Contents

Chapter 9

Chapter 10

Chapter 11

Chapter 12

Chapter 13

Appendix B

15

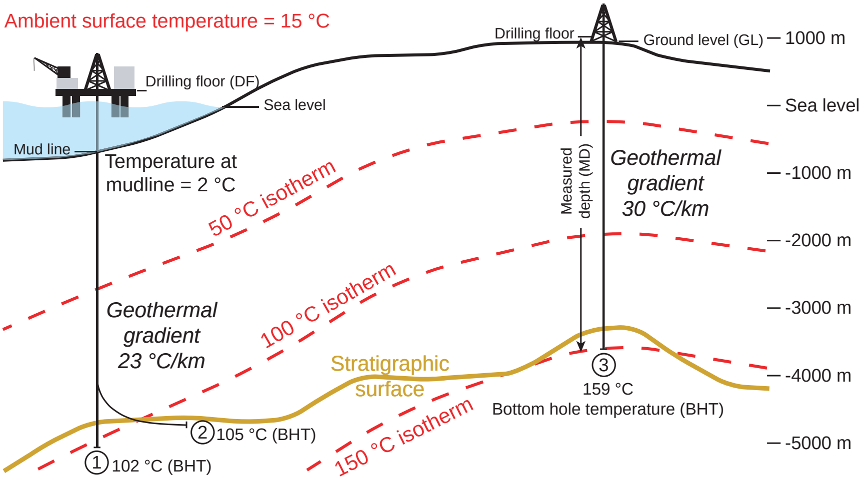
Geothermal and Temperature Maps

Temperature variability within the Earth is an important factor that impacts a wide range of fields. Temperature data are commonly used in geothermal energy assessments, source rock maturity estimates, reservoir diagenetic models, porosity-permeability estimates, mining operational depths, fault detection, resource estimates, and identification of drilling depths or floors at which tools can no longer operate, among other purposes. There are many ways to gather temperature data, from satellites to deep wellbores that penetrate oceanic or continental crust. Most wells fortunately contain temperature data in the form of a maximum bottom-hole temperature (BHT) found within the well header. Many operators also run a continuous temperature log, but these data are more difficult to collate. The most difficult data to collect are often thermal conductivity data, which are required to do thermal modeling. In areas without subsurface data, it is common to use a geothermal gradient of ~25°C/km, which is a typical gradient for wells on continental crust. The average heat flow value for continental crust is ~65 mW/m^2. These values cannot be used for wells on oceanic crust, where values are usually lower, but can be considerably higher (>100 mW/m^2). Heat flow on oceanic crust is a function of crustal age (Fowler 2012).

Temperature data are very valuable but can be underutilized for a number of reasons. These include issues related to corrections, differences in shallow vs. deep well measurements, reported heat flow calculations rather than temperature and thermal conductivity, seasonal-to-diurnal changes, nonunique modeling, the presence of thick salt units, and other data nuances. From a data standpoint, there are many good public domain sources that can be utilized. BHTs and geothermal gradient data are also found in many online resources and within some academic sources. Global satellite and climate data can be used to estimate the mean annual surface temperature, which is needed to calculate geothermal gradients and predict subsurface temperatures.

Temperature Maps

Three common temperature-related maps are: (1) geothermal gradients; (2) the temperature at a specific depth or horizon; and (3) the depth to a certain isotherm (fig. 15–1). Geothermal gradient maps illustrate the lateral variability in the subsurface heat flux, with the Earth's surface as the datum. Typically, the gradient is calculated from ground level or sea bed to the bottom-hole temperature minus the average surface temperature. The units most commonly used are degrees Celsius per kilometer (°C/km), but occasionally other units are used, such as degrees Fahrenheit per thousand feet (°F/1,000 ft) or Kelvin per kilometer (K/km). A heat flow map is similar to the geothermal gradient map, except the heat flow data incorporate the thermal conductivity of the sediment or rock and will be reported in milliwatts per square meter (mW/m^2). It is not always clear what or how much thermal conductivity data were used to convert the temperature data, so it is recommended that the data and maps be kept separate.



1) DF = 30 m; Mud line = -650 m; MD = 5030 m; TVDss = -5000 m; BHT = 102 °C
2) DF = 30 m; Mud line* = -250 m; MD = 5300 m; TVDss = -4700 m; BHT = 105 °C
3) DF = 1000 m; GL = 993 m; MD = 4800 m; TVDss = -3800 m; BHT = 159 °C
*Mudline was approximated to calculate amount of strata above the bottom hole location

Fig. 15–1. An example of subsurface isotherms and calculated geothermal gradients for onshore and offshore wells.

Another common temperature map is an estimation of temperatures at a depth or horizon. This can be thought of as a depth slice through a seismic volume at a consistent depth or as an attribute overlain on a surface with variable depths. These maps are very useful when dealing with temperature-related chemical reactions and variables sensitive to pressure and volume (e.g., resource estimates, reservoir diagenetic models, porosity-permeability estimates, and source rock maturity estimates). Many of these transformations or reactions can occur very quickly at specific temperatures, and therefore it is important to recognize the error bars associated with the temperature measurements, the temperature corrections, and the depth to the horizon.

The last common type of temperature-related map is the depths to significant isotherms map, which is used to depict the depth at which a particular temperature occurs. This type of map can be used to high-grade areas that are more prospective to geothermal energy development, estimate the depth at which subsurface mining may no longer be feasible, or determine at what depths certain drilling and completion technologies may not work. The equations to calculate a geothermal gradient, temperatures at a depth or horizon, and isotherm depths are listed below as equations (15.1)–(15.3). There are no standard units, but it is important to use the same units (e.g., °C or °F, and feet or meters). Also, be careful in areas where the surface elevations are subsea, and in deviated or horizontal wells that only the TVD values are utilized.

$$\text{Geothermal gradient} = (\text{BHT}_c - \text{T}_{surf}) / \text{Z} \tag{15.1}$$

$$\text{Temperature at a depth or horizon} = [(\text{Elv}_{surf} - \text{horizon depth in TVDss}) \times \text{geothermal gradient}] + \text{T}_{surf} \tag{15.2}$$

$$\text{Isotherm depth} = \text{Elv}_{surf} - [(\text{isotherm temperature} - \text{T}_{surf}) / \text{geothermal gradient}] \tag{15.3}$$

where:

BHT_c = Corrected bottom-hole temperature
T_{surf} = Mean annual surface temperature
Z = TVD below ground level or seafloor
Elv_{surf} = Surface elevation

Bottom-Hole Temperature Corrections

BHTs need to be corrected if they are extracted from the well header, and this can be achieved using one of the many BHT correction equations, such as equation (15.4) from Waples et al. (2004). Most of the equations use the maximum BHT, the depth of the measurement, and the time since drilling fluids were last circulated. Occasionally, information regarding the borehole radius and conductivity information may be needed, but these data rarely significantly impact the estimates. In practice, deeper wells and wells that have more time to equilibrate with the ambient formation temperature have smaller correction factors. Wells that stop circulation and record the BHT within 24 hours can have corrections ~5°–10°C (i.e., the formation temperature will be higher than the recorded BHT). Shallow wells (<1,000 meters), wells that encounter significant amounts of gas, and wells near salt bodies are prone to highly variable measurements due to the high thermal conductivity of salt, the cooling effect of gas expansion, and shallow influxes of meteoric water. If these conditions are present, the data will potentially need further interrogation to see if they are appropriate to use. For example, below thick salt intervals, the geothermal gradient is commonly less than the geothermal gradient above the salt unit. Therefore, it may not be appropriate to use one geothermal gradient for the entire wellbore depending on the purpose of the map. In this example, two separate geothermal gradients are commonly used (one suprasalt and one subsalt).

$$\text{Corrected BHT} = T_{surf} + 1.32866^{(-0.005289\times TSC)} \times (\text{measured BHT} - T_{surf}) - 0.001391 \times (Z - 4{,}498) \tag{15.4}$$

where:

BHT = Bottom-hole temperature (°C)
T_{surf} = Mean annual surface temperature (°C)
TSC = Time since mud was last circulated, recorded in the well header (hours)
Z = TVD below ground level or seafloor (meters)

Thermal Modeling

From a modeling perspective, temperatures measured within the lithosphere and sedimentary cover come from three main sources (the mantle, the upper crust, and sedimentary rocks). The thickness of the lithosphere typically is between 40 km and 140 km on oceanic crust and is thicker beneath continental crust (up to ~300 km). The source of geothermal heat is mainly from deep within the Earth and is caused by the decay of radioactive isotopes (mainly uranium, potassium, and thorium). The dominant controlling factor in surface heat flow is the depth to top of the asthenosphere and the thermal conductivities of the intervening rock intervals (fig. 15–2). Unfortunately, these are the least constrained modeling inputs (Allen and Allen 2005). Two perhaps underappreciated factors that impact thermal modeling are the sedimentary rate and the age of the sedimentary fill. Younger sediments and higher sedimentary rates tend to drive down the geothermal gradient because the sediments likely will have lower thermal conductivity due to less compaction. It takes time for temperatures to equilibrate.

Complicating modeling efforts are the variable subdivisions of the Earth's crust and lithospheric based on different thresholds (mechanical, compositional, seismic velocity, thermal, etc.). The depth of the asthenosphere can be somewhat constrained by the Moho discontinuity, which is seismically imageable and will be shallower than the asthenosphere. The depth to the Moho on oceanic crust

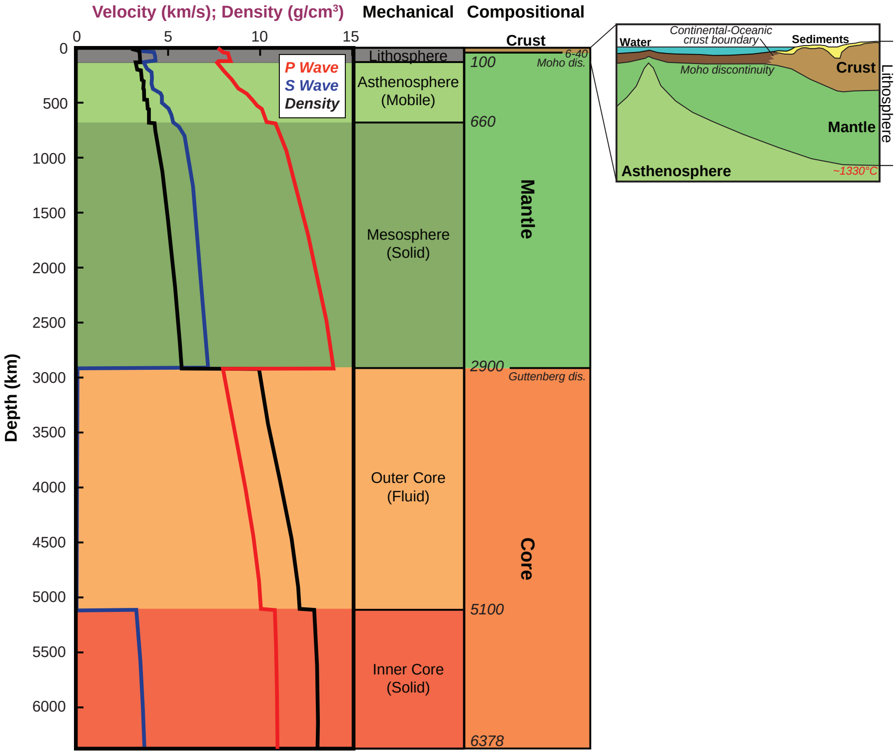


Fig. 15–2. A profile through the Earth with an inset view of the lithosphere. The three main sources of heat measured at the Earth's surface come from the asthenosphere, continental crust, and radioactive materials in the sedimentary section. On oceanic crust, the dominant source of heat comes from the asthenosphere and is a function of crustal age.

Sources: Profile adapted from Carpenter and Keane 2016, Fowler 2012.

will average around 5 to 10 km. The Moho depth will be between 20 and 90 km on continental crust (Hacker et al. 2015). A good average depth to the Moho on the continental crust is ~35 km based on various global potential field models and regional seismic lines. The asthenosphere is also generally aseismic due to its ductile or plastic character, so deep earthquake data may also provide an estimate for the base of the lithosphere. These data are freely available from agencies such as the USGS. In active rifts and oceanic spreading centers, the asthenosphere can be quite shallow, with a thin lithosphere. The lithosphere will gradually thicken away from the rifts to typical depths of more than 100 km (Allen and Allen 2005). In subduction zones, the depths to the Moho and asthenosphere are more difficult to resolve and thermally model.

Crustal type is also important because oceanic crust lacks many of the radioactive minerals that can provide appreciable heat within continental crust. In most offshore areas, it may be difficult to know if an area is underlain by continental, oceanic, or some type of transitional/thinned continental crust (fig. 15–2). Many authors will delineate the transition as a continental-oceanic boundary or transition (COB or COT) (e.g., Allen and Allen 2005, Broad et al. 2012). There is a general observation that oceanic crust is usually found at water depths greater than ~3,000 m (~10,000 ft or 4.0 s TWT). This general bathymetric estimate can be very useful if there are no other regional data available (i.e., deep seismic, gravity, or magnetic data).

Thermal modeling should focus not only on matching temperature data but also on matching the thermal maturity of the sediments by incorporating the burial history for a given area (fig. 15–3). This additional complexity is needed for predictive petroleum modeling, but less so for geothermal exploration. Many sedimentary basins have been exposed to polyphase deformation throughout geologic time, with differing thermal regimes. Heat pulses may have occurred during past rifting events, whereas orogenic processes (i.e., mountain building) may have lowered the heat flow. Volcanism and igneous intrusions also cause localized temperature perturbations in the subsurface, all of which will impact the thermal models and thermal maturity (Allen and Allen 2005). Generally, sills or dikes will cause perturbations on the order of 1 to 2 times the thickness or width of the intrusion (Dow 1977). In contrast, regional volcanism related to subduction zones can cause regional variability (e.g., low geothermal gradients in the fore arc, while the arc and back-arc areas will have high geothermal gradients). Overall, thermal modeling is very difficult and time consuming but is necessary for predictive estimates of subsurface temperatures. It is worth the effort, with the realization that the solutions are nonunique and often yield medium to low confidence estimates.

Geothermal Resources

Geothermal resources are commonly classified into several categories (warm water, hot water/steam, and hot dry rock; fig. 15–4). Warm water resources are available in most regions of the world but may not be cost-effective (Barbier 2002). These resources are not produced in a conventional sense, but relatively shallow wells provide warm water that is circulated around a building or home to warm the building in the winter. Some more advanced systems also provide cooling options during the summer by transferring heat into the ground in the summer. This is the most common form of geothermal energy and is available through various companies. The cost of these systems can be expensive, and economic payback may take a long time. In some countries solar-heated versions of this system are installed on or near homes.

A hot water/steam geothermal system is the type of geothermal resource that often comes to mind when people think of geothermal energy, with visions of

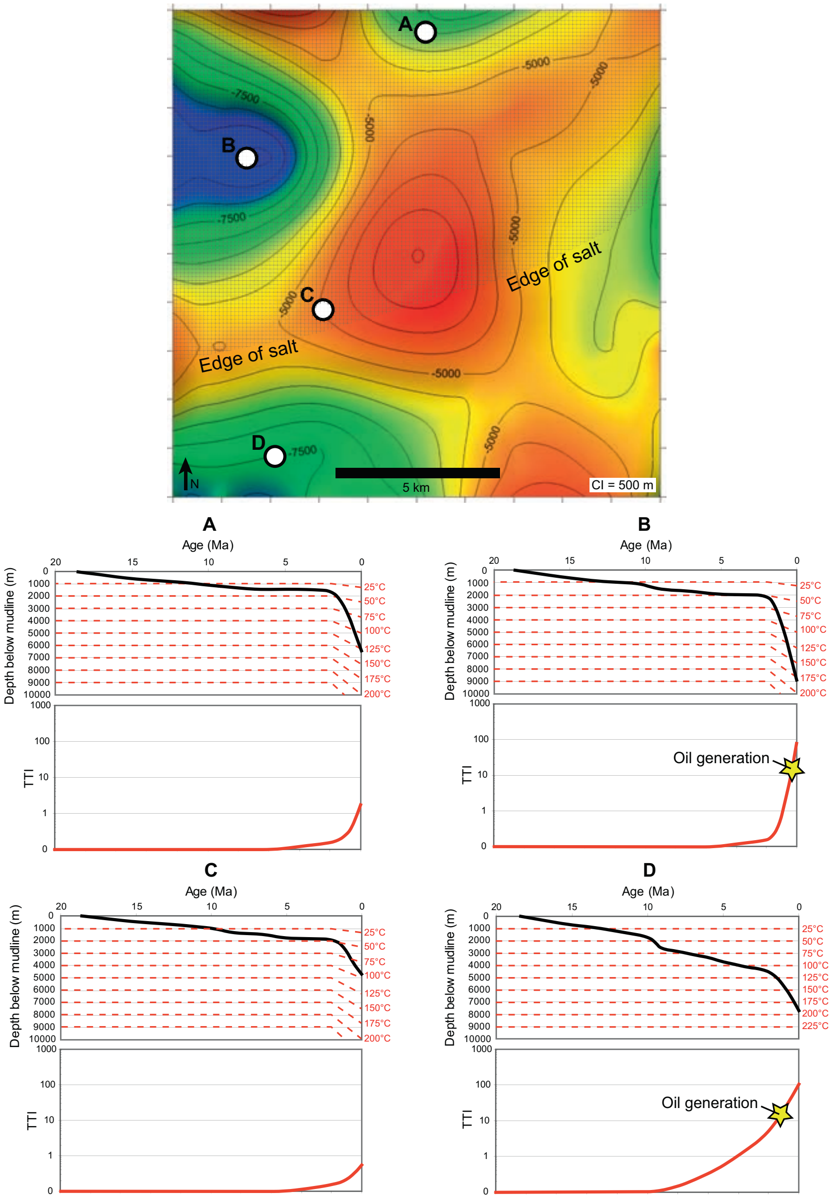
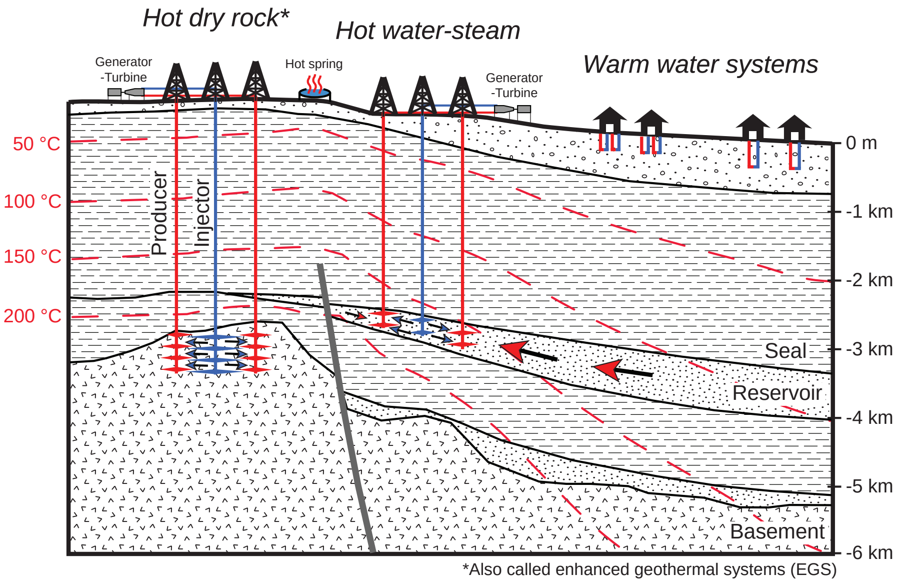


Fig. 15–3. An example of four wells that have similar burial histories but with variations due to the potential source rock maturing at different times, depending on the cumulative thermal stress experienced (based on time-temperature index calculations and relationships from Waples [1980]). Even though well B is currently the deepest well, it was not the first well to generate oil because well D has experienced hotter temperatures for a longer period of time. This example also includes a salt canopy that was emplaced recently, which is reflected in the slightly lower geothermal gradients postemplacement (~1–2 Ma) in models A, B, and C.



*Also called enhanced geothermal systems (EGS)

Fig. 15–4. A schematic figure showing warm water, hot water/steam, and hot dry rock geothermal systems that can be used for power generation or home heating and cooling.

nearby hot springs, geysers, steam vents, and volcanos. This type of geothermal system usually is focused on generating electrical energy via one or more turbines driven by steam and hot water. To produce steam at pressures that will economically generate electricity, not only high temperatures (typically 100°C–350°C) are required, but also high geothermal gradients (to lower drilling depths/costs). The facility must also be located in reasonable proximity to the energy consumer. Hot water/steam systems also require a reservoir with high porosity and permeability, capable of flowing high rates of water or steam with minimal contaminants (Barbier 2002). The facilities will remain in operation longer if pressures can be sustained. Higher pressures will greatly help the rate at which water steam is produced and plant output. Lower pressure reservoirs or reservoirs with limited extent may quickly require pumps, and those extra costs may not be economically recoverable. There are many different development schemes used in hot water/steam systems. In some systems the steam, water, and vapor physically spin the turbine, and in others there is a heat exchange system that heats a low boiling point fluid that spins the turbine (Barbier 2002). The latter may not be as effective, but the turbine and machinery will require less maintenance. The number of wells and types of wells required will also differ among plants because the subsurface geology is different. Some plants may require numerous injection wells (if pressures or water rates drop too low), while others may not. As in conventional oil and gas fields, there will be a time when a plant will have to be abandoned due to decreasing economic returns.

The last type of geothermal system is hot dry rock, frequently referred to as an *enhanced geothermal system* or an EGS. Locations that can support large hot water/steam geothermal power plants are limited. Many places lack adequate subsurface reservoirs capable of producing high rates of hot water. EGS systems attempt to circumvent this issue by generating artificial reservoirs in areas with high geothermal gradients by using oil and gas drilling and completion techniques. This system relies on hydraulically fracturing a brittle formation or even basement and establishing an open fracture network between injector and producer wells. As water is injected into the hot reservoir, the water will be heated as it passes through the artificial reservoir and then is returned to the surface power plant via one or more producer wells. In ideal conditions, the systems will be a closed loop, with the produced steam/water being reinjected into the reservoir after cooling. EGS systems have the potential to be developed around the world, but costs can be very high (Barbier 2002). Many countries are considering EGS systems and examining different ways to drive down production and development costs, along with the length of time required to set up a facility.

Exercise

15–1) Gold and other precious minerals are commonly located within seams that can be related to the fault zones. Some of the deepest gold mines in the world are about 4 km in depth, where water-chilled air and oxygen must be injected in the mine to keep the air breathable and cool enough that workers can work safely. Assuming the formation or rock temperature limit of the mining operation in figure 15–5 is 50°C (122 °F) and the geothermal gradient does not vary appreciably over the area, at what depth would subsurface mining operations have to stop? Using this depth cutoff and the structure contour map, calculate the volume (bulk rock volume) of gold seam that can be accessed.

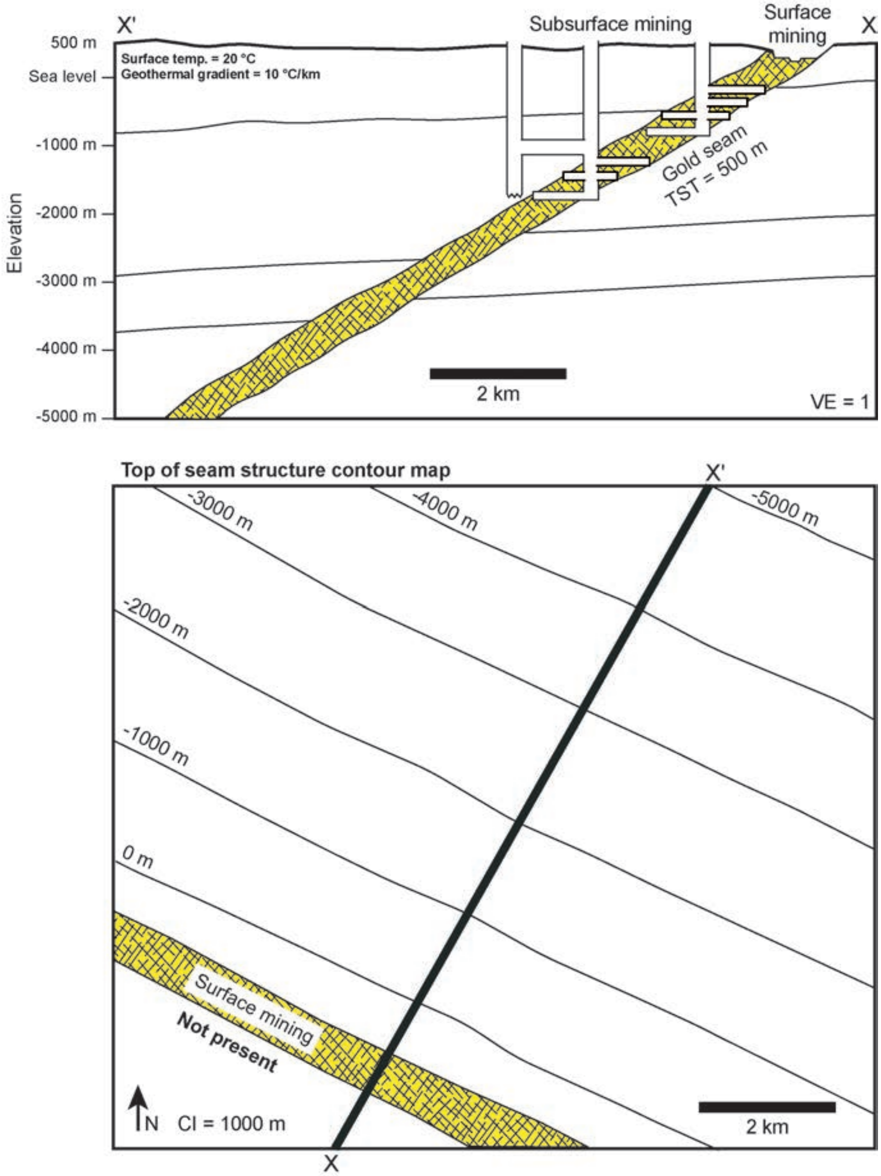

X'
Subsurface mining
Surface mining
X
500 m
Sea level
Surface temp. = 20 °C
Geothermal gradient = 10 °C/km
-1000 m
-2000 m
-3000 m
-4000 m
-5000 m
Elevation
Gold seam
TST = 500 m
2 km
VE = 1
Top of seam structure contour map
X'
-3000 m
-4000 m
-5000 m
-2000 m
-1000 m
0 m
Surface mining
Not present
N
CI = 1000 m
2 km
X

Fig. 15–5.

Questions

1) What are three common types of temperature-related maps?

2) Why do BHTs not reflect the actual in-situ formation temperature and require correction?

3) Well 41-067-20017 in the Swan Creek field has a surface elevation of 399 meters and was drilled to a depth of 3,631 ft TVDss. The corrected BHT was calculated as 47°C, and mean annual temperature of the area is 15°C. What is the geothermal gradient for this well?

4) What are three main categories of geothermal resources?

5) What five factors will help make a geothermal energy project economically feasible?