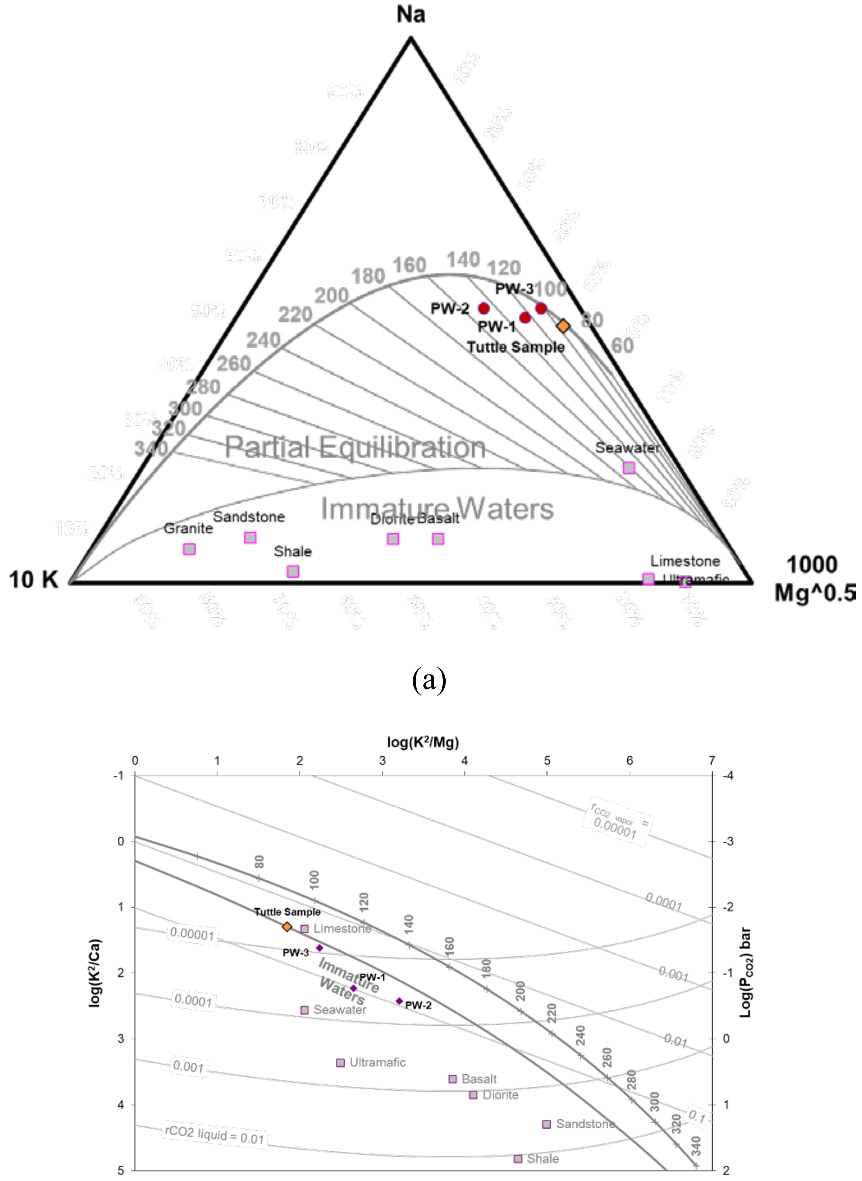
Table 1 Summary of cation geothermometer results for the Tuttle and Grady County samples (Temperature units are in °C, PW: produced water, GW: ground water).

Sample	*Na-K-Ca*[1]	*Na/K*[2]	*Na/K*[3]	*Na/K*[4]	*K/Mg*[5]
PW-1	145	105	125	94	117
PW-2	162	128	148	117	137
PW-3	121	82	103	72	103
Tuttle Well	109	70	92	61	91

[1]Fournier and Truesdell (1973), [2]Fournier (1979), [3]Giggenbach (1988), [4]Nieva and Nieva (1987), [5]Giggenbach (1986)

Figure 4(a) shows the triangular plot of Giggenbach (1988) for the selected water samples. The sample from the Tuttle well fell very close to the equilibrium line indicating a medium water temperature (over 90 °C). Samples from South Grady County wells (PW-1, PW-2, and PW-3) fell within the partially equilibrated waters field and the equilibration temperature ranged between 120 °C and 140 °C. This is interpreted as cooling of thermal water upon migration toward the surface and its Mg enrichment during water-rock interaction.

Relationship between log (K^2/Mg) and log (K^2/Ca) was also plotted for the five samples to estimate the temperature at water-rock equilibrium and partial pressure of carbon dioxide (pCO_2) of geothermal liquids (Figure 4(b)). Tuttle-well sample was in a partial equilibrium condition at temperature around 90°C. All produced water samples (PW-1, PW-2, and PW3) were in immature conditions. Immature water is mainly controlled by water–rock interaction and requires short residence time to gain temperature at depth (or more time to reach the surface). In such hydrogeological conditions, it is unlikely that waters could attain chemical equilibria with host rocks.



(a)

(b)

Figure 4. Cation geothermometers for estimating the geothermal resource temperature: (a) K-Mg-Na ternary diagram (modified from Giggenbach, 1988) for the four selected water samples in the area Tuttle and Grady County and (b) relationship between log (K^2/Mg) and log (K^2/Ca) for Tuttle well sample, selected produced and ground water samples from South Grady County wells

In addition to the reservoir temperature estimation, geothermal fluid type and scaling potential were analyzed using the fluid chemistry data. For produced water chemical analysis, 15 samples from wellhead and 32 samples from separator were collected from oil and gas wells in Grady County. Similarly, for chemical analysis of groundwater 22 samples were collected from nearby water wells penetrating sandstone aquifers. The collected data was then plotted on a Piper diagram, which graphically represents major cations and anions of water analyses expressed in percentage of parts per million (% ppm) or milligrams per liter (mg/L) in three diagram panels shaped by a mesh of equal-sized triangular cells, two triangular and one rhomboidal (Figure 5). Cations (Ca^{2+}, Mg^{2+}, Na^{+}+K^{+}) and anions (SO_4^{2-}, CO_3^{2-} + HCO_3^{-}, Cl^{-}) were represented in the triangular panels and then projected onto the central rhomboidal panel for cationic-anionic facies identification. The results showed that the geothermal brine is expected to be Sodium-Potassium-Chloride-Sulfate type. Such water may be a mixture of alkali chloride water and acid sulphate water, or it can arise from the oxidation in alkali-chloride water or dissolution of S from rock followed by oxidation. The chemistry of produced water samples from the separator was very similar to the groundwater chemistry. As Bicarbonate (HCO_3) concentrations were low (~200 mg/L) and the expected production temperature was moderate (~ 70 °C), calcite scaling is not expected within the wellbore and production pipeline. The chemistry results of samples taken from the separator were very similar to the chemistry of groundwater sample; thus, mixing of groundwater and produced water would not be expected to change the chemical characteristics of the geothermal brine as a heat transfer fluid.

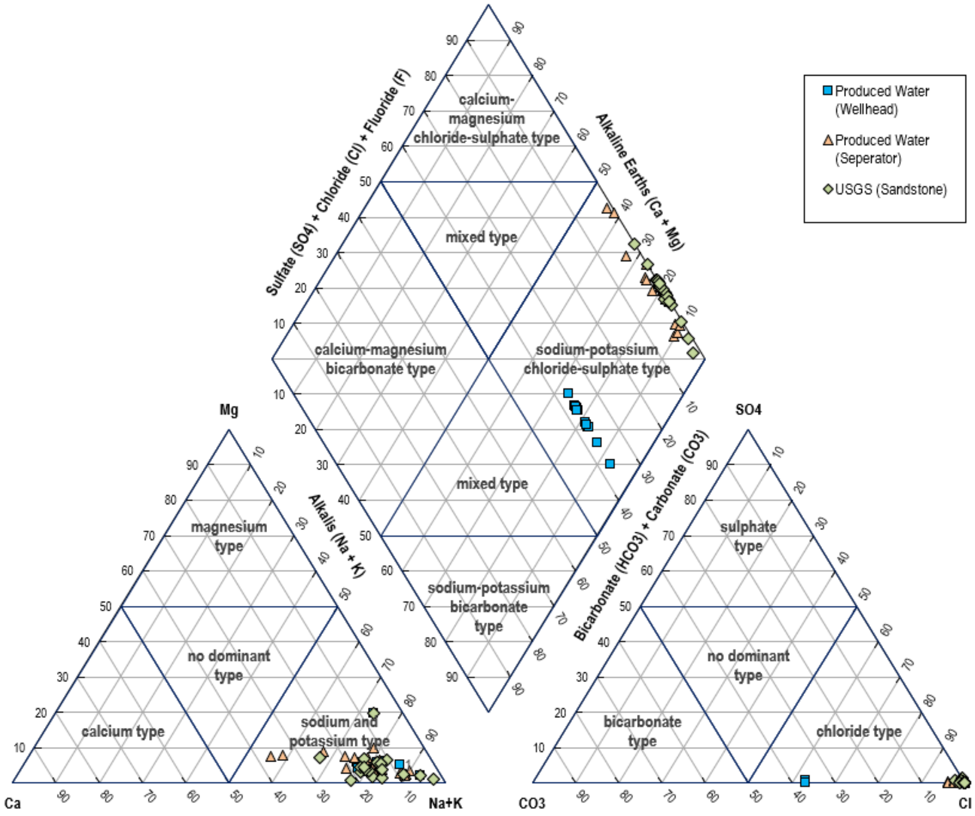


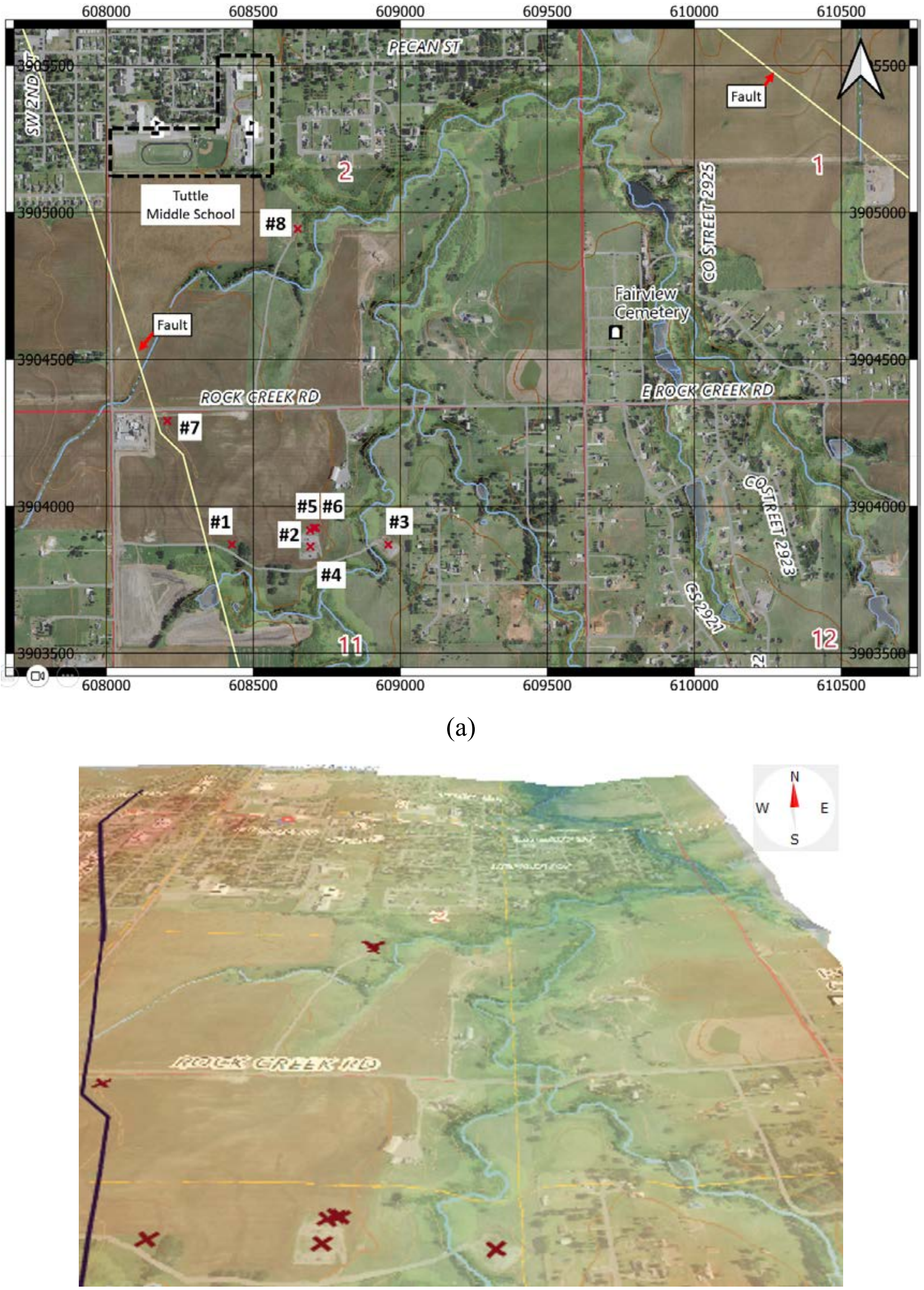
Figure 5. Piper diagram representing the geochemical characteristics and brine types of produced water and groundwater in Grady County, Oklahoma

4. 3D Subsurface Geology and Temperature Distribution Modeling

In addition to the reservoir characterization using geochemistry, subsurface geology and temperature distribution are important for demonstrating geothermal resource potential. The temperature distribution directly addresses the potential of geothermal energy at desired depth, while subsurface formations and lithologies are more closely related to fundamental backgrounds on performance and efficiency of the geothermal system in terms of the resources' hydraulic and thermal properties (e.g., permeable rock or impermeable rock). An accurate model of geological and geothermal variables such as lithology, temperature, pressure, porosity, and permeability, is important to understand the geothermal resource potential (Akar et al, 2011). In this section, subsurface geology and temperature distribution in southern Tuttle area were three-dimensionally modeled using Leapfrog Geothermal, which is a commercial software for building and analyzing conceptual models in 3D.

The Oklahoma Geological Survey has been compiling an interpreted fault map based on oil and gas industry data and published literature (Johnson and Luza 2008; Marsh and Holland 2016). Although Johnson and Luza (2008) indicated no major fault exists in the study area (Figure 2(a)), the Oklahoma Geological Survey's comprehensive fault database (Marsh and Holland 2016) demonstrated there are two faults near the study area (Figure 6(a)). However, due to limited information (e.g., fault type, strike, and dip), the faults were excluded in the modeling assuming lateral continuity. Instead, four boreholes were added to the four targeted wells (total eight wells) to extend the modeling region from the geothermal energy production area (i.e., four targeted wells) to the end users (i.e., two schools and nearby houses). For the eight wells, well logging that includes location, elevation, bottomhole depth, formations, and lithologies was collected from OCC Oil and Gas Conservation database and the operator of the four targeted wells. Since the eight O&G wells have been operated mainly in relatively older geological formations around 3 km in depth, the formation and lithology information were limited for younger formation between 0 km and 1.5 km (e.g., Permian in Figure 2(c)). For a full range of subsurface modeling from 0 km to 3.5 km, the eight borehole logs were thus combined with the information additionally obtained from nearby O&G wells (within 1 mile distance) where the information on young formations is available as well as previous studies (e.g., stratigraphic column in Figure 2(c)), assuming the lateral continuity.

For the surface topography, digital elevation model (DEM), which is a 3D graphical representation of ground topography, was generated for the study area using the National Geospatial Program tool of United States Geological Survey (USGS) (Figure 6(b)). Then, the DEM was processed (e.g., resizing, coordinates) in QGIS, which is a geographic information system (GIS) software, and imported as 3D topography combined with USGS Topo surface map in Leapfrog Geothermal (Figure 6(b)). For temperature distribution modeling, geothermal gradient near the study area, approximately 2.7 miles away from the targeted wells, was also incorporated with ambient temperature and the borehole logs.



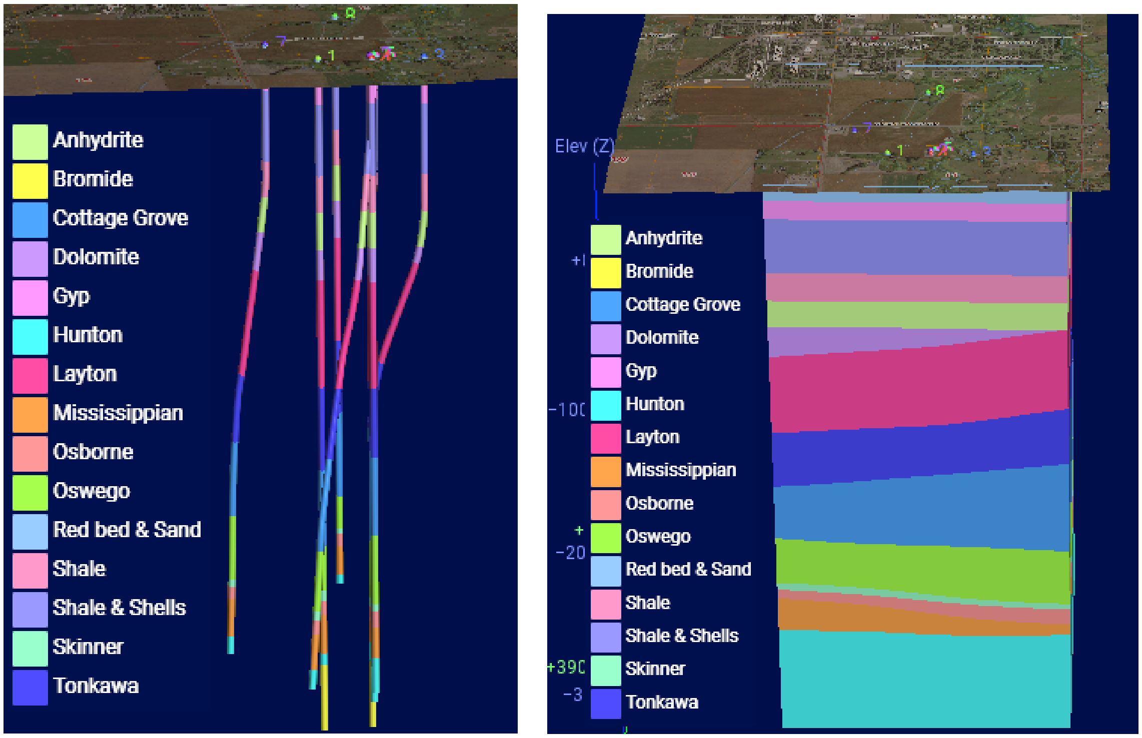
(a)

(b)

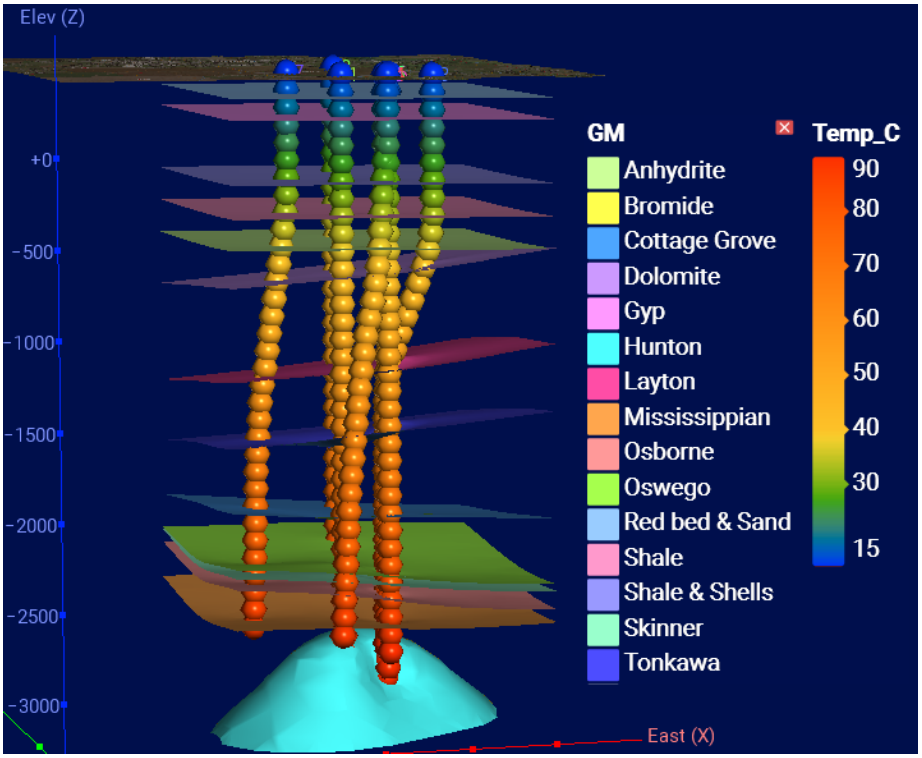
Figure 6 Study area used in the subsurface conceptual modeling: (a) location of four additional wells and two faults in the study area, (b) four targeted wells in digital elevation model (DEM), and (c) USGS Topo map overlaid on the DEM

The 3D conceptual subsurface model is representing the geological formations tops and temperature profiles incorporated with the eight borehole logs (Figure 7). Similar to the regional formation and lithology described in the literature review section, the 3D geological modeling results represented the study area consists of sedimentary formations and lithologies, including Tonkawa, Oswego, Layton, and Cottage Grove sandstones represented by dark blue, green, hot pink, and blue colors, respectively (relatively younger formations) and Mississippian and Hunton limestones represented by orange and light blue colors, respectively (relatively older formations). This result implies that the reservoir has relatively higher porosity approximately ranging between 12% and 22% and higher permeability approximately ranging from 7.63E-20 m^2 for fine sandstone to 3.90E-14 m^2 for coarse sandstone (Wang and Park 2002; Tanikawa and Shimamoto 2009; Zhang et al. 2016). That is, conventional hydrothermal geothermal systems may be thus suitable in the study area, instead of enhanced geothermal system (EGS) or closed-loop geothermal system.

Although the subsurface temperature was estimated using cation geothermometers and regional geothermal gradient without actual temperature measurements in the targeted wells, the subsurface temperature distribution visually showed geothermal energy is available at around 90 °C temperature at 3 km depth where geothermal energy production is targeted (Figure 7(c)). This result implies that the geothermal resources may be exploited for direct-use applications, including heating and cooling systems in the targeted two schools and nearby houses. For example, the geothermal fluid around 80 °C can be used for both space heating and cooling using radiators and absorption chillers where the geothermal energy can be used to drive the cooling cycle.



(a) (b)



(c)

Figure 7. 3D subsurface modeling: (a) lithology and formation logs in eight boreholes, (b) subsurface geological modeling, and (c) deposit contact surfaces with the wellbore temperature distribution

5. Summary and Conclusion

In this study, subsurface geochemistry, geology, and temperature were characterized to demonstrate the potential of geothermal energy production from four existing oil and gas wells in Tuttle, Oklahoma. The subsurface geology model indicated that the study area primarily consists of Permian to Mississippian sandstone and limestone formations, implying a porosity up to ranging between 12% and 22% and a permeability up to 3.90E-14 m^2 (≈ 40 millidarcy) in certain levels of the reservoir. The reservoir temperature is expected between 80 °C to 95 °C at 3.3 km depth, which was aligned with the regional temperature gradient of 22.8 °C/km. Chemical geothermometers also estimated the reservoir temperature at 3 km depth around 90 °C. The geochemistry analysis indicated the geothermal fluid mainly consists of Sodium-Potassium-Chloride-Sulfate with higher Ca and Mg concentrations and lower Na/K ratio possibly due to mixing and intrusion of groundwater, implying lower calcite scaling expected within the wellbore and production pipeline. The 3D subsurface geological model represented the expected geological formation and temperature at depth. Investigation of subsurface geology and geochemistry provided essential information for the geothermal energy production potential in the study area. By repurposing existing oil and gas wells for the geothermal energy production, the new system will bring environmental and economic benefits to the community, including new job opportunities. Detailed techno-economic performance of the repurposed energy system will be further discussed in a separate article at 47th Geothermal Rising Conference. This study will be also extended with the system techno-economic analysis for a full feasibility study.

Disclosure

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