

1. INTRODUCTION

The word "geothermal" comes from the combination of the Greek words *gê*, meaning Earth, and *thérm*, meaning heat. Quite literally geothermal energy is the heat of the Earth. It is a clean, renewable resource that provides energy around the world in a variety of applications and resources. It is considered a renewable resource because the heat emanating from the interior of the Earth is essentially limitless. Although areas with telltale signs like hot springs are more obvious and are often the first places geothermal resources are used, the heat of the earth is available everywhere, and we are learning to use it in a broader diversity of circumstances. Geothermal resources are concentrations of the Earth's heat, or geothermal energy, that can be extracted and used economically, now or in the reasonable future.

Spatial variations of the thermal energy within the deep crust and mantle of the Earth give rise to concentrations of thermal energy near the surface of the Earth that can be used as an energy resource. Heat is transferred from the deeper portions of the Earth by conduction through rocks, by the movement of hot, deep rock toward the surface, and by deep circulation of water. Most high-temperature geothermal resources are associated with concentrations of heat caused by the movement of magma (melted rock) to near-surface positions where the heat is stored. Since rocks have relatively small thermal conductivity, very large intrusions of magma may take millions of years to cool.

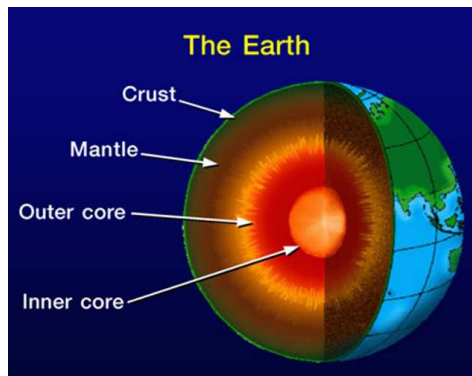


Fig.1.1. Inner structure of the Earth

Our planet consists of a *crust*, which reaches a thickness of about 20-65 km in continental areas and about 5-6 km in oceanic areas, a *mantle*, which is roughly 2900 km thick, and a *core*, about 3470 km in radius (Figure 1.1). The physical and chemical characteristics of the crust, mantle and core vary from the surface of the Earth to its centre. The outermost shell of the Earth, known as the *lithosphere* (Fig.1.2), is made up of the crust and the upper layer of the mantle and it behaves as a rigid body. Ranging in thickness from less than 80 km in oceanic zones to over 200 km in continental areas, the lithosphere behaves as a rigid body. Below the lithosphere is the zone known as the *asthenosphere*, 200-300 km in thickness, and of a 'less rigid' or 'more plastic' behavior.

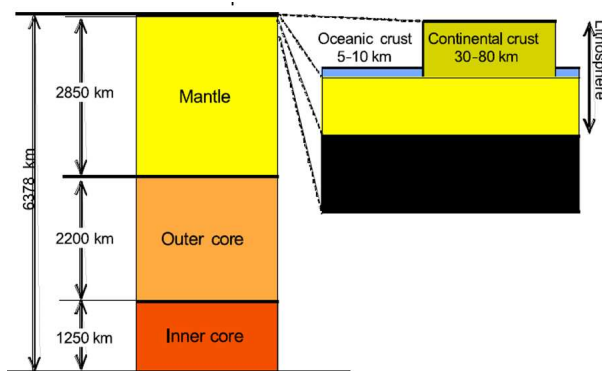


Fig.1.2. Cross section of the Earth [43]

According to Stacey and Loper (1988), the total flow of heat from the Earth is estimated at 42×10^{12} W (conduction, convection and radiation) of which 8×10^{12} W came from the crust (Fig.1.1), i.e from only 2% of the total volume of the Earth but rich in radioactive isotopes, $32,3 \times 10^{12}$ W comes from the mantle (82% of the volume) and $1,7 \times 10^{12}$ W comes from the core (16% of the volume with no radioactive isotopes). Since the radiogenic heat of the mantle is estimated at 22×10^{12} W, the cooling rate of this part of the Earth is $10,3 \times 10^{12}$ W.

With increasing depth through crust, from the surface to the interior of the Earth, temperature raise for $(17 \div 30) \text{ }^\circ\text{C} / \text{km}$. This increasing of temperature is called the temperature gradient and it varies based on factors such as the porosity of the rock, the degree of liquid saturation of the rock and sediments, their thermal conductivity, their heat storage capacity and the vicinity of magma chambers or heated underground reservoirs of liquid.

For example, if the temperature within the first few meters below ground-level, which on average corresponds to the mean annual temperature of the external air, is $15 \text{ }^\circ\text{C}$, then we can reasonably assume that the temperature will be about $65^\circ\text{-}75 \text{ }^\circ\text{C}$ at 2000 m depth, $90^\circ\text{-}105 \text{ }^\circ\text{C}$ at 3000 m and so on for a further few thousand meters. There are, however, vast areas in which the geothermal gradient is far from the average value. In areas in which the deep rock basement has undergone rapid sinking, and the basin is filled with geologically ‘very young’ sediments, the geothermal gradient may be lower than $1 \text{ }^\circ\text{C}/100 \text{ m}$. On the other hand, in some ‘geothermal areas’ the gradient is more than ten times the average value.

A high temperature gradient means that in order to obtain the same energy output, boreholes can be drilled less deep than with lower temperature gradients. This has a direct effect on costs.

Figure 1.3 shows the temperature profile of Earth crust.

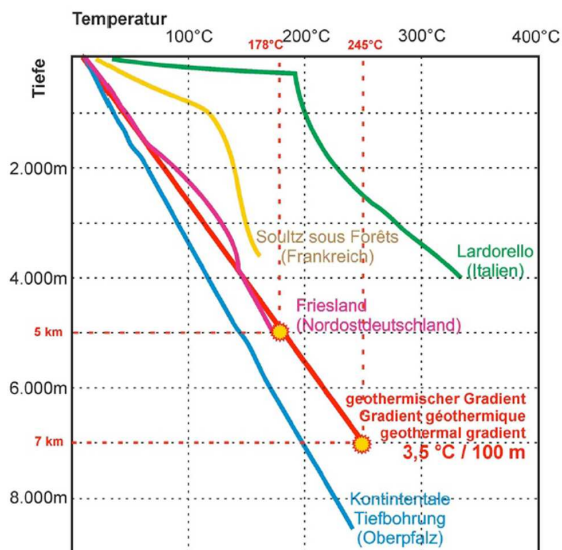


Fig. 1.3. Temperature profile of Earth crust

table for electrical generation is about 135°C . Geothermal resources occur in areas of higher-than-average subsurface temperatures.

The difference in temperature between deep hotter zones and shallow colder zones generates a conductive flow of heat from the former towards the latter, with a tendency to create uniform conditions, although, as often happens with natural phenomena, this situation is never actually attained. The mean *terrestrial heat flow* of continents and oceans is 65 and 101 W/m^2 , respectively, which, when areally weighted, yield a global mean of 87 W/m^2 (Pollack *et al.*, 1993).

Average geothermal heat flow through a crust to the surface of the Earth, with a temperature gradient of $30^\circ\text{C}/\text{km}$ is $0,06 \text{ W/m}^2$. For regions with higher temperature gradient, geothermal heat flow is $(10\div 20) \text{ W/m}^2$. The interior of the Earth is expected to remain extremely hot for billions of year to come, ensuring an essentially limitless flow of heat. Therefore, these

Because the temperature of the earth's crust rises with increasing of depth, allows convection of heat from the core to the surface of the Earth. Temperature increasing (temperature gradient) is different in different parts of the Earth and it ranges from 10 to over $80^\circ\text{C}/\text{km}$. Average increasing of temperature is about $30^\circ\text{C}/\text{km}$. Geothermal heat flow is changed by changing the temperature gradient.

Temperature increases with depth within the Earth at an average of about $30^\circ\text{C}/\text{km}$. Thus, assuming a conductive gradient, the temperature of the earth at 10 km would be over 300°C . So if the average surface temperature is 20°C , the temperature at 3 km is only 95°C . Although direct use applications of geothermal energy can use temperatures as low as about 35°C , the minimum temperature suitable for electrical generation is about 135°C .

sites are suitable for construction of thermal power plants for the utilization of geothermal energy.

The estimated total thermal energy above mean surface temperature to a depth of 10 km is 1.3×10^{27} J, equivalent to burning 3.0×10^{17} barrels of oil. Since the global energy consumptions for all types of energy, is equivalent to use of about 100 million barrels of oil per day, the Earth's energy to a depth of 10 kilometers could theoretically supply all of mankind's energy needs for six million years (Wright, 1998).

Under crust is a Earth's mantle, layer which is composed of highly viscous, partially molten rock, whose temperature at a depth of about (80÷100) km is (600÷1250)°C. In the Earth's core, which is composed of outer liquid and inner solid core (Fig.1.1), the temperature ranges from (4000÷ 7000)°C.

Because of the difference in temperature between the different parts of the asthenosphere, convective movements and, possibly, convective cells were formed some tens of millions of years ago. Their extremely slow movement (a few centimeters per year) is maintained by the heat produced continually by the decay of the radioactive elements and the heat coming from the deepest parts of the Earth. Immense volumes of deep hotter rocks, less dense and lighter than the surrounding material, rise with these movements towards the surface, while the colder, denser and heavier rocks near the surface tend to sink, re-heat and rise to the surface once again, very similar to what happens to water boiling in a pot or kettle

Geothermal energy is one of the alternative energy sources many nations have been increasingly exploring as hydrocarbon fuels become more expensive. Although geothermal energy will not in the foreseeable future meet but a very few percent of the total energy consumption of the world, it is of great importance to many of the individual countries that harness it. An example of this is Iceland, which has no oil, gas or coal reserves, and meets about one-third of its energy needs with geothermal energy. Because of the nature of the geological processes concerned, many parts of the world which are without oil reserves have geothermal energy potential. Geothermal research is now under way in about 60 countries. Most of these are developing countries.

All existing applications of geothermal energy use a circulating fluid to carry the heat from depth to its use at the surface. In most cases, that fluid originates in the geothermal reservoir, but where permeability is low or there is no in-situ fluid, there are techniques for injecting cooler water at the surface, circulating it through natural or induced fractures in the rock to gain heat, and returning it to the surface for use. Produced fluids at lower temperatures (below about heating for buildings, food drying, or industrial processes. These applications can be very cost-effective, especially where conventional fuel prices are high, but have the principal disadvantage that they must be near the resource. With higher temperature and sufficient flow rate, geothermal fluids can be used to generate electricity, allowing the end user to be geographically distant from the geothermal resource. This requirement for fluid, however, emphasizes the need for drilling. Except for the few cases where direct use applications can be supplied from natural hot springs, access to the geothermal fluids can only be achieved through drilling into them—and in many cases, the fluids must be re-injected into the reservoir once their heat is surrendered, requiring even more holes.

Main characteristics of geothermal energy which make it a very important future energy sources are (IGA 2005):

- *Extensive global distribution.* That makes it accessible to both developed and developing countries.
- *Environmentally friendly,* i.e. low greenhouse gases production, few solid or liquid wastes, minor land usage.

- *Sustainable resource.*
- *Indigenous*, make it independent of external supply/demand effects and fluctuations in exchange rates; saves on overseas expenditure; allows “local” fossil resources such as oil, coal and natural gas to be saved or exported to earn hard currency or reduce overseas debt.
- *Independent of season and day time.*
- *Immune from weather effects*, i.e. vagaries of rainfall, wind, sunshine etc.
- *Contributes to development of diversified power sources* that help sustain economical growth.
- *Effective for distributed application* in both on and off grid development, and is especially useful in rural electrification schemes.

2. GEOTHERMAL RESOURCES AND RESERVOIRS

2.1. Definition of geothermal resources

A geothermal energy requires heat, permeability, and water. The heat from the Earth’s core continuously flows outward. Sometimes the heat, as magma, reaches the surface as lava, but it usually remains below the Earth’s crust, heating nearby rock and water—sometimes to levels as hot as 370°C. When water is heated by the earth’s heat, hot water or steam can be trapped in permeable and porous rocks under a layer of impermeable rock and a geothermal reservoir can form. This hot geothermal water can manifest itself on the surface as hot springs or geysers, but most of it stays deep underground, trapped in cracks and porous rock. This natural collection of hot water is called a geothermal reservoir (Fig.2.1.1).

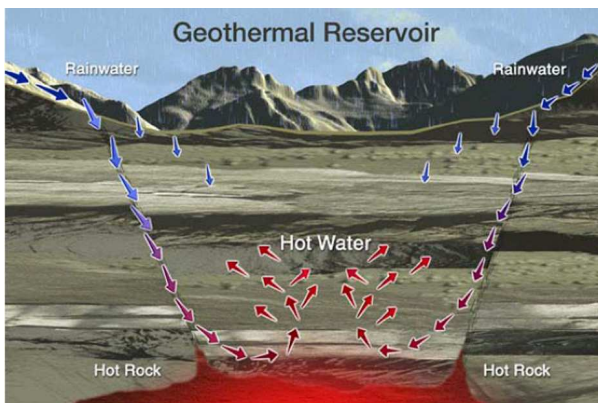


Fig.2.1.1 The Formation of a Geothermal Reservoirs

It is a proven fact that the Earth’s crust is saturated with water (Fig.2.1.1). Not only do bore-holes in fractured rock or chalk fill with water up to between 5 -70 meters beneath the earth’s surface, but this has also been confirmed in hard (crystalline) rock. This last finding is critical as it allows exploitation of heat energy in all geographical locations, irrespective of the presence of subterranean hot water or steam reservoirs.

There is no standard international terminology in use throughout the geothermal energy, which is unfortunate, as this would

facilitate mutual comprehension. The following are some of the most common definitions and classifications in this discipline.

According to Muffler and Cataldi (1978), when we speak generically about geothermal resources, what we are usually referring to is what should more accurately be called the *accessible resource base*; that is, all of the thermal energy stored between the Earth’s surface and a specified depth in the crust, beneath a specified area and measured from local mean annual temperature. The accessible resource base includes the *useful accessible resource base* (= *Resource*) — that part of the accessible resource base that could be extracted economically and legally at some specified time in the future (less than a hundred years). This category includes the *identified economic resource* (= *Reserve*) and *unidentified* resources (Fig.2.1.2). The identified resources are part of the resources of a given area that can be extracted legally at a cost

competitive with other commercial energy sources and that are known and characterized by drilling or by geochemical, geophysical and geological evidence.

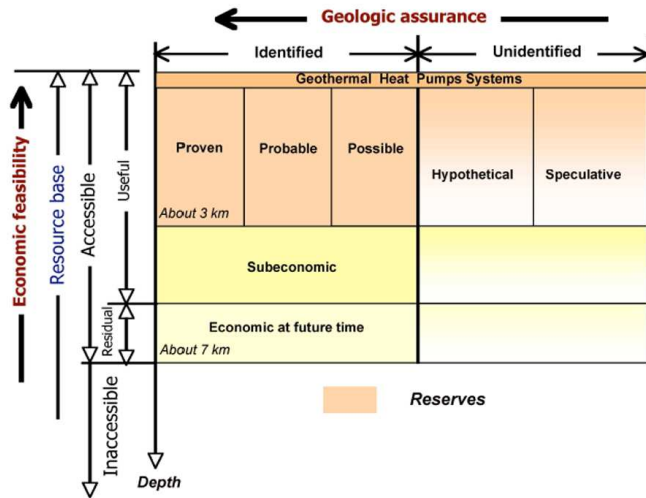


Fig.2.1.2. The Formation of a Geothermal Reservoirs

The most common criterion for classifying geothermal resources is, however, that based on the enthalpy of the geothermal fluids that act as the carrier transporting heat from the deep hot rocks to the surface. *Enthalpy*, which can be considered more or less proportional to temperature, is used to express the heat (thermal energy) content of the fluids, and gives a rough idea of their 'value'. The resources are divided into low, medium and high enthalpy (or temperature) resources, according to criteria that are generally based on the energy content of the fluids and their potential forms of utilization.

Frequently a distinction is made between water- or liquid-dominated geothermal systems and vapor-dominated (or dry steam) geothermal systems (White, 1973). In *water-dominated systems* liquid water is the continuous, pressure-controlling fluid phase. Some vapor may be present, generally as discrete bubbles. These geothermal systems, whose temperatures may range from < 125 to > 225 °C, are the most widely distributed in the world. Depending on temperature and pressure conditions, they can produce hot water, water and steam mixtures, and wet steam and, in some cases, dry steam. In *vapor-dominated systems* liquid water and vapor normally co-exist in the reservoir, with vapor as the continuous, pressure-controlling phase. Geothermal systems of this type, the best-known of which are Larderello in Italy and The Geysers in California, are somewhat rare, and are high-temperature systems. They normally produce dry-to superheated steam.

Geothermal fluid - a hot, sometimes salty, mineral-rich liquid and/or vapor - is the carrier medium that brings geothermal energy up through wells from the subsurface to the surface.

A geothermal resource that uses an existing accumulation of hot water or steam is known as a “hydrothermal” resource. All geothermal electricity produced today derives from the hydrothermal resource base. Characteristics of the geothermal fluid, including temperature, chemistry, and non-condensable gas content (NCG), can influence power plant design.

The presence of water facilitates not only vertical hydrothermal energy flows (convection), but also horizontal hydrothermal energy flows (through convection, advection and diffusion). The full utilization of all these hydrothermal energy flows enables commercially viable geothermal energy exploitation. Differences in pressure activate the energy flows.

Geothermal resources are often discovered under certain land features such as:

- *Geyser* – hot spring which periodically erupts a jet of hot water and steam (the word “geyser” derives from the Icelandic word “geyser”, which means “the gusher”);
- *Fumaroles* – vent steam and gas from which steam is emitted at high velocity;
- *Hot spring and pool* – a vent from which hot water flows, or depression into which hot water collects; often ebullient. Edges may be raised by precipitation of silica or calcium carbonate;

- *Silica sinter terrace* – terrace formed of opaline silica precipitated from waters of geysers and hot springs. Where the waters originate in calcareous rocks (limestone) the mineral precipitated will be travertine (calcium carbonate). Travertine terraces are rare, but splendid examples are found in Yellowstone National Park (USA) and at Pamukkale (Turkey);
- *Thermal area* – area of heated ground. It is often bare, or has only stunted, heat-tolerant vegetation;
- *Mud pool* – hot pool in which adjacent rock or soil has been dissolved to form a viscous mud, usually sulfurous and often multi-colored;
- *Algal mat* – mat of colored algae found in hot flowing streams carrying water away from geysers or hot pools. Colors range from white (hottest water) through orange and green to black (coolest water);



Fig.2.1.3. The Pohutu **Geyser** in New Zealand

Geysers are a specific case of hot springs as a consequence of superheated water circulation in a confined space. Intermittent, pressure build up and a slight decrease of pressure (or a slight increase in temperature) causes a certain amount of water to boil leading to impressive explosions of water and steam into the air, which is spouted to several dozen meters above ground, as shown in fig.2.1.3. Geysers are particularly rare and are found near volcanic activity regions. The total number of geysers recorded worldwide does not exceed 1000, located mainly in the USA, the Russian Republic, New Zealand, Iceland and Chile.

Fumaroles are naturally occurring vents which emit steam and gases at remarkably stable fluxes. Fumaroles are formed when the water supply is limited, so that water evaporates before reaching the surface. Around the vent, mineral deposits usually accumulate derived from the fluids it usually forms. In extreme cases the gas temperature may reach 600°C; however usual temperatures for such mixture remain at 100°C. The most common gases emitted with the steam are carbon dioxide, sulfur dioxide, hydrogen sulfide and other volcanic or non-volcanic gas species in small quantities though. Fumaroles containing significant amounts of sulfurous gases are called solfataras, while those containing only carbon dioxide are called mofettes.



Fig.2.1.4. Mud pool

Mud pools (or mud pots) are formed when the water of a spring does not have sufficient flow and pressure to carry the aluminum silicates particles away from the spring. This results in concentration of these particles at the outlet or “pool” of the thermal

manifestation, while steam along with non-condensable gases concentrate on the thick mud surface “popping” with characteristic sound and shape as shown in Fig.2.1.4.

Thermal area – or hot ground are usually formed due to the rock thermal convection (non-permeable geological formation), between certain points at ground surface and extremely warm liquids at shallow depths. Surface temperatures may reach. The geothermal temperature gradient, i.e. the increasing temperature with depth within the Earth’s crust, fluctuates between 5 and 70°C/km, with an average geothermal gradient, most of them are concentrated at plate tectonic boundaries.

On average, the temperature of the Earth increases about 30°C/km above the mean surface ambient temperature. Thus, assuming a conductive gradient, the temperature of the earth at 10 km would be over 300°C. However, most geothermal exploration and use occurs where the gradient is higher, and thus where drilling is shallower and less costly. These shallow depth geothermal resources occur due to:

- (1) Intrusion of molten rock (magma) from depth, bringing up great quantities of heat.
- (2) High surface heat flow, due to a thin crust and high temperature gradient.
- (3) Ascent of groundwater that has circulated to depths of several kilometers and been heated due to the normal temperature gradient.
- (4) Thermal blanketing or insulation of deep rocks by thick formation of such rocks as shale whose thermal conductivity is low; and
- (5) Anomalous heating of shallow rock by decay of radioactive elements, perhaps augmented by thermal blanketing (Wright, 1998).

2.2. Classification of geothermal resources

Geothermal field is a geographical definition, usually indicating an area of geothermal activity at the earth's surface. In cases without surface activity this term may be used to indicate the area at the surface corresponding to the geothermal reservoir below (Axelsson and Gunnlaugsson, 2000).

A common geothermal field consists of three parts: a thermal *source*, the *reservoir* and the *fluids* which act as heat carriers (Fig.2.2.1). The thermal source could be either a magma penetration (with temperatures in the range of 600-1200°C) that reaches relatively shallow depths (3-10 km), or a normal heat flow that creates progressively warmer formations with depth. The reservoir consists essentially of a thermally and permeable rock formation that allows the circulation of the fluids or their entrapment. The geothermal fluids are primarily waters of meteoric or surface origin, but in rare occasions, they may come from magma. These fluids are in liquid or vapor state and vary often contain important quantities of dissolved solid substances and gases. The state of the geothermal fluids depends on their pressure and temperature.

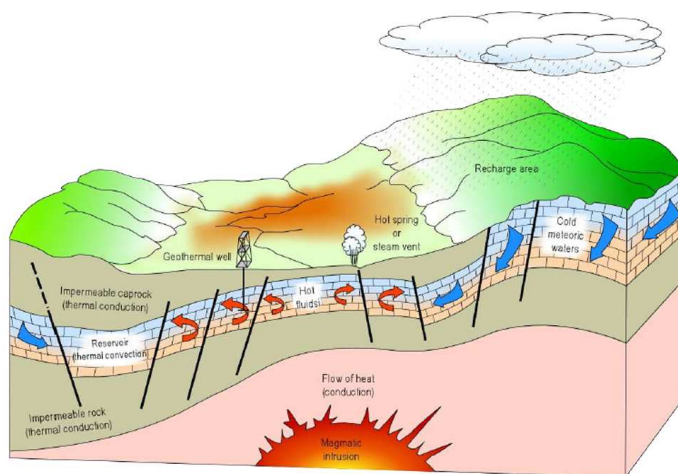


Fig.2.2.1. Schematic representation of ideal geothermal system [26]

Geothermal systems can therefore be found in regions with a normal or slightly above normal geothermal gradient, and especially in regions around plate margins where the geothermal gradients may be significantly higher than the average value. In the first case the systems will be characterized by low temperatures, usually no higher than 100°C at economic depths; in the second case the temperatures could cover a wide range from low to very high, and even above 400°C.

Geothermal systems can be classified on the basis of several criteria, such as: the type of geothermal resource, the type and temperature of fluids, the category of the rock, the heat source type and fluid circulation modes within the reservoir.

The *geothermal system* can be described schematically as ‘*convecting water in the upper crust of the Earth, which, in a confined space, transfers heat from a heat source to a heat sink, usually the free surface*’ (Hochstein, 1990). A geothermal system is made up of three main elements: a *heat source*, a *reservoir* and a *fluid*, which is the carrier that transfers the heat. The heat source can be either a very high temperature (> 600 °C) magmatic intrusion that has reached relatively shallow depths (5-10 km) or, as in certain low-temperature systems, the Earth's normal temperature, which, as we explained earlier, increases with depth. The reservoir is a volume of hot permeable rocks from which the circulating fluids extract heat. The reservoir is generally overlain by a cover of impermeable rocks and connected to a superficial recharge area through which the meteoric waters can replace or partly replace the fluids that escape from the reservoir through springs or are extracted by boreholes. The geothermal fluid is water, in the majority of cases meteoric water, in the liquid or vapor phase, depending on its temperature and pressure. This water often carries with it chemicals and gases such as CO₂, H₂S, etc. Figure 6 is a greatly simplified representation of an ideal geothermal system.

The mechanism underlying geothermal systems is by and large governed by *fluid convection*. Figure 7 describes schematically the mechanism in the case of an intermediate-temperature hydrothermal system. Convection occurs because of the heating and consequent thermal expansion of fluids in a gravity field; heat, which is supplied at the base of the circulation system, is the energy that drives the system. Heated fluid of lower density tends to rise and to be replaced by colder fluid of high density, coming from the margins of the system. Convection, by its nature, tends to increase temperatures in the upper part of a system as temperatures in the lower part decrease (White, 1973).

Table 2.2.1. Geothermal Resource Types

Resource Type	Temperature Range (°C)
Convective hydrothermal resources	
Vapor dominated	240°
Hot-water dominated	20 to 350°+
Other hydrothermal resources	
Sedimentary basin	20 to 150°
Geopressured	90 to 200°
Radiogenic	30 to 150°
Hot rock resources	
Solidified (hot dry rock)	90 to 650°
Part still molten (magma)	>600°

Geothermal resources are usually classified as shown in Table 2.2.1, modeled after White and Williams (1975). These geothermal resources range from the mean annual ambient temperature of around 20°C to over 300°C. In general, resources above 150°C are used for electric power generation, although power has recently been generated at Chena Hot Springs Resort in Alaska using a 74°C geothermal resource (Lund, 2006). Resources below 150°C are usually used in direct-use projects for heating and cooling. Ambient temperatures in the 5 to 30°C range can be used with geothermal (ground-source) heat pumps to provide both

heating and cooling.

Convective hydrothermal resources occur where the Earth's heat is carried upward by convective circulation of naturally occurring hot water or steam. Some high temperature convective hydrothermal resources result from deep circulation of water along fractures. Hydrothermal resources are categorized as vapor dominated (steam) or liquid-dominated (hot water) according to the predominant fluid phase. These reservoirs are tapped by drilling wells to deliver hot water to the surface for generation of electricity or direct use.

Vapor dominated systems (Fig. 2.2.2) produce steam from boiling of deep, saline waters in low permeability rocks. These reservoirs are few in number, with The Geysers in northern California, Larderello in Italy and Matsukawa in Japan being ones where the steam is exploited to produce electric energy.

Water dominated systems (Fig.2.2.3) are produced by ground water circulating to depth and ascending from buoyancy in permeable reservoirs that are a uniform temperature over large volumes. There is typically an up-flow zone at the center of each convection cell, an outflow zone or plume of heated water moving laterally away from the center of the system, and a down-

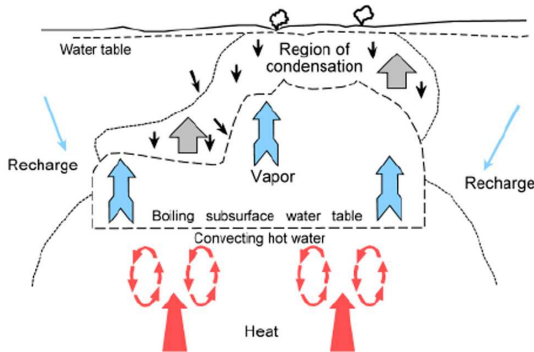


Fig.2.2.2. Vapor dominated geothermal resource [1]

flow zone where recharge is taking place. Surface manifestations include hot springs, fumaroles, geysers, travertine deposits, chemically altered rocks, or sometimes, no surface manifestations (a blind resource).

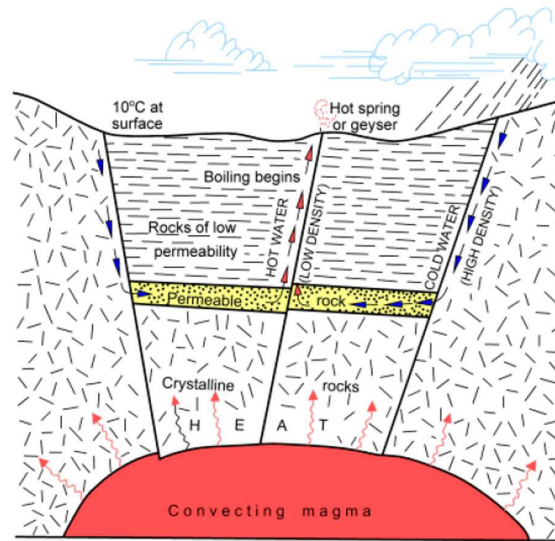


Fig.2.2.3. Hot water dominated geothermal resource [1]

Sedimentary basins (Fig. 2.5) produce higher temperature resources than the surrounding formations due to their low thermal conductivity or high heat flow or both producing geothermal gradients $>30^{\circ}\text{C}/\text{km}$. These generally extend over large areas and are typical of the Madison Formation of North Dakota, South Dakota, Montana and Wyoming area of the northern United States and the Pannonian Basin of central Europe where it has been used extensively in Hungary.

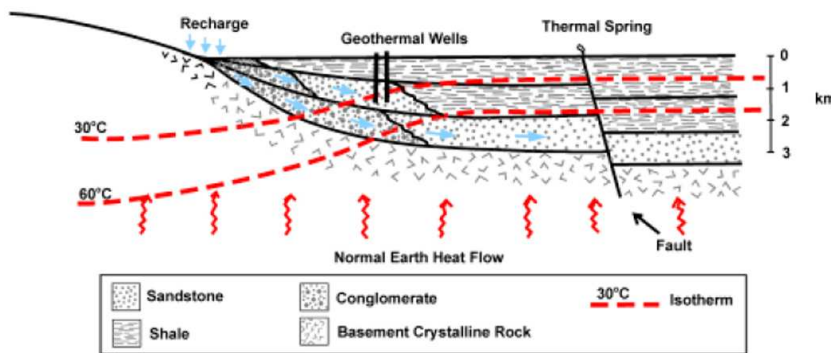


Fig. 2.2.4. Sedimentary basin geothermal resource. (Anderson & Lund, 1979)

Formation of North Dakota, South Dakota, Montana and Wyoming area of the northern United States and the Pannonian Basin of central Europe where it has been used extensively in Hungary.

Geo-pressured resources (Fig. 2.2.5)

occur in basin environments where deeply buried fluids contained in permeable sedimentary rocks are warmed in a normal or enhanced geothermal gradient by their great burial depth (approximately 3 to 6 km). The fluids are tightly confined by surrounding impermeable rock and bear pressure much greater than hydrostatic. Thermal waters under high pressure in sand aquifers are the target for drilling, mainly as they contain dissolved methane. The source of energy available

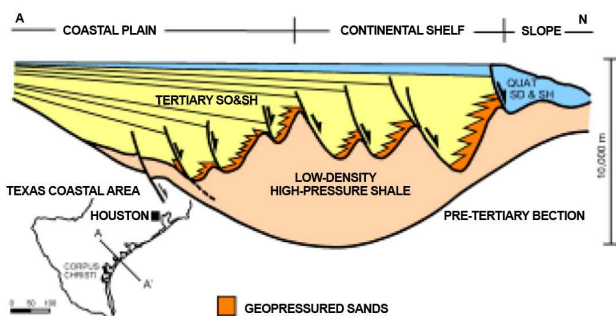


Fig.2. 2.5. Geo-pressured geothermal resource. (Bebout, et al., 1978)

in basin environments where deeply buried fluids contained in permeable sedimentary rocks are warmed in a normal or enhanced geothermal gradient by their great burial depth (approximately 3 to 6 km). The fluids are tightly confined by surrounding impermeable rock and bear pressure much greater than hydrostatic. Thermal waters under high pressure in sand aquifers are the target for drilling, mainly as they contain dissolved methane. The source of energy available

from this type of resource consists of: (1) heat; (2) mechanical energy; and, (3) methane. The Texas and Louisiana Gulf Coast in the United States has been tested for the geothermal energy; however, due to the great depths of several kilometers, they have not proved economic.

Radiogenic resources (Fig. 5) are found where granitic intrusions are near surface heating up the local groundwater from the decay of radioactive thorium, potassium and uranium. This localized heating increases the normal geothermal gradient providing hot water at economical drilling depths. This type of resource occurs along the eastern United States, but has not been developed commercially.

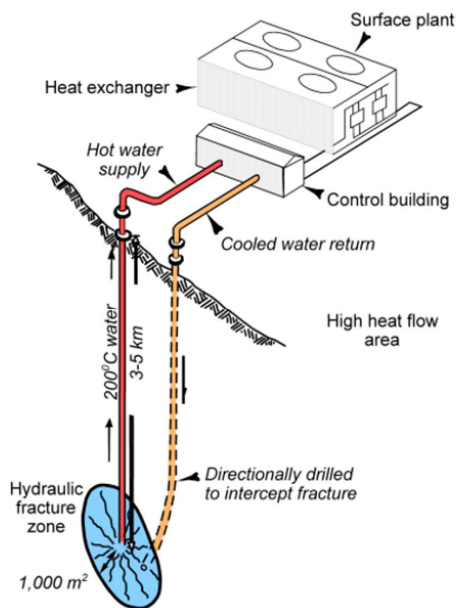


Fig.2.2.6. Hot dry rock exploitation. [1]

Hot dry rock resources (HDR) (Fig. 2.2.6), with temperatures from 200 to 350°C, are defined as heat stored in rocks within about 10 km of the surface from which energy cannot be economically extracted by natural hot water or steam. These hot rocks have few pore space, or fractures, and therefore, contain little water and little or no interconnected permeability. In order to extract the heat, experimental projects have artificially fractured the rock by hydraulic pressure, followed by circulating cold water down one well to extract the heat from the rocks and then producing from a second well in a closed system. Early experimental projects were undertaken at Fenton Hill (Valdes Caldera) in northern New Mexico and on Cornwall in southwest England; however both of these projects have been abandoned due to lack of funds and poor results. Projects are currently underway in Soultz-sous-Forêt in the Rhine Graben on the French-German border, in Switzerland at Basil and Zurich, in Germany at Bad Urach, several locations in Japan, and in the Cooper

Basin of Australia (Tenzer, 2001).

Molten rock or magma resources, with temperature from 600 to 1400 °C, have been drilled in Hawaii experimentally to extract heat energy directly from molten rock. It has been used successfully at Heimaey in Iceland (one of the Westmann Islands) after the 1973 eruption. A heat exchanger constructed on the surface of the lava flow recovered steam resulting from boiling of downward percolation water from the surface. The heat was used in a space heating system for over 10 years; but, is now shut down due to cooling of the surrounding rock.

The World Bank classifies the geothermal resources based on temperature as:

- high temperature (>150°C),
- medium-temperature (100-150°C), and
- low-temperature (<100°C) resources.

The high-temperature reservoirs have been classified into several types based on the water temperature, pressure and phases. Water can be in a liquid or vapor phase or combined as two-phase fluid. The phases of water found within the reservoirs as:

- warm water reservoirs,
- hot water reservoirs, and
- vapor-dominated reservoirs.

A *warm water reservoir* is defined as one containing water at a sufficiently low temperature (<100°C) which can be exploited for district heating, agricultural purposes and balneological use, etc.

TABLE 2.2.2: Geothermal reservoir temperatures and common technologies

Reservoir temperature	Reservoir fluid	Common use	Technology commonly chosen
High temperature ->220°C	Water and/or steam	Power generation Direct use	Flash steam Combined (flash and binary) cycle Direct fluid use Heat exchangers Heat pumps
Intermediate temperature - 100-220°C	Water	Power generation Direct use	Binary cycle Direct fluid use Heat exchangers Heat pumps
Low temperature -50-150°C	Water	Direct use	Direct fluid use Heat exchangers Heat pumps

A *hot water reservoir* contains fluid in a liquid state in the temperature range 100-250 °C. Boiling can, however, occur in hot water reservoirs in both the natural and exploited states. In the natural state, and especially after exploitation, boiling can occur in the reservoir due to draw-down. The two-phase zone then created is often referred to as the

steam zone or steam cap. It should be remembered, however, that it contains water as well as steam, and that the pressure gradient with depth is nearly hydrostatic, but for some steam caps there is almost constant pressure until the water level is reached.

Vapor-dominated reservoirs are full of steam. The term “vapor-dominated” was first used by D. White in 1971. The main characteristics of this system are:

- (a) A discharge of steam only;
- (b) The discharge comes from a region where the pressure is nearly constant with depth.

The steam discharge may initially be wet, saturated or super-heated. The pressure of the production zone is usually around 33 bars, equivalent to a saturation pressure for water and steam at 235°C.