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# Geothermal Gradient Estimation and Geothermal Energy Potentiality of Oil Wells in Oilfields

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# تقدير التدرج الحراري وإمكانية الحصول على الطاقة الجيوحرارية من آبار النفط في الحقول النفطية

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**Abstract:**
Many applications in oilfields require knowledge of the geothermal gradient. The purpose of this study is to assess the potential of oil wells as sources of geothermal energy by determining the geothermal gradient present in rock formations. In the Gialo 59E oil field, bottom hole temperature (BHT) data from twelve wells were gathered to determine the trend of the geothermal gradient across different rock formations. Regional geothermal gradients differ substantially between wells and at different depths. The average temperature is approximately 2.9°C/100 m, with a range of 2.25–3.19°C. Notably, the depth and sedimentary column thickness affect the geothermal gradient. The geothermal gradient and depth of the many wells under investigation in different formations are generally correlated. Given the kind of rock, its specific heat, and heat transport, the quantity of geothermal gradient is undoubtedly significant. The average depth was 643.30–945.73 m, and the observed bottom hole temperatures, which ranged from 144–195°C, were 802.65 m and 168.42°C, respectively, for each of the twelve wells. The temperature increases with depth, according to the recorded bottom hole temperatures. The quantity of the water cut indicated the possibility of using these wells as a source of geothermal energy in power plants for the production of electricity. It may also be categorized as a source of low and medium enthalpy.

**Keywords**: Geothermal Gradient, Geothermal Energy, Oil Wells, Well Temperature, Well Depth, Rock Formation, Power Generation.

**الملخص**
يتطلب العديد من التطبيقات في حقول النفط معرفة التدرج الحراري الأرضي. إن الغرض من هذه الدراسة هو تقييم إمكانات آبار النفط كمصدر للطاقة الحرارية الأرضية من خلال تحديد التدرج الحراري الأرضي الموجود في التكوينات الصخرية. ففي حقل النفط جالو 59E، تم جمع بيانات درجة حرارة تجويف قاع البئر (BHT) من اثني عشر بئرًا لتحديد اتجاه التدرج الحراري الأرضي عبر التكوينات الصخرية المختلفة. حيث تختلف التدرجات الحرارية الأرضية الإقليمية بشكل كبير بين الآبار وعلى أعماق مختلفة. ويبلغ المتوسط حوالي 2.9 درجة مئوية/100 متر، مع نطاق يتراوح ما بين 2.25-3.19 درجة مئوية. وقد لوحظ أن العمق وسمك العمود الرسوبي يؤثران على التدرج الحراري الأرضي. كما وجد أن التدرج الحراري الأرضي وعمق العديد من الآبار قيد الدراسة في التكوينات المختلفة مرتبطان بشكل عام من حيث تغير درجة الحرارة. وبالنظر إلى نوع الصخور، وحرارتها النوعية، والانتقال الحراري فيها، فإن كمية التدرج الحراري الأرضي تكون كبيرة بلا شك حيث كان متوسط العمق يتراوح ما بين 643.30-945.73 متر ودرجات حرارة قاع البئر المرصودة، والتي تراوحت ما بين 144-195 درجة مئوية، 802.65 متر و168.42 درجة مئوية على التوالي، لكل بئر من الآبار الاثني عشر. وترتفع درجة الحرارة مع العمق وفقاً لدرجات حرارة قاع الآبار المسجلة. وتشير كمية المياه المُنتجة إلى

إمكانية استخدام هذه الآبار كمصدر للطاقة الحرارية الأرضية في محطات توليد القوى لإنتاج الكهرباء، كما يمكن أيضًا تصنيفها كمصدر للمحتوى الحراري الإنثالبي المنخفض والمتوسط.

**الكلمات المفتاحية:** التدرج الحراري، الطاقة الجيو حرارية، آبار النفط، درجة حرارة البئر، عمق البئر، التكوين الصخري، توليد الطاقة.

## Introduction

Together with the continuous increase in the global population, there has been a considerable increase in energy consumption over the past few decades. Energy consumption is predicted to increase by a factor of three over the next 50 years, along with a robust worldwide demographic shift that will lead to 7.4 billion people on Earth in 2016 and 11.2 billion in 2100 (United Nations 2015). Fossil energy resources, chiefly coal, oil, and gas, are burned to meet the world's energy needs. This process produces greenhouse gases, which have a severe impact on the climate. The burning of fossil fuels has catastrophic effects on Earth's life. An increasingly significant role for geothermal energy is played in this environment, in addition to the use of hydropower, biomass, solar electricity, and wind power. Owing to the rapid expansion of the geothermal sector, there is a need for shared information and the cohabitation of professional planning tools. Deep geothermal energy applications are supported by technical data and financial advice included in the pamphlet "Deep Geothermal Energy-Principles and Application Possibilities." Deep geothermal energy is introduced, and an overview of the state of the art through an understandable explanation of physical and geothermal engineering concepts and their interrelationships is given. The thermal energy produced and stored in the Earth is known as geothermal energy. One of the synonyms is geothermal heat. Geothermal energy is, in theory, accessible anywhere, at any time. Because of its constant natural heat generation, it is potentially endless if it is used appropriately. When conduction dominates heat transmission, the average subsurface temperature decreases by 20–25°C /km, depending on the type of rock. With less heat generation in the crust, it may be lower in older continental shields. The temperature gradient, also known as the geothermal gradient, is the rise in temperature per unit depth. It is expressed in K per km, which is equivalent to °C per km in colloquial terms. The heat movement from deep to the Earth's surface is connected to this gradient.

Geothermal energy is a new type of clean energy that is inexpensive and can be used directly. It makes use of both existing injection water technique equipment and broad-sense abundant geothermal resources. The deep-seated high-temperature liquid (oil–gas–water mixture) draws a geothermal warming flow layer to transit heat upwards, decreasing viscidity and increasing fluidity. A geothermal resource is defined as a useful component that comes from the crust and adapts to current technological and economic conditions.

The petrothermal approach was initially described by Al Rashed and Al Al Anzi (2022). They detailed the use of an enhanced geothermal system (EGS) for thermal energy storage and provided a comprehensive account of petrothermal methods. These authors suggested that the petrothermal process has the potential to be a more efficient and economically viable solution for geothermal heat extraction than conventional methods.

Baymatov et al. (2023) reported that geothermal energy offers continuous, 24/7 electricity generation, is free from the inconsistency of solar and wind energy, and is beneficial for remote regions, where geographical or logistical challenges make conventional power plants unfeasible.

Temperature measurements in wells are used to determine the undisturbed (static) formation temperature, geothermal gradient and heat flux density (heat flow). Knowledge of geothermal temperature profiles is also needed to increase the accuracy of electric and temperature log interpretations. The drilling process greatly disturbs the temperature of the formations around the wellbore (Kutasov, 2022). Data on the geothermal temperature and the temperature gradient of the earth's crust are necessary for solving several fundamental and applied problems (Ramazanov et al., 2023).

### 1.1. Geothermal Resources

The hydrothermal resources that make up natural aquifers are deep geothermal energy. Moreover, enthalpywise, these aquifers may be separated into high and low-quality aquifers. When dealing with low-enthalpy systems, an extra cycle such as the organic Rankine cycle (ORC) or the Kalina process is necessary. In contrast, high-enthalpy systems permit the employment of Flash or Dry-Steam processes.

In Figure 1, Younger (2015) proposed a system for classifying geothermal resources on the basis of their enthalpy, temperature, and pressure. The internal energy of a system plus the product of its pressure and volume is known as its enthalpy, which is a characteristic of thermodynamic systems.

### 1.2. Geothermal potential

Geothermal potential is the quantity of geothermal energy that can be used throughout a year and is subject to technical and financial constraints, as per the International Geothermal Association's (IGA) proposal.

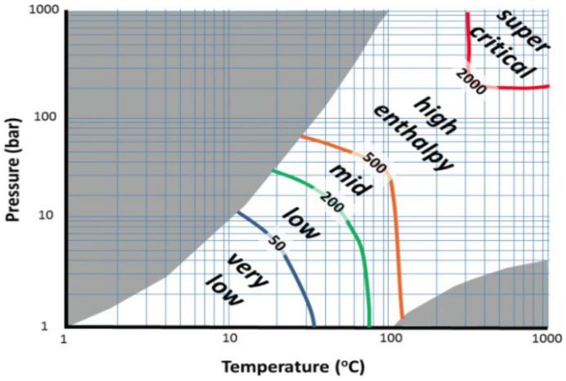



**Figure 1:** Categorization of geothermal resources. The number on the lines are approximate values of enthalpy in kJ/kg (Younger, 2015)

### 1.2.1. Elements of Geothermal Potential Estimation

The primary components for estimating the geothermal potential are as follows:

1. Porosity components in the local porosity model
2. Compaction patterns in basin-fill sediments: porosity versus depth
3. Thermal characteristics (heat capacity and specific heat conductivity)
4. Permeability estimation via porosity
5. Geothermal gradient and temperature as a function of depth
6. Clay contents of the porous sediments
7. Maps and estimated thickness of the basement carbonates
8. The thickness of basic conglomerates and altered zones above foundation rocks
9. Geothermal heat flux (calculated on the basis of basin depth) (Ramazanov et al., 2023).
10. Calculating the technical specifications**.**

### 1.2.2. Classification of Geothermal Potential

On the basis of the economic evaluation and dependability, Figure 2 depicts the five categories of geothermal potential, which are as follows:

1. Theoretical = physically feasible energy source (heat in situ).
2. Technical = percentage of theoretical capacity that can be realized with existing technologies.
3. Economic = location- and time-dependent percentage of technically possible uses.
4. Sustainable = percentage of economic potential that may be realized via the application of environmentally sound rules and sustainable production levels.

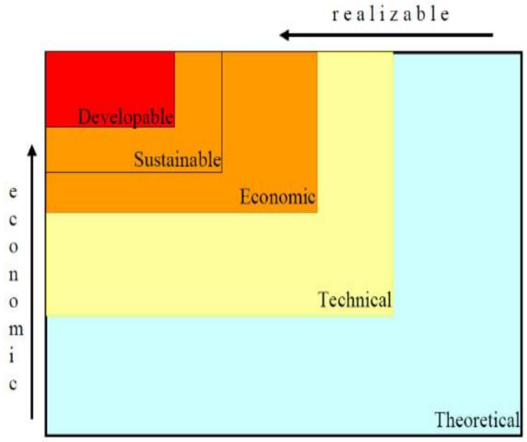



**Figure 2:** Classification of geothermal potential.

The McKelvey diagram (Figure 3) and a study-oriented approach are essential to resource assessment and classification. In this approach, resources progress from being inferred at an early exploration stage to being discovered after drilling and ultimately being economically recoverable at the production stage. Drilling a reservoir is the first step in the exploration process and takes a resource from an inferred (undiscovered) state to a discovered state. This process can verify the existence of a resource and estimate its productivity.

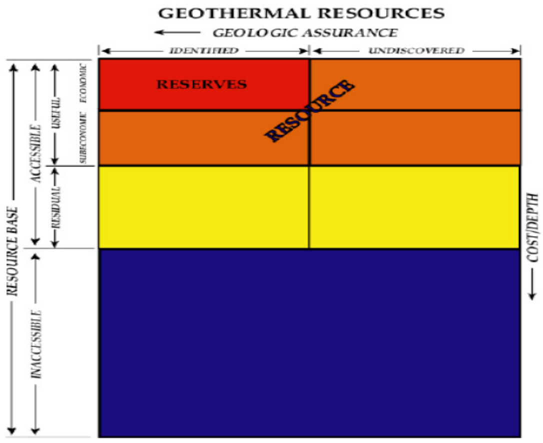



**Figure 3:** McKelvey diagram illustrating geothermal resource and reserve terms in relation to economic viability and geologic certainty (Williams et al., 2008).

Understanding heat transport, geothermal gradients, and subsurface temperatures is essential for comprehending sediment thermal maturation and previous basin thermal regimes. The maturation and subsequent conversion to hydrocarbons in a sedimentary basin are determined by its temperature history. The heat produced by the radioactive elements found in sediments and the heat flow from the Earth's core are the sources of heat in a sedimentary basin (Kutasov, 2022). According to Sleep (1971), the mechanisms involved in basin formation are connected to the temperature history of a sedimentary basin.

Heat often moves from the basement rock into the sedimentary series above it. Heat is carried upwards by a mechanism called heat flow, whereas in sedimentary basins, the temperature increases with depth. Depending on the medium, heat is often transferred by conduction, convection, or radiation. In sedimentary basins, conduction is the primary mode of heat transfer. Tester et al. (2006) and the Information Energy Agency (IEA) (2011) noted that the growth of geothermal energy is heavily reliant on technical improvements that can remove obstacles to the production of fluids from deeper inside the ground with a moderate rise in cost.

### 1.3. Geothermal Gradient

At depths of approximately 18 to 20 m, the temperature under the Earth becomes nearly constant and equivalent to the average air temperature, with daily swings of a few centimetres and seasonal variations of a few metres. As shown in Figure 4, below this depth, it essentially increases with depth (geothermal gradient).

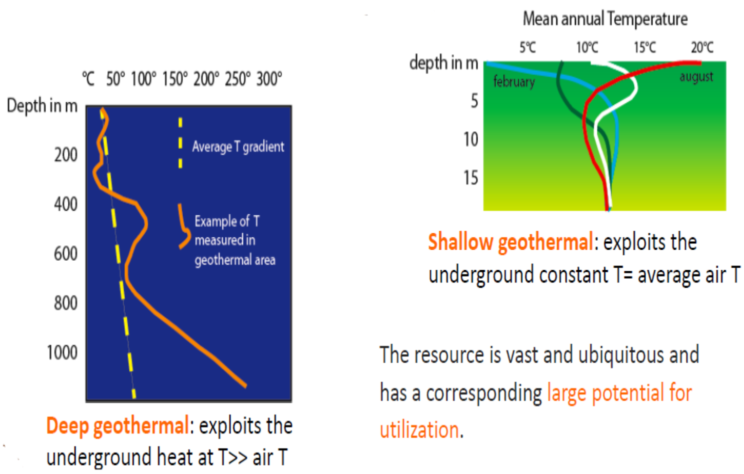



**Figure 4:** Geothermal gradient (IEA, 2011)

The quantity of heat released into space from the interior through a unit area in a unit of time is known as the Earth's surface heat flow. Milliwatts per square meter (mWm-2).

As the unit of measurement, the geothermal gradient and the thermal conductivity of rocks combine to produce heat flow. The heat flow is 40–90 mW/m2 on average. The world's total production exceeds 4×1013 W, which is four times greater than the current 1013 W global energy consumption. The life of an oil or gas reservoir does not need to be terminated when the water level is high.

The geothermal potential from historic and near-depleted oil and gas fields may be understood and calculated via the extensive information gained from oil and gas reservoirs. Thermal energy may be computed to comprehend the thermal energy that is ready to be recovered from the subsurface via heat in situ calculations.

The determination of formation temperatures in oil and gas basins requires caution. Because drilling mud cools down the hole, bottom hole temperatures (BHTs) determined from wireline logs are often lower than real temperatures.

A more accurate approximation of the real reservoir temperature is to use pressure data or drill stem test temperatures. The presence of extreme values for both variables is confirmed by the exploratory examination of the BHT and GG data. The composition of sedimentary deposits is an important consideration in geology (Ramazanov et al., 2023).

In general, Figure 5 depicts sedimentary formations composed of sandstones, shales, limestones, and granites at depth (Balling et al., 1981).

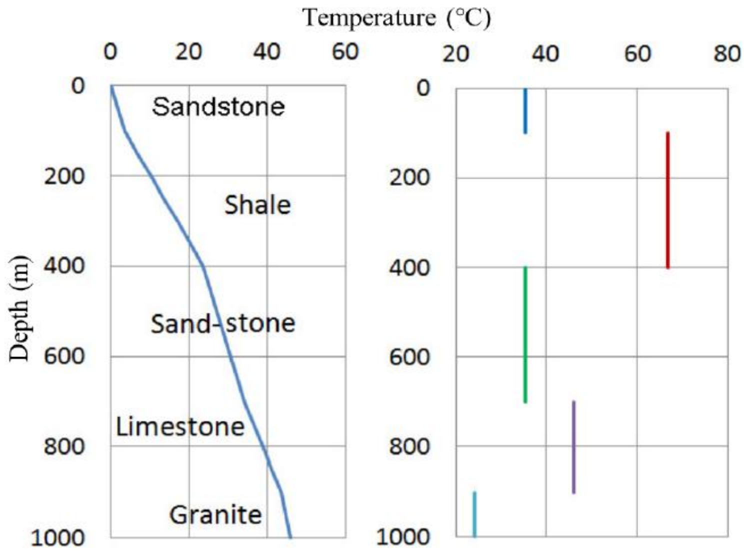



**Figure 5:** Generic relationship of temperature as a function of depth for lithologies in sedimentary basins, illustrating changes in the geothermal gradient with lithology (Morgan & Scott, 2014).

However, the variation between Figures 4 and 5 is attributed to the various formation lithologies and the specific heats and characterizations of each rock type.

### 1.4. Study Area

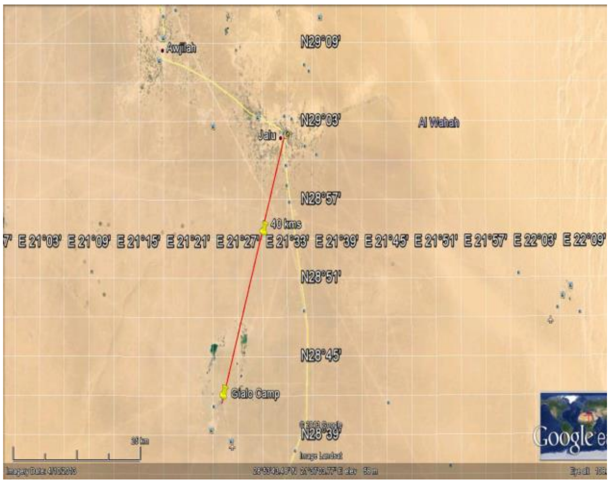
#### 1.4.1. General Geological Setting

The case of our study is in Gialo 59E, the second largest oil field operated by the Waha Oil Company. The field is in the Sirte Basin, which is approximately 35 km south of the Jalo Oasis. The field started production in 1961 from a few wells. Currently, the number of drilled wells exceeds 400.

#### 1.4.2. Study location

Gialo 59E is situated 35 km south of Jalu Oasis, the center of Waha. The field area is approximately 218,550,587 sq. m. at longitude °21 05" 33' and altitude °29 03" 30' (Figure 6). Conversely, Figure 7, a map, displays oil resources and ports in eastern Libya.

Kofra Road runs through the region where the wells are divided into those to the east and west of the road. The field generating the wells is spread out over a broad, level desert with sporadic, tiny sand dunes. Summertime temperatures are often hot and dry, whereas winter temperatures are typically chilly and dry, especially at night. Rainfall is infrequent in this region.



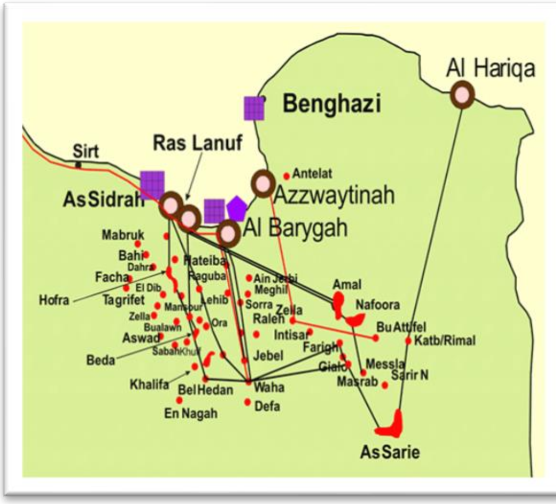




**Figure 6:** Coordinates of Gialo Field.

**Figure 7:** A map showing the oil fields and terminals in eastern Libya

On the other hand, Figure 8 shows the location map of Gialo 59 and the stratigraphic column of the Gialo area.

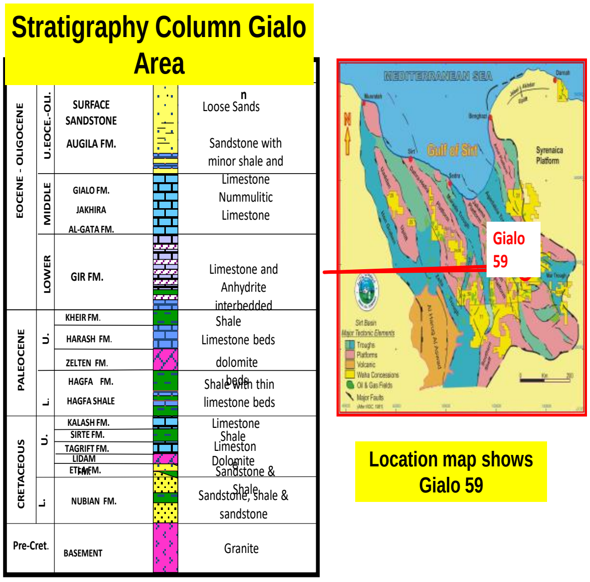



**Figure 8:** Gialo location map and the stratigraphy column.

### 1.4.3. Gialo Palaeocene Reservoir

Drilling of well E1 yielded the initial discovery of the Gialo Palaeocene limestone reservoir in March 1961, which was put into production in November 1964. In the Palaeocene Reservoir, 54 wells were built, and as of December 2015, 41 of those wells were producing.

### 1.4.4. Geological and Reservoir Description

The upper Palaeocene Epoch's Zelten Limestone component is the source of the production of the Gialo Palaeocene reservoir. Three distinct facies differ only slightly in their characteristics. In the Gialo horst block, the Palaeocene is the least productive reservoir. In the east-central portion of the reservoir, the greatest gross thickness is 150 feet, and it thins out towards the west. Faults define the main reservoir, which is a structural trap in Zelten limestone. Situated at a depth between 2,700 and 3,000 feet, the Gialo Palaeocene reservoir is situated in the middle Eocene upper productive phase of the Gialo limestone. The reservoir is ten miles long and four miles wide. The two strata that make up the oil-bearing interval in the reservoir are approximately 100 feet thick and are separated by a largely impermeable gap. The top layer, known as the Shoal facies, is the reservoir's most productive layer. The Gialo Block created a structural high where oil became trapped (Figure 9).

Figures 6 through 9 illustrate the locations of the Libyan oil fields and the coordinates of the investigated Gaussian field, the geology of the area and the geological and reservoir descriptions under consideration.

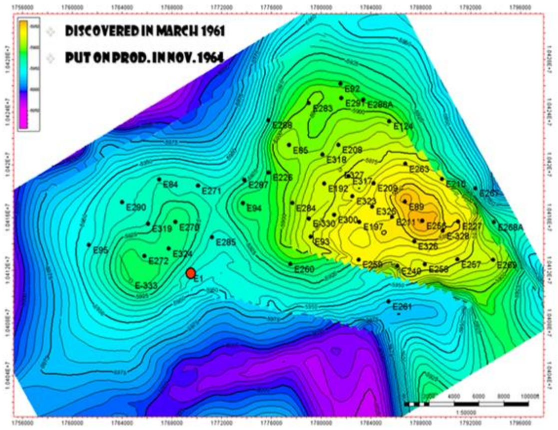



**Figure 9:** Gialo Palaeocene structure map.

### 1.5. Study Objectives

The main aims of this study can be categorized as follows:

1. The determination of the reservoir's temperature gradient and temperature at a reference depth through geothermal analysis, is crucial in any reservoir research.
2. The reservoir temperature, which is regarded as an important parameter of geothermal energy for power generation, is estimated.
3. 3This paper highlights the prediction of energy production throughout a temperature gradient and well depth by providing a thorough examination of the relevant data for reservoir geothermal analysis.

### 1.6. Study Significance

The importance of this study involves the following:

1. The prediction of reservoir temperature by using oil wells data and estimating the geothermal gradient.
2. To identify the potentiality of the conversion of geothermal energy into electricity.
3. To identify the nature of geothermal energy and their classifications on which the power plant will be selected.

### 1.7. Geothermal Energy Production Via Oil wells

Drilling holes into water-bearing layers, or aquifers, allows for the extraction of heat from the Earth (Figure 10). These aquifers supply warm, salted water that is pumped to the surface, where a heat exchanger transfers heat to heat networks. The water that is circulated in a different system from the water that reaches the end user is pumped to the surface and stays inside a closed system. After cooling, the water is reinjected (pumped) into the aquifer, where it warms once more from the Earth's core's continuous heat.

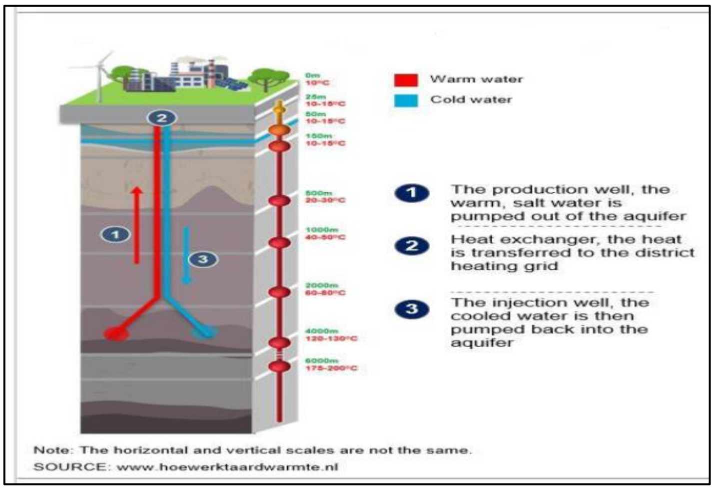



**Figure 10:** Schematic of a geothermal energy plant.

## 1.8. Power Generation

The most common power plant design for geothermal energy harvesting is a condensation system (Figure 11), which has a long and dependable service life and strong load following capacity. Geothermal resources with reservoir temperatures between 200° and 320°C are often processed by condensing systems (Eliasson, Thorhallsson, & Steingrímsson, 2011). Because condensing systems have  respectable thermal efficiency, they are preferable to binary cycle and back pressure power plants.

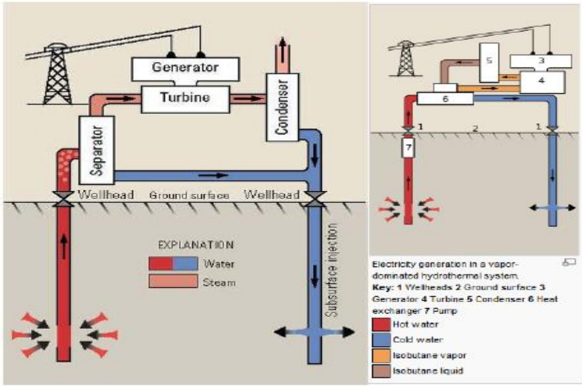



**Figure 11:** General design of a geothermal power plant utilizing a condensing system (left); General design of a geothermal power plant utilizing a binary cycle (right) (Duffield & Sass, 2004)

Figure 10 shows the classification of geothermal heat and the mechanism of its extraction, whereas Figure 11 illustrates the design of the power plant on the basis of the extracted temperature.

## 2. Materials and Methods

The data of twelve oil wells in the Gialo oilfield were collected to provide the bottom hole temperatures that were employed in the investigation of geothermal analysis. The temperatures at the bottoms of the oil wells were measured in Fahrenheit and translated to degrees Celsius for this study. These fundamental analyses were performed on the temperature data.

The geothermal analysis was carried out according to the following methods:

### 2.1. Determination of Geothermal Gradient

The pace at which the temperature changes with depth is measured by the geothermal gradient. Using the following empirical formula, one can calculate the geothermal gradient by dividing the difference between the formation's temperature at a certain depth and the mean annual surface temperature by the depth of the formation (Emujakporue and Leonard, 2016):

$$Tz = mZ + T0 \quad (1)$$

Where:

Tz : Wellbore temperature in °C at depth Z km

T0 : Mean surface temperature in °C

m : Geothermal gradient in °C/km

Geothermal gradients are mostly calculated using bottom-hole temperatures recorded in boreholes since heat flow and thermal conductivity data are rarely accessible for petroleum applications. This is the basic equation for the computation and the methodology used in this study:

$$\textbf{Geothermal gradient} = \frac{\textbf{formation temperatire} - \textbf{mean annual surface temperature}}{\textbf{Formation depth}\ (\textbf{true vertical depth})} \quad (2)$$

The average surface temperature is regarded as 26°C. The geothermal gradient is measured in °C/km.

### 2.2. Determination of Heat Flow

It is commonly known that Earth's temperature rises with depth, suggesting that heat is produced below and rises to the surface through layers of rock and silt.  Thermal conductivity and thermal gradient combine to produce heat movement (Beardsmore and Cull, 2010). Using Fourier's one-dimensional heat flow equation, this is as follows:

$$Q = -K\frac{dT}{dZ} \quad (3)$$

Where:

$Q$: Heat flow

$K$ = Thermal conductivity

$dT/dZ$ = m : geothermal gradient.

Because heat moves in the negative, Z direction while the temperature increases in the positive depth direction, Equation 2 has a negative sign. For this project, the thermal conductivities of the sand and shale were found in published works. Q, or heat flow, is measured in Watts per square meter ($Wm^{-2}$).

### 2.3. Statistical Analysis

For the computation of the geothermal gradient and heat flow, simple statistical formulas were used. Statistical methods are utilized to analyze the geothermal data in every well.

### 2.4. Average of Geothermal Data

For every borehole, the average (mean) of the sample locations' heat flow and geothermal gradient was computed. The geothermal data from the five wells was also processed using the same methodology. The following formula was used to get the average geothermal data (Hamza, et al., 2005b):

$$m = \frac{1}{n}\sum_{i=1}^{n} X_i = E(X) \quad (4)$$

Where:
x : the value geothermal data
n :the number of samples
E (X): the expected value
m : Mean

### 2.5. Variance of Geothermal Data

A measure of spread is the variance. The data's average squared deviation from the mean is what it is. The following equation yields it (Hamza, et al., 2005b):

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(X_i + m^2) \quad (5)$$

Where:
S2: Variance
M: Mean
n: No of data
x: Value of data

### 2.6. Standard Deviation of Geothermal Data

The variance squared is equal to the standard deviation. Because it has the same units as the mean whereas the variance has squared units, it is frequently referred to be the preferable measurement of spread. Using the following formula, the data's standard deviation was calculated (Hamza, et al., 2005b):

$$S = \sqrt{S^2} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i + m^2)} \quad (6)$$

Where:
S2 : Variance
S : Standard deviation
2.7. Standard Error
The following formula may be used to get the standard error related to the geothermal data from the standard deviation (Hamza, et al., 2005b):

$$S_e = \frac{S}{\sqrt{n}} \quad (7)$$

Where:
n: numbers of datasets
Se = standard error
S: standard deviation

## Results And Discussion

### 3.1. Calculating Geothermal Gradients

The data source was used to calculate geothermal gradients, which are derived from additional well bottom-hole temperatures.

Table 1 presents the computed geothermal gradient in several boreholes together with well characteristics (such as depth dug, highest temperature recorded in the borehole, etc.). These wells are widely dispersed across the vast research region under investigation.

The average depths of the twelve wells range from 2110 to 3102 m, with observed bottom hole temperatures between 144 and 195°C. The bottom hole temperatures recorded from the wells demonstrate that the temperature increases with depth. Additionally, it falls under the low and medium enthalpy categories, according to Younger (2015).

**Table 1**: primarily selected geothermal fountain oil wells in Gialo oilfield.

| Studied wells | Well depth (m) | Bottom hole temperature (ºC) | Mean of geothermal gradient (ºC/100m) | Water production, Q (bb/d) |
|---|---|---|---|---|
| GWX1 | 2240 | 155 | 2.90 | 1320 |
| GWX2 | 2310 | 163 | 2.85 | 1410 |
| GWX3 | 2150 | 145 | 3.15 | 1152 |
| GWX4 | 3102 | 192 | 2.99 | 1940 |
| GWX5 | 2380 | 170 | 3.09 | 2609 |
| GWX6 | 3018 | 165 | 3.12 | 1197 |
| GWX7 | 2750 | 154 | 2.75 | 5015 |
| GWX8 | 3100 | 160 | 2.55 | 3770 |
| GWX9 | 2950 | 188 | 2.82 | 4100 |
| GWX10 | 2110 | 190 | 2.25 | 1590 |
| GWx11 | 2480 | 144 | 3.10 | 899 |
| GWX12 | 3002 | 195 | 3.19 | 4022 |
| Range | 2110-3102 | 144-195 | 2.25-3.19 | 899-5015 |
| Average | 2632.67 | 168.42 | 2.90 | 2418.67 |

### 3.2. Statistical Analysis

Table 2 presents a summary of the average geothermal gradient and heat flow statistical values that were obtained for each well.

**Table 2:** Statistical calculations of geothermal data.

| Studied wells | Mean of geothermal gradient (ºC/100m) | Mean of heat flow | Variance of gradient | Variance of heat flow | Standard deviation of gradient | Standard deviation of heat flow |
|---|---|---|---|---|---|---|
| GWX1 | 2.90 | 33.12 | 0.021 | 0.044 | 0.130 | 0.254 |
| GWX2 | 2.85 | 31.20 | 0.019 | 0.039 | 0.112 | 0.221 |
| GWX3 | 3.15 | 36.18 | 0.201 | 0.412 | 0.322 | 0.315 |
| GWX4 | 2.99 | 31.90 | 0.022 | 0.040 | 0.115 | 0.241 |
| GWX5 | 3.09 | 31.82 | 0.203 | 0.416 | 0.349 | 0.415 |
| GWX6 | 3.12 | 34.15 | 0.229 | 0.492 | 0.452 | 0.466 |
| GWX7 | 2.75 | 32.14 | 0.217 | 0.366 | 0.398 | 0.412 |
| GWX8 | 2.55 | 31.78 | 0.211 | 0.359 | 0.384 | 0.320 |
| GWX9 | 2.82 | 31.92 | 0.240 | 0.411 | 0.366 | 0.314 |
| GWX10 | 2.25 | 30.12 | 0.045 | 0.092 | 0.145 | 0.244 |
| GWx11 | 3.10 | 31.85 | 0.038 | 0.088 | 0.136 | 0.239 |
| GWX12 | 3.19 | 31.99 | 0.245 | 0.419 | 0.371 | 0.342 |
| Range | 2.25-3.19 | 30.12-36.18 | 0.021-0.245 | 0.039-0.492 | 0.112-0.398 | 0.221-0.466 |
| Average | 2.90 | 32.35 | 0.141 | 0.265 | 0.273 | 0.315 |

Figure 12 shows a visual representation of the computed statistical parameters. The variance in these characteristics across the wells under investigation is clearly responsible for the variation in the well data.

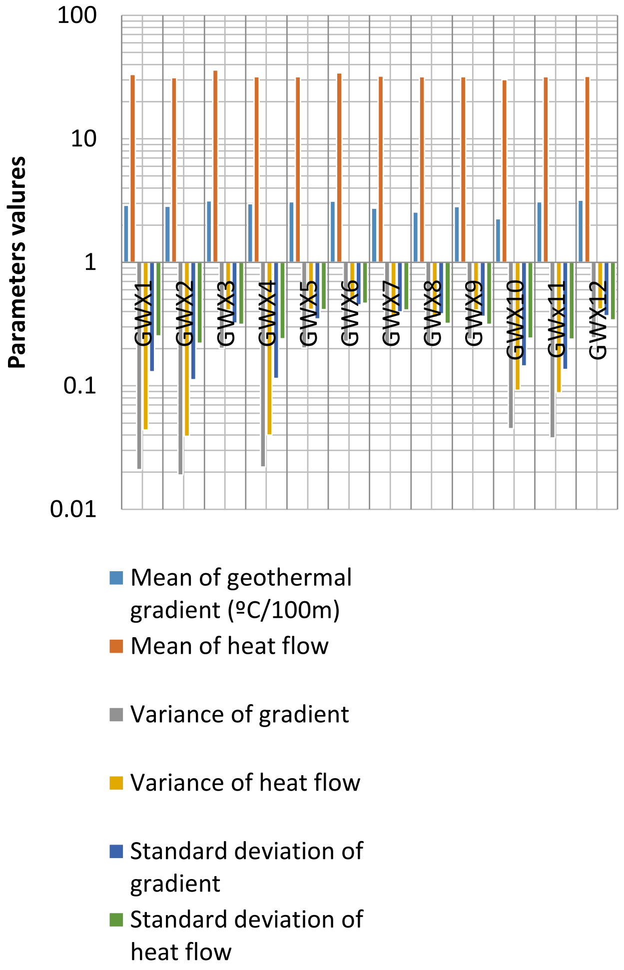



**Figure 12:** Correlation between the various parameters of studied wells.

Figure 13 shows, however, the geothermal gradient of the examined oil wells across the various rock types. The temperature variation trend with depth for a subset of wells is shown in the image. The fact that the geothermal gradient is not constant throughout the borehole is clearly visible from the trend. Owing to the unique thermal characteristics of each kind of rock, the pace at which the temperature changes with depth in sedimentary rocks differs from formation to formation.

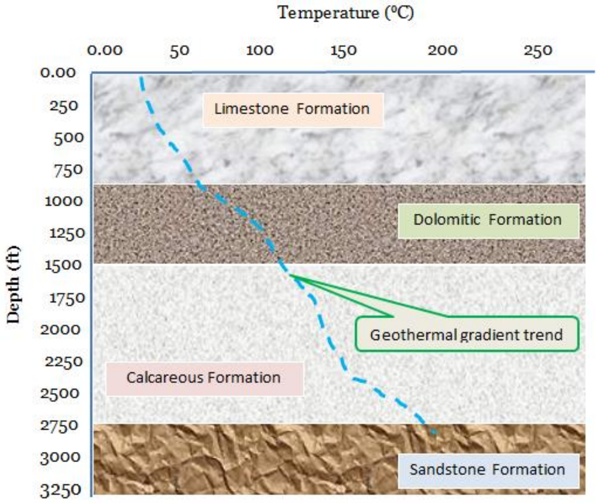



**Figure 13:** shows the average geothermal gradient in rock formations.

For some wells, Figure 14 displays the link between temperature and depth. The link between the two variables is clearly linear.

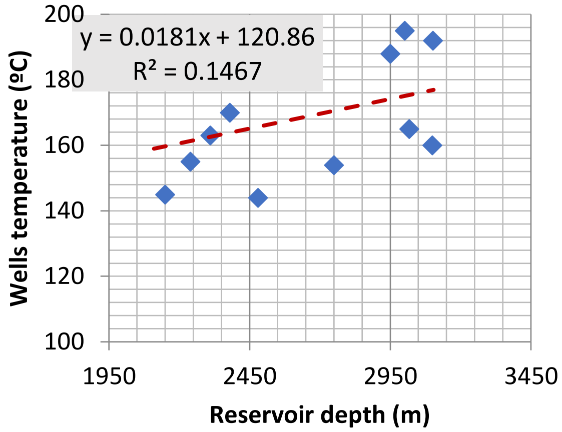



**Figure 14:** Temperature versus depth of investigated wells.

In the end, the potential of geothermal energy utilization can be achieved as a sustainable energy source and a low cost for construction because of the lack of drilling wells through the use of production or abandonment oil wells, in addition to its environmental benefit from the project because it is regarded as a clean energy source due to the lack of emission of greenhouse gases and high capacity factors as well as a small footprint.

## Conclusion

There are obvious differences in the regional geothermal gradient between wells and at different depths. Its average value is 2.90°C°C/100 m, with a range of 2.25–3.19°C. The depth and sedimentary column thickness affect the geothermal gradient. A broad link is found between the depths of several wells under investigation in different formations and the geothermal gradient. It is clear that the quantity of the geothermal gradient affects both the heat flow and the kind of rock and its specific heat.

The average depths of the twelve wells ranged from 2110 to 3102 m, with observed bottom hole temperatures between 144 and 195°C. The bottom hole temperatures recorded in the wells demonstrated that the temperature increased with depth. It may also be categorized as a source of geothermal energy and has a low to medium enthalpy.

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