

Temperatures are Rising – An Introduction to Geothermal

John J. Hirschmiller, P. Geo.

GLJ Ltd., jhirschmiller@gljpc.com, www.gljpc.com

Introduction

Geothermal is a renewable source of continuous reliable energy that can be used for both heat and power generation. Geothermal energy is heat stored and generated within the Earth, partially residual heat from the planet's formation and partially new heat generated by radioactive decay within the Earth's crust. The energy is harnessed as hot water and is brought to surface and used directly for heating and commercial applications, or indirectly for power generation.

Over the last decade there has been increased interest in geothermal energy as a source of clean energy. At the end of 2020 there were 368 geothermal power facilities located around the globe which could provide up to 15,414 MW of electricity capacity (Think GeoEnergy, 2020). Worldwide, these power plants are predominantly in areas with active tectonics and volcanism, such as the "Ring of Fire". These areas have higher volcanic activity which results in higher heat flow and in turn higher geothermal reservoir temperatures. However, in the last few years, there has been increased interest in the potential for geothermal energy from lower temperature sedimentary basins, as well as trying to unlock the potential from deep hot rocks.

Geothermal Geological Settings

The most developed geothermal setting is a hydrothermal/volcanic system. These hydrothermal systems target hot reservoirs proximal to volcanoes. They use hot geothermal fluids which have been heated by being in close proximity to volcanic areas. Historically, they have been the most common type of geothermal system because of the very high temperatures at relatively shallow depth that allow for substantial power generating capacities.

Hydrothermal or volcanic geothermal systems harvest water or steam in the country rock which is proximal to volcanoes or magma chambers. The geothermal reservoirs in the country rock are composed of either sedimentary, fractured igneous or metamorphic rocks and/or rocks located in fault zones.

Geothermal fluids may be created when meteoric water recharge contacts a magma chamber of a volcano. The super-heated water, water under pressure which is over 100°C, migrates away from the volcano into the country rock and eventually to the surface as a hot spring. An optimal geothermal reservoir is situated far enough away from a magma chamber to avoid the considerable number of technical challenges that come with such proximity, but close enough to provide high temperatures. The figure below is a conceptual diagram of a volcanic geothermal system with the blue circle representing the idealized location for a geothermal reservoir in a fluid migration pathway.

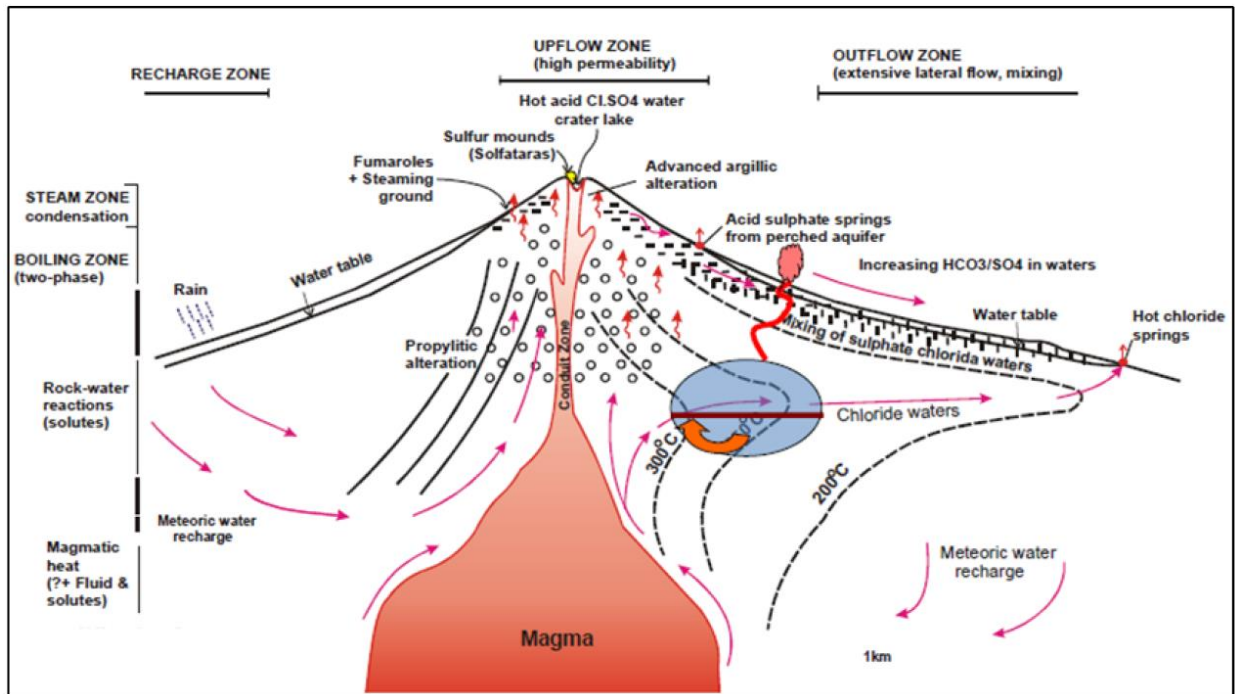


Figure 1: Conceptual Model of a volcanic geothermal system (Ochieng L., 2013).

The second most common geological setting for geothermal energy is in sedimentary basins/hot sedimentary aquifers. Sedimentary basins are an underutilized resource as they are lower temperature than hydrothermal systems. The lower temperature fluid of sedimentary basins requires a higher fluid rate to produce an equal power capacity of a higher temperature resource.

Generally, in sedimentary basins, temperature increases with depth. The change in temperature with depth is the geothermal gradient. The geothermal gradient varies due to many factors, but the primary control is usually proximity to a heat source such as underlying hot basement rocks. By understanding the geothermal gradient, subsurface temperatures can be predicted if the basin's sediment thickness is known. A geothermal gradient can be calculated from temperature measurements recorded at various depths. These data are commonly derived from well bore logging. The formula to calculate geothermal gradient is the following:

$$\text{Geothermal Gradient} = \frac{\text{Temperature at Depth} - \text{Surface Temperature}}{\text{True Vertical Depth}}$$

Currently, direct use geothermal heat projects in Europe have targeted these sedimentary geothermal reservoirs. Direct use geothermal refers to immediately using the produced hot water for heating or cooling applications rather than using the hot water for electricity generation. A problem with reservoirs in sedimentary basins is that in general, the deeper and therefore hotter the reservoir, the lower the porosity and permeability. These lower permeability formations are historically difficult to exploit for geothermal energy using conventional technologies as the required production rates may not be achieved. Utilizing hydraulic fracturing as well as horizontal drilling technology, the permeability of the reservoir surrounding the well bore can be improved.

The increase in permeability will allow increased production rates of hot fluids opening new geothermal potential in sedimentary basins.

Hot and deep systems are a third type of geothermal system. These hot and deep systems target hot, deep, impermeable rock. A fracture network is created to establish permeability within the formation. The fracture network can either be established using hydraulic fracturing, or a technique called hydroshearing. Hydroshearing pumps cold water into the formation to generate fractures due to the temperature difference. These systems in theory could be created anywhere as hot basement rocks are located everywhere below sedimentary cover. There are considerable drill and completion challenges in developing these systems. Currently hot and deep EGS systems are not commercial and are still in trial phases worldwide, particularly in the USA and Europe.

Geothermal Potential in the WCSB

The Western Canadian Sedimentary Basin (WCSB) is a relatively shallow basin, with most of the basin being less than 4000 meters thick, but areally extensive with excellent data availability. These data primarily come from the drilling of a substantial amount of oil and gas wells. The well data allows the geothermal gradient to be mapped and to predict subsurface temperatures. However, some interpretation of the log data may need to be made. For example, bottom hole temperatures (BHT) from wireline logs are generally known to be lower than the actual reservoir temperature. In a localized area, pressure test temperature as well as DST temperature data can help in understanding true temperature as well as using Horner corrections (Lachenbruch and Brewer, 1959). There have been a few published studies over the years which have used a statistical increase in BHT to correct for cooling (Kehle et al., 1970, Harrison, 1983 & Förster and Merriam, 1995). In Alberta, Nieuwenhuis et al. (2015) illustrated BHT in the WCSB are substantially less than pressure test temperatures. This study also had shown even Horner corrections and DST temperatures are lower than pressure test data. BHT from wireline logs can be corrected by applying a bulk shift increase of these BHT so the average temperature gradient of pressure test data, agrees with the average pressure test temperatures.

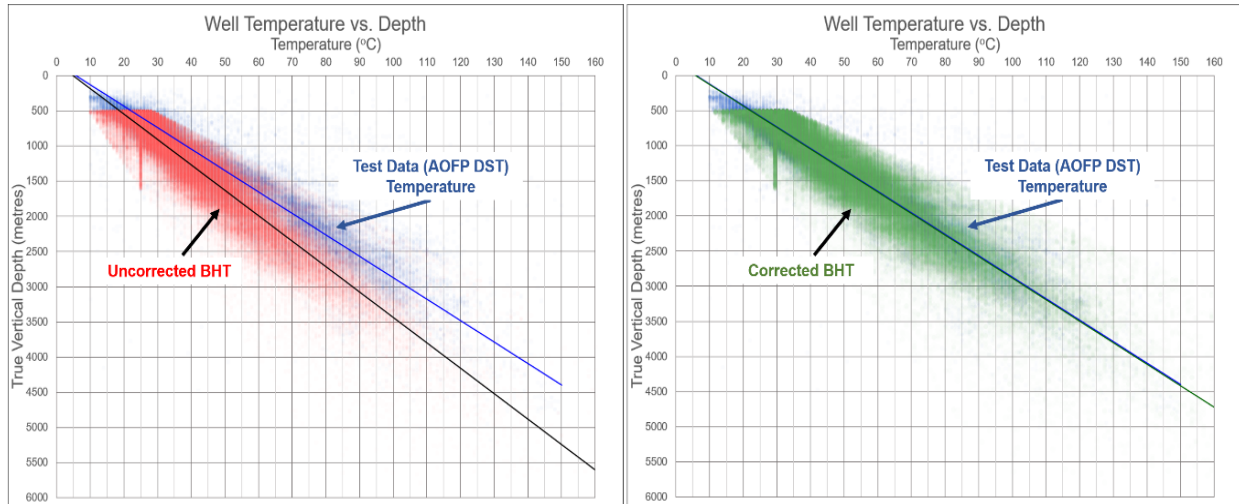


Figure 2: Temperature correction of BHT in the WCSB. A bulk correction was applied to correct the average BHT gradient from wireline logs to correspond to the average pressure test temperature gradient.

With the corrected BHT, a geothermal gradient can be calculated on an areal extent using the geothermal gradient formula described above. The mean surface temperature used in the formula, the X intercept of the line of best fit for the average geothermal gradient, is approximated 5°C in the WCSB. As rock lithologies change with thickness, the thermal properties such as specific heat capacity or thermal conductivity effect the geothermal gradient with depth. However, gradients usually behave linearly and differences seen on a local scale can be averaged in regional mapping. The geothermal gradient was calculated for wells across the WCSB and mapped as an average geothermal gradient using a 5km radius to account for sampling bias as well as vertical differences (Figure 3a).

The geothermal gradient formula can be re-arranged to predict temperature at a particular depth with the formula: $Temperature\ at\ Depth = (Geothermal\ Gradient * TVD) + Surface\ Temperature$. Estimated reservoir temperatures can be calculated at a particular depth, for example at 3000 m (Figure 3b), or temperature can be calculated along a formation structural surface. With structural depth mapping we can understand the maximum temperature of the WCSB. By mapping the true vertical depth (TVD) to the top of the Precambrian basement we can estimate the maximum temperature which could be achieved in the basin (Figures 3c&d). Banks & Harris (2018) completed a similar study looking at the geothermal potential of a handful of formations within the WCSB.

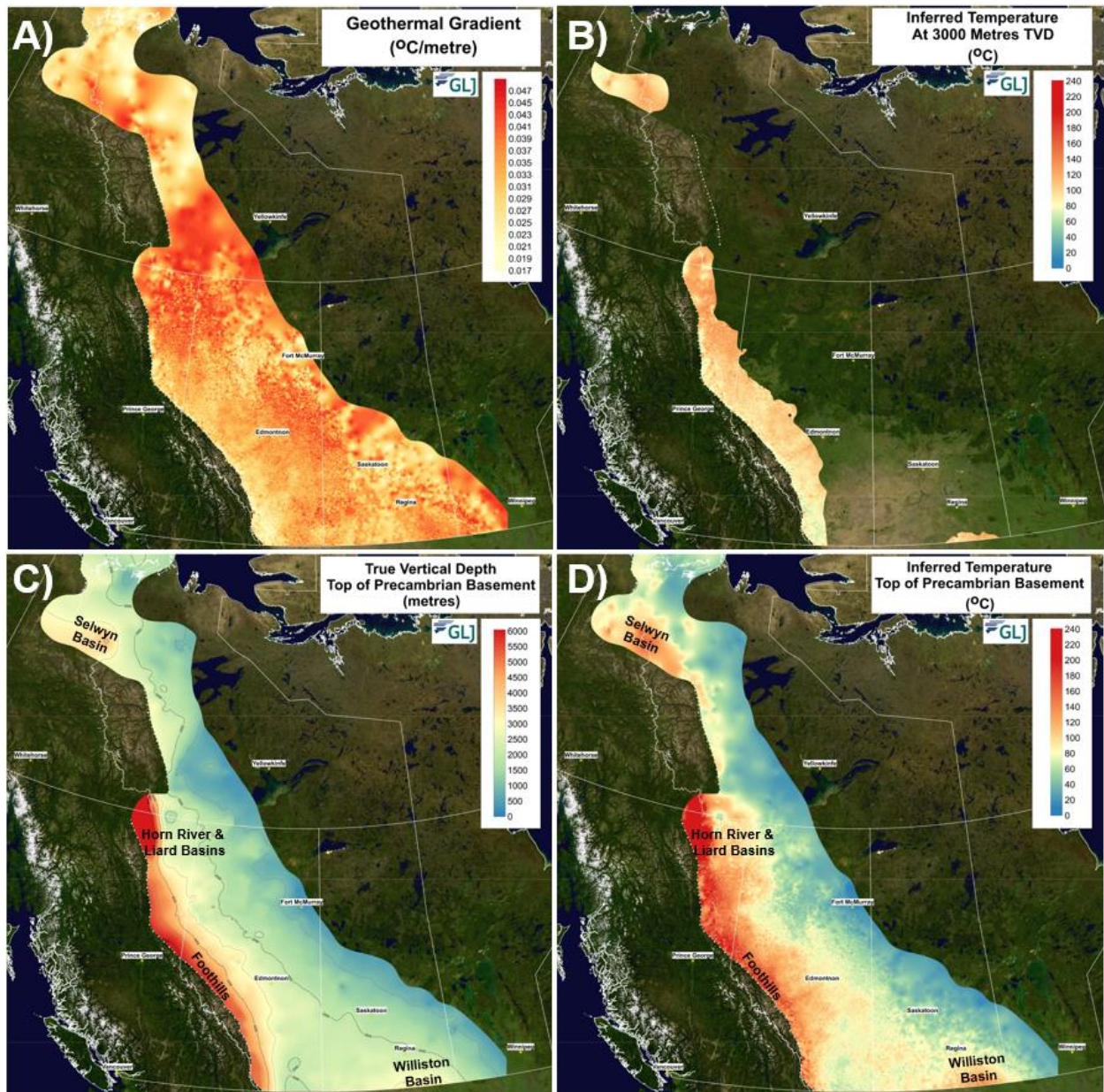


Figure 3: A) Average Geothermal Gradient from corrected BHT and Pressure test temperatures. B) Inferred temperature at a TVD of 3000m. C) TVD to the top of the Precambrian basement. D) Inferred Temperature at the top of the Precambrian basement.



Geothermal Extraction Technology

Geothermal extraction technologies can be grouped into three different categories; conventional geothermal, enhanced geothermal systems (EGS) and advanced geothermal systems (AGS).

Conventional geothermal systems use a producing and injector well pair, or multiple wells usually called doublets (Figure 4a). In a conventional basic system, the producing well pumps hot brine from the formation to a power generating plant or a heat exchanger for a direct use heat application. The produced brine is reinjected into the same formation to maintain pressure, or an adjacent formation if pressure maintenance is not an issue. Currently, almost all the world's geothermal electricity generation is produced from conventional geothermal systems. The downfall to these conventional systems is that a high flow rate is required to generate any significant amount of power. Operational costs from conventional geothermal can be high if substantial pumping is needed to extract the brine. The energy needed for the pumping is referred to as parasitic load.

Enhanced geothermal systems are similar to conventional geothermal systems, however an enhanced fracture network is created to produce fluid from. EGS systems target ultra-hot basement or volcanic rock (Figure 4b). One well injects cold water at high rates, causing the surrounding rock to fracture, also known as hydroshearing. The expectation is to create a fracture network which will communicate with the second producer well. The water injected heats up within the induced fractures and is produced from the producer well. By continuing to inject water, the fracture network will remain open. The development of these systems requires a strong understanding of the geomechanical properties and stresses of the rock to estimate the direction of growth of the fracture network. Currently there have been some trials in Australia, the Rhine Valley in France and Germany and in the United States. However, there is currently no commercial production worldwide from EGS.

Advanced geothermal systems are at the forefront of geothermal technology development. The AGS name is a catch-all name for different technologies which are exploiting new technologies to harvest geothermal energy where conventional geothermal systems have difficulties. For example, closed loop systems have been developed where fluid is pumped down into hot formations, heated by conduction and returned to the surface. The significant difference with closed loop systems is the fluid is isolated from the reservoir. At the surface, the heat is extracted the same, but the cooled fluid is pumped back down and is continually circulated. There have been two notable technologies to date which have demonstration projects utilizing convection technologies: Eavor Technologies Inc. and GreenFire Energy Ltd.

Eavor uses horizontal drilling technology from the oil and gas industry to create an underground radiator (Figure 4c). Multilateral horizontal wells are connected at depth. Cold fluid flows down the inlet well travelling through the horizontal wellbores at depth heating up and travelling up the outlet well as hot fluid. Eavor has completed a successful demonstration project of this technology in Alberta (Vany et al., 2020). GreenFire Energy Ltd. has used a similar technology as Eavor with the use of conduction. With GreenFire's technology, a single well is drilled into hot deep rock up to 350°C (Figure 4d). This technology pumps a fluid of supercritical CO₂ down the inner tubing and up the outer tubing. This fluid heats up at depth and travels up the tubing to a power generator

at surface (Van Horn et al., 2020). GreenFire has demonstrated a successful project in the Coso geothermal field, located in east central California.

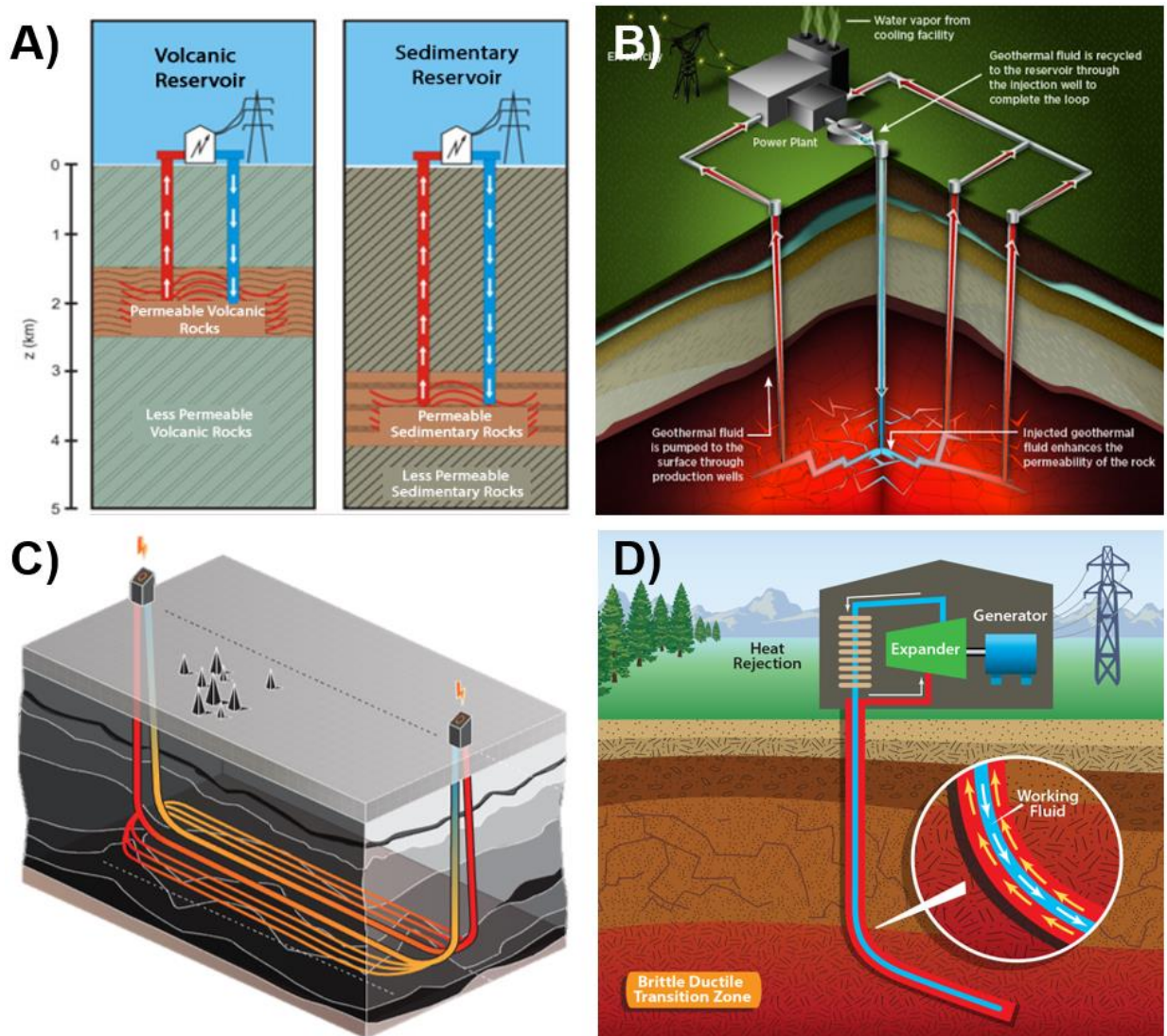


Figure 4: Conceptual diagrams of different geothermal technologies A) Conventional geothermal schematic (Zinsalo & Lamarch 2017) B) EGS diagram (DOE Geothermal Technologies Office, 2012) C) Eavor Loop technology (Eavor Technologies Inc., 2021) D) GreenLoop diagram of closed loop concentric pipe-in-pipe deviated well configuration (Van Horn et al., 2020)

Geothermal Power Plant Types and Design

In the last century, geothermal energy has been used indirectly for power generation, not just as a source of hot fluid for heating. Conventional geothermal power generation can be simplified into three general plant types: dry steam, flash steam, or binary plant/organic rankine cycle (Figure 5). The geothermal plants operate by utilizing hot water or steam from the subsurface. The type

of plant used depends on the type and temperature of the fluid produced from the geothermal wells.

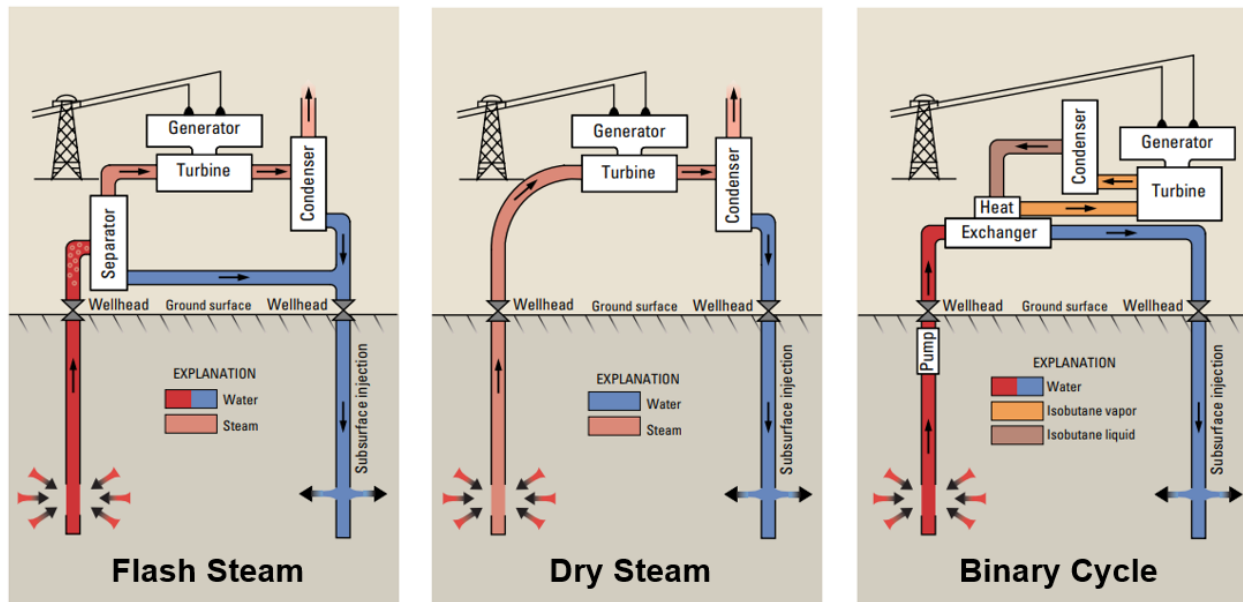


Figure 5: Geothermal power plant types (Duffiel, W. & Sass, J., 2004).

Dry steam plants (Figure 5 - middle) are the simplest and historically most mature technology. Pressurized steam is produced to surface at temperatures above 150°C, with typical plant designs operating with steam temperatures above 240°C. The steam drives a turbine to create electricity and the cooled condensed steam is reinjected into the reservoir.

Flash steam plants (Figure 5 - left) utilize a drop in pressure at the surface causing the pressurized hot water to flash and turn to vapour (steam), which drives the turbine. The steam travels to a condenser which turns the steam to water and is reinjected into the formation. Typically, the fluid temperatures are higher than 160°C.

Binary cycle plants (Figure 5 - right) are a newer technology compared to the other plant types. Binary cycle plants flow the geothermal produced hot water in a heat exchanger. The produced geothermal waters flash the fluid in the heat exchanger to vapour which can then be used to generate electricity. This system allows for power generation using geothermal fluids at temperatures down to 57 °C. This combination of two thermodynamic cycles, one with a higher temperature boiling point (produced hot brine) and one lower a lower boiling point (fluid in the heat exchanger), is what gives it the name binary. The development of the technology is based on the use of fluids which are typically butane or pentane hydrocarbons which are circulated in a closed loop surface system in the heat exchanger. The Organic Rankine Cycle (ORC) plant design is a form of a binary cycle process where the organic refers to the type of fluid.

Geothermal Heat Calculation and Energy Utilization

One of the most widely used methods for estimating geothermal resources, is the heat-in-place method, which is also known as the volumetric method. The heat-in-place method is calculated similarly to how oil-initially-in-place in the oil and gas industry is determined but uses different parameters to account for heat. The method was first proposed by Bolton (1973) and was expanded by Nathenson (1975). The method uses the reservoir's matrix and fluid densities, specific heat capacity of the fluid and matrix, porosity and temperature of the reservoir at depth and at surface. A recovery factor is then applied to the heat-in-place calculation. There are many factors which can go into the recovery factor. Williams (2007) provides a detailed discussion on how to calculate an appropriate recovery factor. Williams (2017) proposed that recovery factors may range from 0.08-0.2 in fracture dominated reservoirs and 0.1-0.25 in sediment hosted reservoirs. Banks & Harris (2018) in their assessment of geothermal potential in areas of the WCSB summarized the complete methodology of calculating heat in place, particularly for sedimentary basins.

Understanding the power generating capacity of a well or reservoir relies heavily on the flow rate from the wells. Sanyal & Butler (2010) presented a correlation of net power versus temperature of the geothermal water. The conclusion of their correlation was at a constant flow rate of 1000 gallons per minute (63 liters/second), the higher the temperature of the geothermal water the higher the generating potential. In the WCSB, geothermal target temperatures are in the range of 110-140°C. With temperatures in this range, projects would estimate to be able to produce around 1 MW of energy with a flow rate of 1000 gallons per minute (Figure 6).

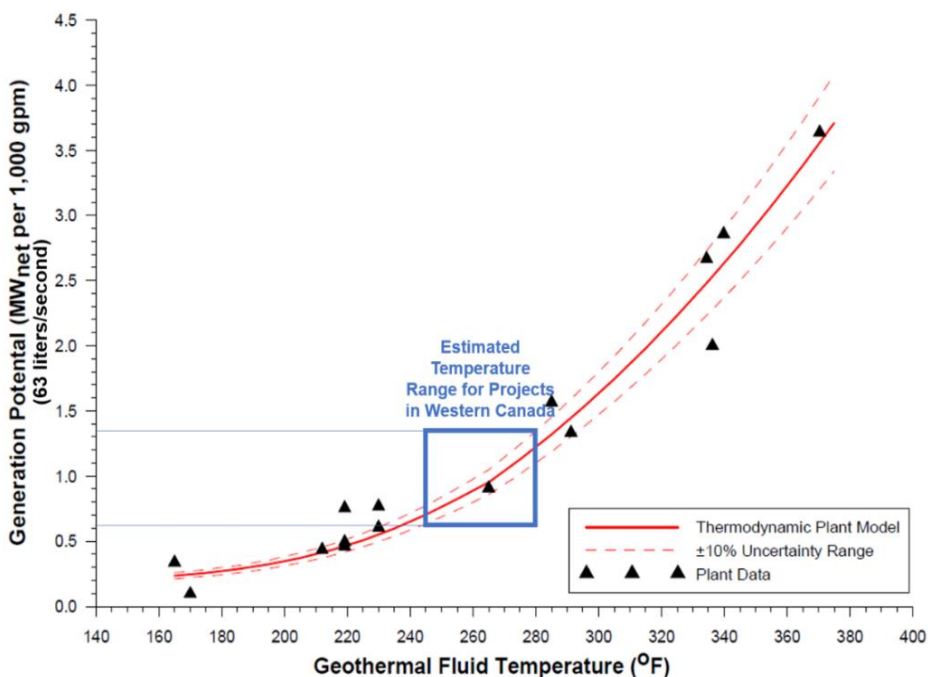


Figure 6: Empirical correlation of net power per 1,000 gallon per minute production versus temperature of geothermal water (modified from Sanyal & Butler, 2010).

Geological settings, extraction technologies and plant types can be summarized on a single chart. Figure 7 illustrates which plant type is suitable by geothermal resource depth, temperature and by geologic setting. Extraction technologies either traditional or new technologies such as EGS and AGS are also included. As deeper, hotter and less permeable reservoirs are targeted, conventional geothermal development moves to new unconventional geothermal technologies. The conventional technologies are typically utilized in the top half of the chart and in porous sedimentary rocks. Emerging unconventional technologies such as EGS and AGS may need to be utilized in the bottom deeper portion of the chart even though some conventional projects have had success in these hot and deep rocks.

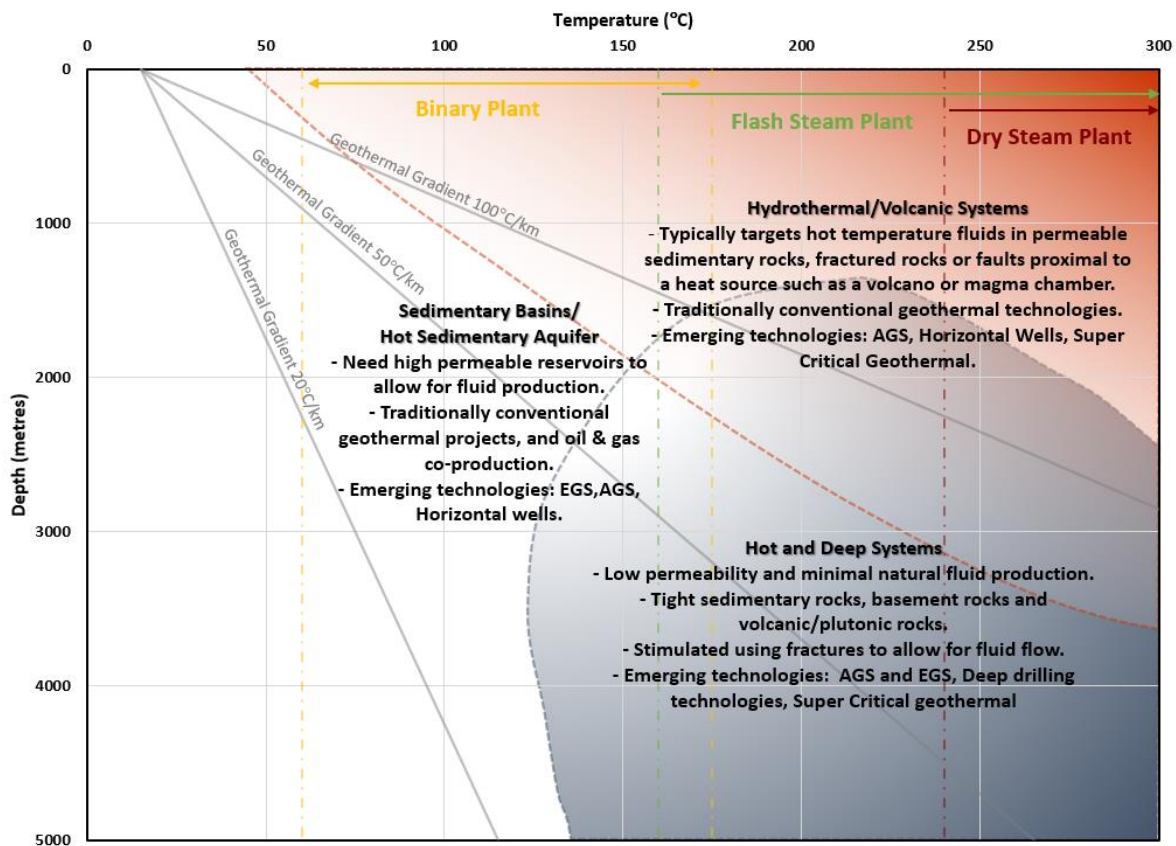


Figure 7: Geothermal technology by depth and temperature.

Summary

In the last few years there has been a significant increase in the geothermal potential in Canada. With the large availability of subsurface data in the WCSB, from oil and gas exploration and development, there is the ability to map and understand the potential for geothermal and reduce exploration risks. Drilling equipment is readily available, and drilling costs are significantly less than in many countries worldwide, making Canada an attractive environment for geothermal development.



References

- Banks J., Nicholas B. Harris N. B., (2018) Geothermal potential of Foreland Basins: A case study from the Western Canadian Sedimentary Basin, *Geothermics*, Volume 76, Pages 74-92, ISSN 0375-6505, <https://doi.org/10.1016/j.geothermics.2018.06.004>.
- Bolton, R.S. (1973) Management of a geothermal field. In *Geothermal Energy—Review of Research and Development*; Armstead, H.C.H., Ed.; The United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France; pp. 175–184.
- DOE Geothermal Technologies Office (2012) What is an Enhanced Geothermal System. https://www1.eere.energy.gov/geothermal/pdfs/egs_basics.pdf
- Duffiel, W. & Sass, J. (2004) *Geothermal Energy – Clean Power from the Earth’s Heat*. U.S. Geological Survey (USGS), Circular 1249. <https://pubs.usgs.gov/circ/2004/c1249/>
- Eavor Technologies Inc. (2021). Eavor-Loop™ Process Diagram. <https://eavor.com/about/technology>
- Förster, A., Merriam, D.F., and Davis, J.C., (1996) Statistical analysis of some bottom-hole temperature (BHT) correction factors for the Cherokee Basin, southeastern Kansas: *Tulsa Geol. Soc. Trans.*, pp. 3-9.
- Harrison W. E., Luza, K.V., Prater, M. L., and Chueng, P. K., (1983) Geothermal resource assessment of Oklahoma, Oklahoma Geological Survey, Special Publication 83-1.
- Kehle, R.O., Schoepel, R. J., and Deford, R. K., (1970) The AAPG Geothermal Survey of North America, *Geothermics*, Special Issue 2, U.N Symposium on the Development and Utilization of Geothermal Resources, Pisa 1970, Vol. 2, Part 1.
- Lachenbruch A.H., Brewer M.C. (1959) Dissipation of the Temperature Effect of Drilling a Well in Arctic Alaska, *Geol. Surv. Bull.* 1083-C.
- Nathenson, M. (1975) Physical Factors Determining the Fraction of Stored Energy Recoverable from Hydrothermal Convection Systems and Conduction-Dominated Areas; Open-File Rept. 75-525; U.S. Geological Survey: Menlo Park, CA, USA.
- Nieuwenhuis, G., Lengyel, T., Majorowicz, J.A., Grobe, M., Rostron, B., Unsworth, M.J., Weides, S., (2015) Regional-scale geothermal exploration using heterogeneous industrial temperature data; A case study from the Western Canadian Sedimentary Basin. In: *Proceedings of the World Geothermal Congress*. Melbourne, Australia, 19–25 April.
- Ochieng, L. (2013) Overview of Geothermal Surface Exploration Methods, Short Course VIII on Exploration for Geothermal Resources, *UNU-GTP, GDC and KenGen*, Lake Bogoria and Lake Naivasha, Kenya Oct 31-Nov 22, 2013.
- Sanyal S.K., Butler S.J. (2010) Geothermal Power Capacity from Petroleum Wells – Some Case Histories of Assessment, *Proceedings of the World Geothermal Congress*, Bali, Indonesia, 25-29 April 2010.
- Think GeoEnergy (2020), Global Geothermal Powerplant Map, <https://www.thinkgeoenergy.com/map/>
- Van Horn, A., Amaya, A., Higgins, B., Muir, J., Scherer, J., Pilko, R., & Ross, M. (2020). New Opportunities and Applications for Closed-Loop Geothermal Energy Systems. *GRC Transactions*, 44. Available from Geothermal Rising Library: <https://www.geothermal-library.org/>
- Vany, J., Hirschmiller, J., Toews, M., (2020) Subsurface Characterization Methods For Multilateral Closed Loop Geothermal Systems. Case Study of Field Scale Technology Demonstration Project in Alberta, Canada., *Geoconvention 2020*, Calgary Alberta, September 21-23, 2020.
- Williams, C.F. (2007) Updated methods for estimating recovery factors for geothermal resources. In: *Proceedings, Thirty-Second Workshop on Geothermal Reservoir Engineering*. Stanford University, January 22–24, 2007, SGP-TR 183. 7 p.



Zinsalo, Lamarche. (2017) Electricity Generation from Deep Geothermal Energy, May 01, 2017, www.substance.etsmtl.ca/en/electricity-generation-from-deep-geothermal-energy