INTRODUCTION

Kiril Popovski, Sanja Popovska Vasilevska

Geothermal energy is expression representing the earth's natural heat which can be used for different needs of the humankind. That is practically a part of the heat continuous flow from the earth's interior to its surface, derived primarily from the decay of the long-lived radioactive isotopes of uranium (U^{238}, U^{235}), thorium (Th^{232}) and potassium (K^{40}), plus the contribution of the slight cooling of the earth. 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 comes from the crust (Fig.1), i.e. from only 2% of the total volume of the Earth but rich in radioactive isotopes, 32.3×10^{12}W comes from the mantle (82% of the volume) and 1.7×10^{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 10.3×10^{12}W.

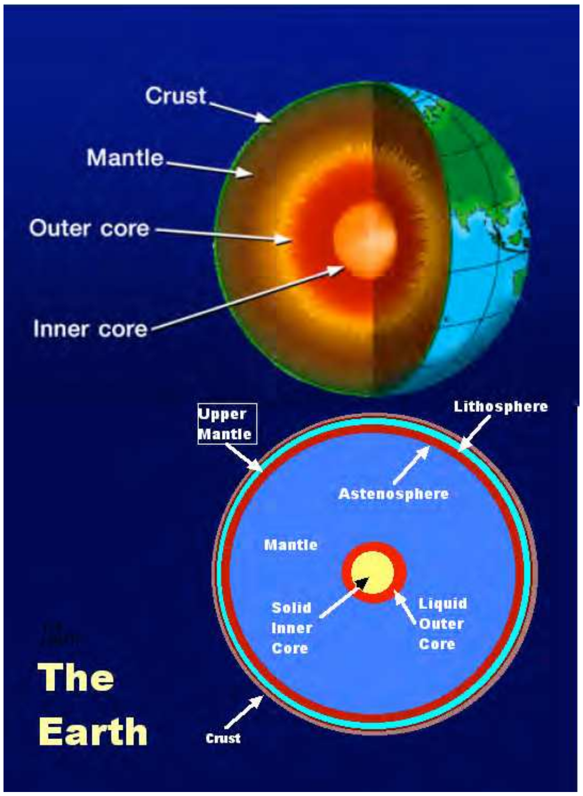

Fig.1. Inner structure of the Earth

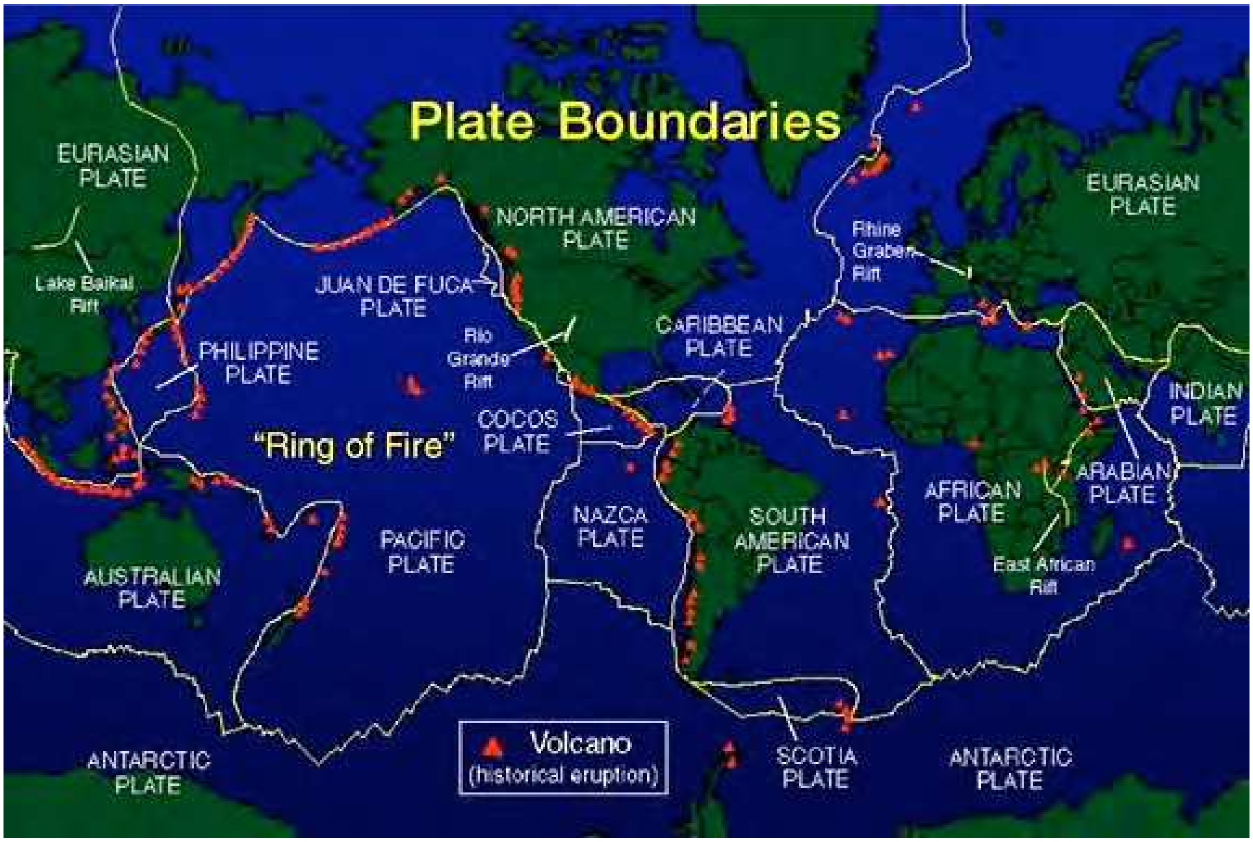

Fig.2. World pattern of plates, oceanic ridges, subduction zones and geothermal fields

As it can be understood from the above said, Earth relates as a kind of heat engine, transferring continuously heat to its surface by conduction through the rocks and, locally, by convection in moving fluids, including groundwater and molten rock (magma). However, the conductive heat flow is very diffuse, averaging no more than 60 mW/m^2. It varies considerable, being highest in the regions of active tectonics and volcanism (Fig.2), and lowest over the Precambrian shields. Away from these zones, local variations in the regional patterns of conductive heat flow can be caused by differences in heat production reflecting lateral variations in the occurrence of radioactive isotopes, as well as by convective transfer from the movement of ground water.

The nature of geothermal energy results with different type of appearances and different temperature levels. Systems permitting the exploitation can be classified as either high (with temperatures higher than 150ºC) or as low enthalpy ones (lower than 150ºC or even 100ºC). In both cases it is supposed that an aqueous solution acts as a heat carrier, taking it from the hot rocks and transporting it to the surface, where it can be exploited. However, such a classification can be taken as a classic one nowadays, when the system for using heat from hot dry rocks is developed, or the ground source heat pumps are already in a very wide use. The later ones use shallow subsurface heat with temperatures below 30ºC. That means some other classifications are possible, either connected to the nature of geothermal energy source, type of heat carrier and type of heat use. That means that classical approach to this energy resource that being on disposal only at concrete locations should be corrected. That is valid only for the manifestations connected to the aqueous brines as heat carrier, being the most important ones at the present level of technologies development.

Relation of people to this energy source has been and it is rather strange and emotional. It was discovered very early that geothermal waters and steam can be used either for healing or for different heatings. However, un-known origin of it also resulted with some kind of fear. From one side, eruptions of volcanoes have been destructive and resulted with death of people living around them. On the other side, the same people used the benefits of very fertile land around them and healed the wounds and illnesses with the hot high mineral waters below the volcanoes. It was, in the same time, appearance of the hell below the earth surface and the present of God(s) for a better life. We have no direct proves for the very early uses of geothermal energy. However, the earliest known one are connected to the balneological uses and different "natural" heatings and indirect uses for amelioration of the agricultural production (rice warm fields). The real energetic uses of it are of rather recent date. Electricity production began since 1904 (Lardarello, Italy), when also first industrial application has been organized in the same place. The use of "effluent" warm geothermal water for "floor" heating of the baths was known from the Roman and Otoman times, but "normal" heating systems appeared in the years before the second world war. Geothermal heating of greenhouses began in 1961 in Bansko, Macedonia) and the industrial uses in Iceland and other countries, after that.

In comparison with the other renewable energy sources, development of geothermal energy was always followed with different constraints and difficulties. Probably the most important one has always been the limited knowledge about the nature and real possibilities and advantages of this special energy source. That resulted with many mistakes in the projects design, influencing negatively the public opinion needed for the development support.

In any case, based on the known advantages of geothermal energy use, a significant development is already reached. Both for different direct uses (Table 1) and for generating electricity (Table 2).

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

- *Extensive global distribution*. That makes it accessible to both developed and developing countries
- *Environmentally friendly*, i.e. low greenhouse gas 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 the 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 economic growth
- Effective for distributed application in both on and off grid developments, and is especially useful in rural electrification schemes.

In addition, also the economic advantages to the most of known renewable energy sources are already proven and further amelioration expected (Table 3).

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Table 1. Summary of direct-use data from individual countries (Lund, 2005)

Country	Capacity MWt	Use TJ/yr	Use GWh/yr	Capacity Factor
Albania	9.6	8.5	2.4	0.03
Algeria	152.3	2,417.0	671.4	0.50
Argentina	149.9	609.1	169.2	0.13
Armenia	1.0	15.0	4.2	0.48
Australia	109.5	2,968.0	824.5	0.86
Austria	352.0	352.0	2,229.9	0.20
Belarus	1.0	13.3	3.7	0.42
Belgium	63.9	431.2	119.8	0.21
Brazil	360.1	6,622.4	1,839.7	0.58
Bulgaria	109.6	1,671.5	464.3	0.48
Canada	461.0	2,546.0	707.3	0.18
Caribbean Islands	0.1	2.8	0.8	0.89
Chile	8.7	131.1	36.4	0.48
China	3,687.0	45,373.0	12,604.6	0.39
Columbia	14.4	287.0	79.7	0.63
Costa Rica	1.0	21.0	5.8	0.67
Croatia	114.0	681.7	189.4	0.19
Czech Republic	204.5	1,220.0	338.9	0.19
Denmark	821.2	4,360.0	1,211.2	0.17
Ecuador	5.2	102.4	28.4	0.62
Egypt	1.0	15.0	4.2	0.48
Ethiopia	1.0	15.0	4.2	0.48
Finland	260.0	1,950.0	541.7	0.24
France	308.0	5,195.7	1,443.4	0.53
Georgia	250.0	6,307.0	1,752.1	0.80
Germany	504.6	2,909.8	808.3	0.18
Greece	74.8	567.2	157.6	0.24
Guatemala	2.1	52.5	14.6	0.79
Honduras	0.7	17.0	4.7	0.77
Hungary	694.2	7,939.8	2,205.7	0.36
Iceland	1,791.0	23,813.0	6,615.3	0.42
India	203.0	1,606.3	446.2	0.25
Indonesia	2.3	42.6	11.8	0.59
Iran	30.1	752.3	209.0	0.79
Ireland	20.0	104.1	28.9	0.17
Israel	82.4	2,193.0	609.2	0.84
Italy	606.6	7,554.0	2,098.5	0.39
Japan	413.4	5,161.1	1,433.8	0.40
Jordan	153.3	1,540.0	427.8	0.32
Kenya	10.0	79.1	22.0	0.25
Korea (South)	16.9	175.2	48.7	0.33
Lithuania	21.3	458.0	127.2	0.68
Macedonia	62.3	598.6	166.3	0.30
Mexico	164.7	1,931.8	536.7	0.37
Mongolia	6.8	213.2	59.2	0.99
Nepal	2.1	51.4	14.3	0.78
Netherlands	253.5	685.0	190.3	0.09
New Zealand	308.1	7,086.0	1,968.5	0.73
Norway	450.0	2,314.0	642.8	0.16
Papua New Guinea	0.1	1.0	0.3	0.32
Peru	2.4	49.0	13.6	0.65
Philippines	3.3	39.5	11.0	0.38
Poland	170.9	838.3	232.9	0.16
Portugal	30.6	385.3	107.0	0.40
Romania	145.1	2,841.0	789.2	0.62
Russia	308.2	6,143.5	1,706.7	0.63
Serbia	88.8	2,375.0	659.8	0.85
Slovak Republic	187.7	3,034.0	842.8	0.51
Slovenia	48.6	712.5	197.9	0.46
Spain	22.3	347.2	96.5	0.49
Sweden	3,840.0	36,000.0	10,000.8	0.30
Switzerland	581.6	4,229.3	1,174.9	0.23

Thailand	1.7	28.7	8.0	0.54
Tunisia	25.4	219.1	60.9	0.27
Turkey	1,177.0	19,623.1	5,451.3	0.53
Ukraine	10.9	118.8	33.0	0.35
United Kingdom	10.2	45.6	12.7	0.14
United States	7,817.4	31,239.0	8,678.2	0.13
Venezuela	0.7	14.0	3.9	0.63
Vietnam	30.7	80.5	22.4	0.08
Yemen	1.0	15.0	4.2	0.48
GRAND TOTAL	**27,824.8**	**261,418.0**	**72,621.9**	**0.30**

Table 2. Summary of electricity production data from individual countries, (Bertani, 2005)

Country	Installed Capacity [MW]	Running Capacity [MW]	Annual Energy Produced [GWh/y]	Number of Units	% of National Capacity	% of National Energy
Australia	0.2	0.1	0.5	1	Negligible	Negligible
Austria	1	1	3.2	2	Negligible	Negligible
China	28	19	95 7	13	30% Tibet	30% Tibet
Costa Rica	163	163	1 145	5	8.4%	15%
El Salvador	151	119	967	5	14%	24%
Ethiopia	7	7	N/a	1	1%	n/a
France	15	15	102	2	9% Guadeloupe island	9% Guadeloupe island
Germany	.2	.2	1 5	1	Negligible	Negligible
Guatemala	33	29	212	8	1.7%	3%
Iceland	202	202	1 406	19	13.7%	16.6%
Indonesia	797	838	6 085	15	2.2%	6.7%
Italy	790	699	5 340	32	1.0%	1.9%
Japan	535	530	3 467	19	0.2%	0.3%
Kenya	127	127	1 088	8	11.2%	19.2%
Mexico	953	953	6 282	36	2.2%	3.1%
New Zealand	435	403	2 774	33	5.5%	7.1%
Nicaragua	77	38	270.7	3	11.2%	9.8%
Papua New Guinea	6	6	17	1	10.9% Lihir island	
Philippines[1]	1 931	1 838	9 419	57	12.7%	19.1%
Portugal	16	13	90	5	25% San Miguel island	
Russia	79	79	85	11	Negligible	Negligible
Thailand	3	.3	1 8	1	Negligible	Negligible
Turkey	20	18	105	1	Negligible	Negligible
USA	2 544	1 914	17 840	189	0.3%	0.5%
TOTAL	**8 912**	**8 010**	**56 798**	**468**		

Chapter 1

1. NATURE OF GEOTHERMAL RESOURCES

Michael Fytikas, Nikos Andritsos, Burkhard Sanner

1.1 Earth Heat and Thermal Manifestations

The earth's interior is hot and active. Visual evidence of the earth's heat is provided by many surface shows, among which volcanic eruptions are the most impressive manifestations, while earthquakes prove the most destructive natural events. These phenomena demonstrate the vitality of our planet, whose tectonic plates are constantly moving, as discussed later. The cause of plate movement is the existence of convective heat currents in many regions of the earth mantle. Earthquakes, along with the related faults, facilitate the upward movement of hot molten material (magma), and particularly of geothermal fluids. The latter carry large quantities of thermal energy closer to the earths' surface, making it more accessible to humans. In seismically active regions which frequently match active tectonics the geothermal fluids reach the earth surface creating impressive natural phenomena and thermal manifestations. Most important manifestations address:

- **Hydrothermal or phreatic craters**, which are formed following an "explosion" of over-heated geothermal fluids, trapped under pressure at relatively shallow depths. The explosion causes the upper impermeable rocks to blast, thus forming a crater.
- **Hot Springs** are natural discharges of groundwater at elevated temperature found in favourable geological conditions. In a few cases hot springs produce impressive quantities of water for thousands of years.

The Thermopylae Springs in Central Greece are active from antiquity, at least since Leonidas' time (~500 BC). They flow until to-day continuously for more than 2500 years at significant rates, proving incidentally the renewable character of geothermal energy sources. As a rule, however, thermal waters are trapped in subsurface areas, "waiting" for geothermal drillings.

The deposition of minerals in the discharge areas of thermal springs or other geothermal manifestations (fumaroles, geysers) is of common occurrence. Amorphous silica precipitates in hot waters containing a high content of dissolved silica, while carbonate sinters (travertines) are deposited from CO_2-enriched waters. Some of these give rise to spectacular edifices, such as the travertine terraces formed at Mammoth Hot Springs in the Yellowstone National Park, U.S.A. (Fig. 1.1) and at Pamukkale, Turkey.

- **Geysers** are a special case of hot springs as a consequence of superheated water circulation in a confined space. Intermittedly, pressure builds 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 are spouted to several dozen meters above ground, as shown in Fig. 1.2. 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 U.S.A., the Russian Republic, New Zealand, Iceland and Chile.

Fig. 1.1. Calcium carbonate deposits at the Mammoth Hot Springs in the Yellowstone National Park, U.S.A.

Fig. 1.3. The Old Faithful geyser in the Yellowstone National Park,U.S.A.

- **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 surface. Around the vent, mineral deposits usually accumulate derived from the fluids is usually formed. In extreme cases the gas temperature may reach 600^{o}C; however usual temperatures for such mixture remain at ca 100oC. The most common gases emitted with the steam are carbon dioxide, sulphur dioxide, hydrogen sulphide and other volcanic or non-volcanic gas species in small quantities though. Fumaroles containing significant amounts of sulphurous gases are called solfataras, while those containing only carbon dioxide are called mofettes.

Figure 1.4. Mud pool at Yellowstone National Park, U.S.A.

- **Mud pools** (or mud pots) are formed when the water of a spring does not have sufficient flow and pressure to carry the aluminium 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. 1.3.
- **Hot grounds** are usually formed due to

the rock thermal convection (non-permeable geological formations), 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 value of about 30°C/km. There are many regions showing higher than average geothermal gradient, most of them are concentrated at plate tectonics boundaries.

1.2. The Global Plate Tectonics Theory

Our planet consists mainly of three distinct concentric layers, as shown in Fig. 1.4, and gets hotter towards its centre. The outermost layer, called crust, reaches a thickness of about 30-80 km in continental areas and 5-10 km (7 km on average) under ocean basins. At the bottom of the continental crust the temperature stands at ca 1000ºC. Beneath the crust is a complex layer, the mantle, which extends from the base of the crust down to ca 2850 km, accounting for about 70% of the earth's volume. It is separated into the upper and lower mantle. The crust has apparently been created by accretion from the mantle over geologic times. At the earth centre is the core, some 3450 km in radius. It is generally believed to be composed primarily of iron and some nickel. The outermost 2250 km of the core are liquid (outer core), while the inner core is solid. Geologists speculate that the temperature of the outer core is in the 3500-5000ºC range, whereas the inner core is as hot as 7000ºC. The physical and chemical characteristics of the three layers vary from the surface of the Earth to its centre. The Earth's crust and the uppermost part of the mantle jointly constitute the lithosphere, which behaves as a rigid body. The lithosphere is about 100 km thick beneath the oceans and about 150 km beneath the continents. Below the lithosphere lies a distinct, "less rigid" and plastic layer, known as the asthenosphere, extending to depths of roughly up to 300 km.

The global plate tectonics theory is a unifying theory capable of explaining a variety of geological phenomena, which has revolutionised geologists thinking oft Earth. The theory is a landmark for geosciences and was formulated in the late 1960s, although most of the concepts had been presented long before. According to this theory, the Earth's lithosphere is fragmented into a number of thin, rigid slabs or plates (identified in Fig 1.5), called tectonic (or lithospheric) plates, each consisting of both oceanic and continental fractions, and a dozen or more smaller plates. Plates are in a relative motion with respect to each other, with relative velocities no more than a few centimetres per year. It is generally accepted that convection currents in the asteno-

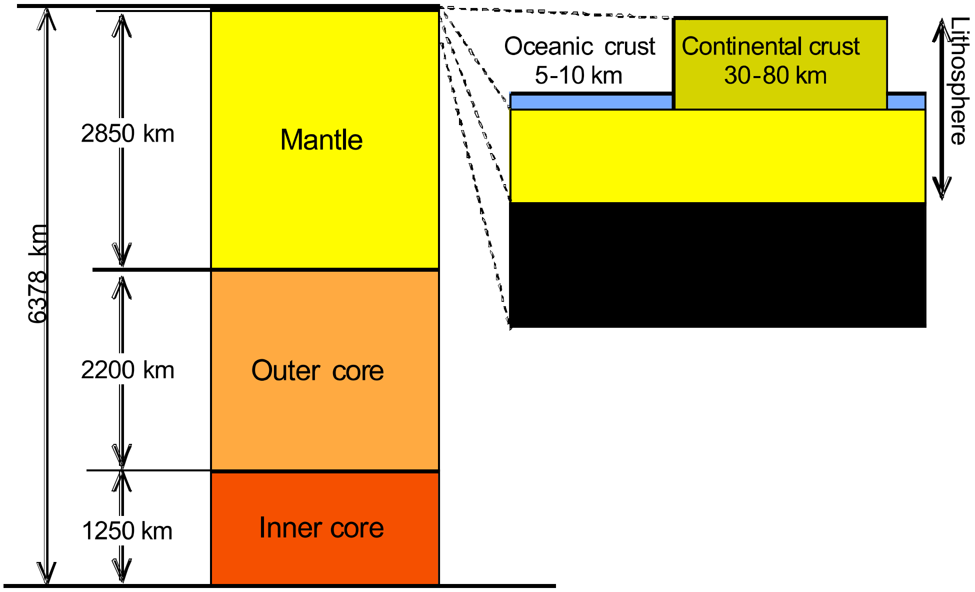
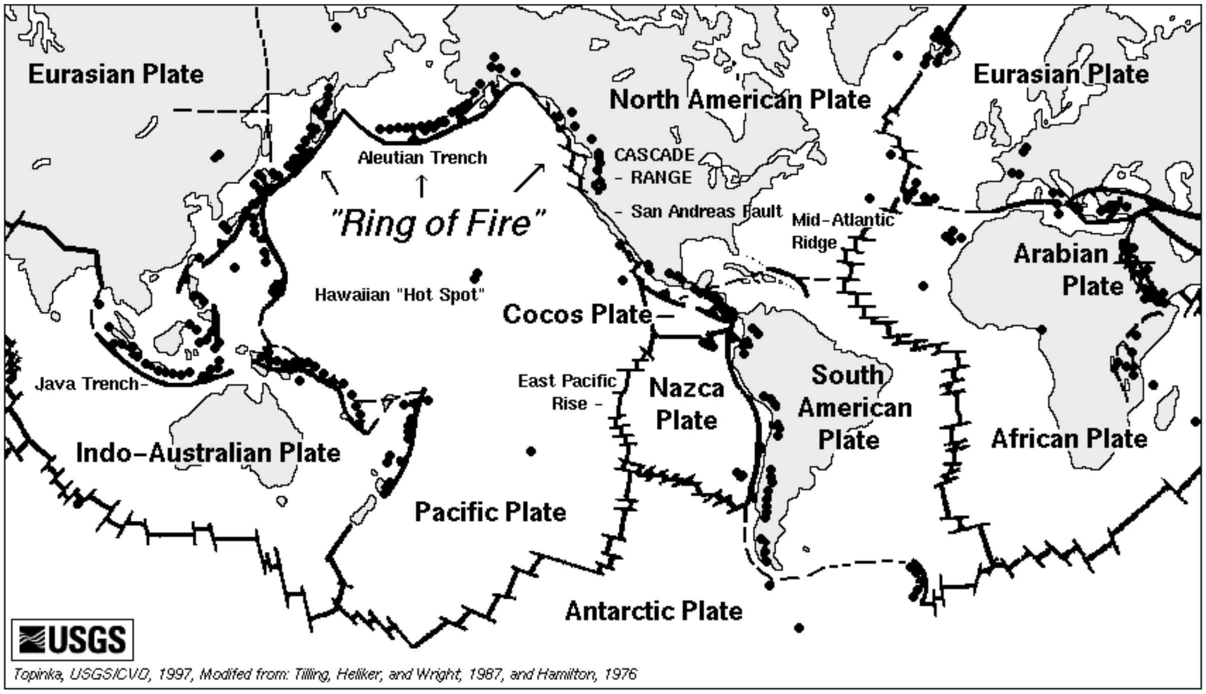


Fig. 1.4. Cross section of the Earth



Topinka, USGS/CVO, 1997, Modifed from: Tilling, Heliker, and Wright, 1987, and Hamilton, 1976

Figure 1.5. World pattern of plates, oceanic ridges, oceanic trenches and subduction zones.

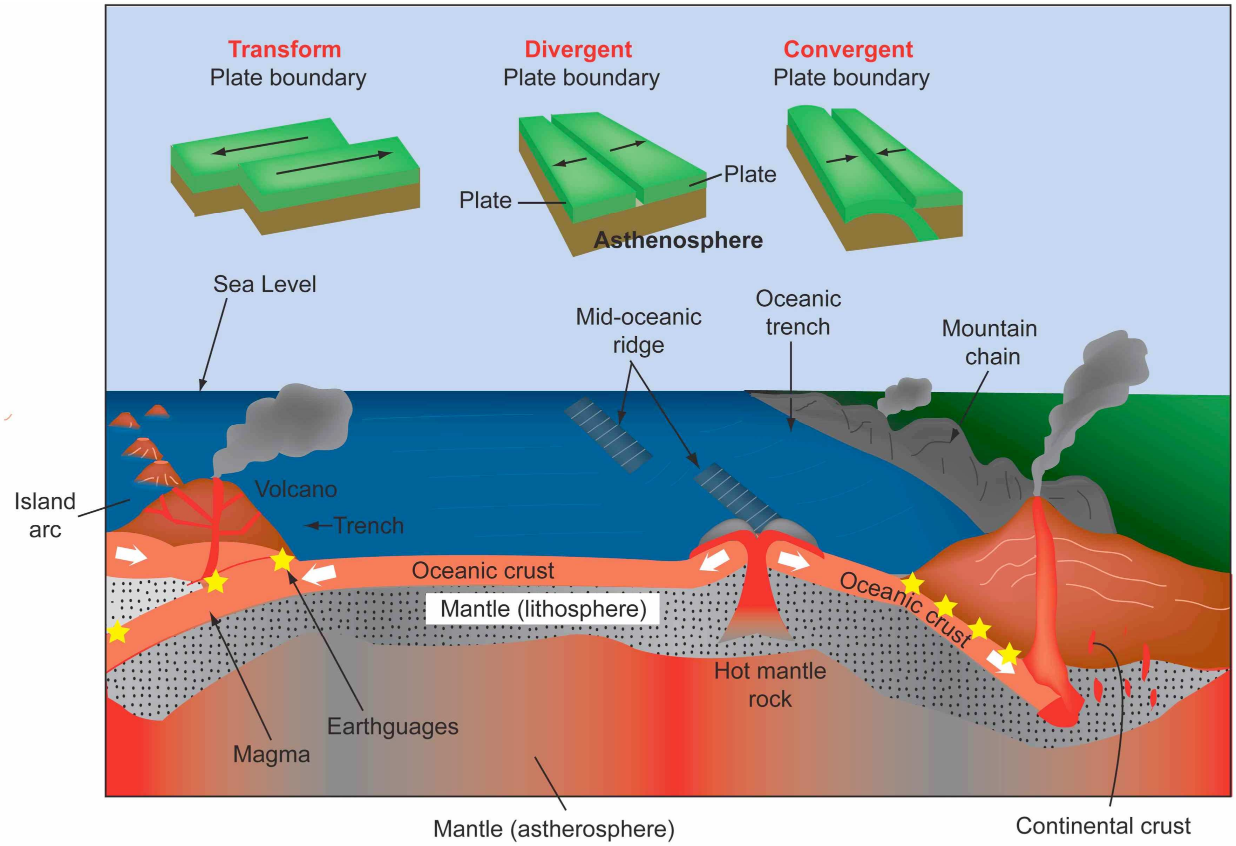


Figure 1.6. Schematic cross-section showing plate tectonic processes. a) East African Rift Zone: Three plates are pulling away from one another (triple junction).b)Oceanic-Oceanic convergence.c) Oceanic-continental convergence

sphere are the primary driving force of plate movements. Therefore, since continents and ocean floors are parts of these plates, they move relative to each other similarly to their placement above underlying asthenosphere. Plates either move away from each other, toward each other, or slide past each other. In the past, these plate movements have created mountains and ocean trenches; they are also responsible for tectonic earthquakes. Tectonic plate boundaries are defined by surface areas displaying high seismic activity and may be categorized as follows:

2. *Divergent plate boundaries*. These are the boundaries observed in cases where lithospheric plates move away from each other and the ascending magma tends to fill the gap forming new ocean crust, a process known as sea floor spreading (Fig. 1.6). These boundaries coincide with the underwater mountain crests, called mid-oceanic ridges. In rare occasions, parts of these formations can be found above water and are particularly interesting from the geothermal point of view, as the in the cases of Iceland and Azores islands, in the mid-atlantic ridge (Fig. 1.5).

3. *Convergent plate boundaries.* They correspond to the ocean trenches, the island complexes and the "folded" mountains. These boundaries are observed in areas where two plates move toward each other in such a way that one of them slides and sinks below the other, causing itself to be re-absorbed by the earth mantle. The new ocean crust that is formed in areas where the plates move away from each other is counterbalanced by the material destroyed in subduction zones. As a result, the total surface of the plates remains constantly steady.

4. *Transform plate boundaries or transform faults*. These are faults caused when two plates drift apart, and they be found both in land and under the ocean. Most transform faults are found on the ocean floor. The San Andreas fault in California, U.S.A., is an example of a transform plate boundary, where the Pacific Plate slides past the North American Plate. This area is characterized by intense seismic activity, and lack of any volcanic activity.

1.3 Origin and Transport of Earth's Heat

The origin of the heat of the Earth is not precisely known. There are certainly various theories referring to the mechanisms participating in its production. The main mechanisms are:

1. Radiocative decay of certain minerals which contain radioactive isotopes with a long half-live period, such as ^{238}U, ^{235}U, ^{232}Th and ^{40}K. The characteristics of these isotopes are presented in Table 1.1. The decay mechanism of the radioactive isotopes is the most important mechanism for thermal energy production (e.g. Muffler, 1993) and can account for at least 60% of the Earth's heat output.

2. Earth's heat emanates from activities that led to Earth's own creation, i.e primordial heat left over from the time of accretion. The contribution of this primordial heat to the current heat budget has been considered to be small (see e.g. Stacey, 1969). The internal part of the Earth was always hot, and as a matter of fact it was much hotter in its initial state than today, i.e. it is currently cooling down slowly.

Other non-radiogenic mechanisms that scientists consider as candidate contributors (in a much lesser degree) to Earth's heat include: earthquake induced gravitational energy, thermal contraction and tidal friction (e.g. Verhoogen, 1980).

Table 2.2. Characteristics of radioactive isotopes that contribute to the earth's heat (Turcotte and Schubert, 1982).

Radioisotope	**Half-life, 10^9 years**	**Concentration, kg/kg x 10^{-9}**	**Potential for heat production, W/kg x 10^{-5}**
^{238}U	4,47	25,5	9,37
^{235}U	0,704	0,185	56,9
^{232}Th	14,0	103	2,69
^{40}K	1,25	32,9	2,79

The Earth's heat flow (or better heat flux) is defined as the amount of heat escaping per unit time and unit area from the interior of the Earth's solid surface. It is eventually lost to atmosphere through the earth's surface. The heat flow is a continuous and steady phenomenon everywhere on our planet. These Earth heat losses occur at slow rates per unit surface, because of the low thermal conductivity of solid crust rocks. It is quite certain that the total thermal flow of the Earth surface does not address solely conductive losses (or even convective losses, at a lesser degree); there are also other mechanisms with much lower impact. These mechanisms include: heat released through volcanic explosions, distortion energy due to earthquakes, energy consumed for rock metamorphism, and gravitational potential energy (mountain elevation). The heat stored within the Earth's crust is considered to stand around 5,4x10^{21} MJ (Armstead, 1983), indeed an enormous figure.

Our knowledge of the Earth's interior is indirect and derives from both the study of our solar system and from specific scientific analyses and theories such as geological studies, geochemical analyses, geophysical measurements, and their interpretations.

Geological maps provide information regarding the geological structure at a depth that does not exceed a few kilometres. We can acquire more direct information through boreholes; however, this knowledge of the earth's interior refers only to selected points and to limited depths (currently up to 3 km, and maximum up to 10 km).

The basic law of physics states that heat moves from a hot region to a cold one.

Consequently, a constant heat flow is derived from the very hot earth interior to the cold surface and subsequently to the atmosphere. As a result, there is a natural heat flow from the core (which is estimated to have a temperature of over 4000^{o}C) to the Earth surface (with a mean yearly value of 15^{o}C) and finally to the atmosphere. This thermal energy transport from the Earth's interior to surface can be utilised by humans to meeting part of their energy needs.

The heat flow, $\dot{q}$, is determined by measuring the thermal gradient, dT/dz, in near surface rocks and their thermal conductivity, k, according to Fourier's law of heat conduction. Heat flow is now usually reported in SI units as mW/m^2. To determine the heat flow it is necessary to measure both these two parameters under conditions unaffected by other factors. Thermal conductivity measurements are usually carried out in the laboratory on sediments or rock samples collected in boreholes or on cores. In land areas the geothermal gradient measurements are made almost exclusively in boreholes. However, in these cases the circulation of water within the drilled rocks usually influences the temperature. As a result, the measured geothermal gradient in the borehole and, subsequently, the estimated heat flow may be both wrong. The temperature within aquifers remains steady because of convection phenomena. In addition, in certain occasions there is an inversion of the gradient because of extended faults with intense water circulation near the measurement site (Fig. 1.7).

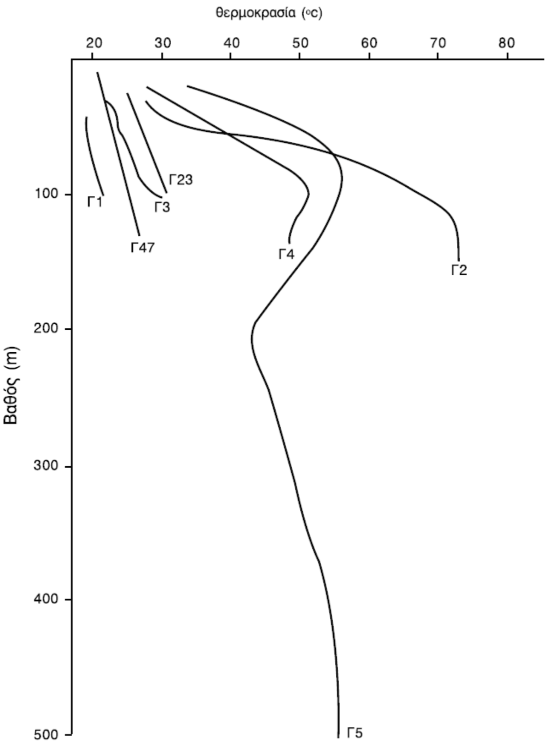


Fig. 1.7. Temperature gradients in several wells of the Sousaki field, Greece (Fytikas and Kavouridis, 1985).

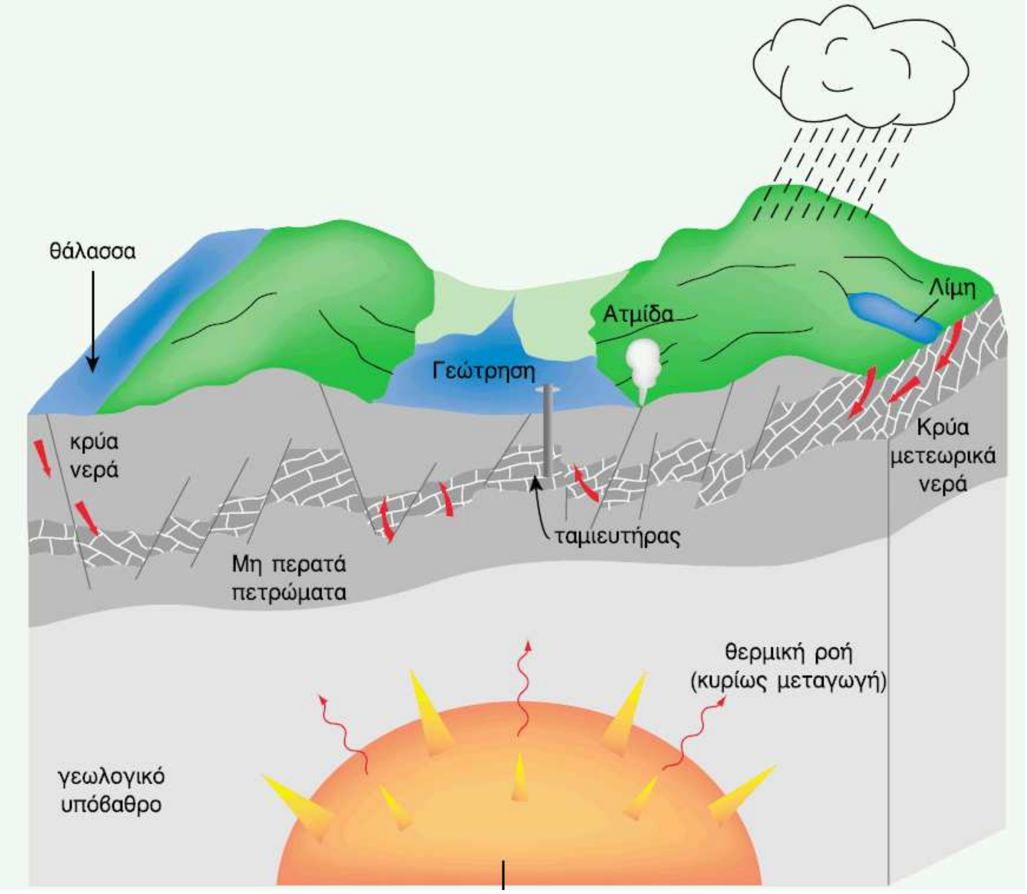


Fig. 1.8. Formation of a geothermal reservoir

1.4 Geothermal Systems

A common geothermal field consists of three parts: a *thermal source*, the *reservoir* and the *fluids* which act as heat carriers (Fig. 1.8). 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 vapour state and very often contain important quantities of dissolved solid substances and gases. The state of the geothermal fluids depends on their pressure and temperature.

Measurements in deep hydrocarbon exploration wells seem to be more reliable; however, when these drillings are not exploitable for technical or economic reasons they are clogged within hours following drilling stop. In the meantime the geothermal gradient has been altered during drilling as a result of mud circulation which cools well walls and the friction of the drillbit that heats the rocks. When dealing with measurements in drillholes it is imperative to allow considerable time (e.g. a few days after the project completion) before any measurement is taken, to secure thermal equilibrium between the well walls and the surrounding rocks.

Assuming an average universal heat flow of 80 mW/m^2, the total heat flow that reaches the Earth surface (~ 5,1x10^{14} m^2) would exceed 4x10^{13} W (40 TW), an energy supply four times higher than today's world energy consumption.

1.6. Favourable Geothermal Conditions

Several geodynamic and geotectonic phenomena contribute to achieving favourable geothermal conditions. These phenomena facilitate heat flow to access to the surface and, under certain conditions, the heat can be concentrated in the form of trapped hot fluids in a confined space, which can be reached by drilling. In our effort to locate such geothermal systems we seek *positive thermal anomalies* in combination with other favourable geological features.

In a relatively recent past, it has been evidenced along the axial rift zone, which is called *accretion zone, extension zone* or *mid-oceanic ridge*, a vertical ascent of hot (1200°C) magma. These areas (e.g. the mid-atlantic ridge) are not always located under oceans, since there exist selected areas above sea level, such as Iceland and the Afar Region in East Africa, where it is possible to observe directly tectonic, seismic, and volcanic-magmatic phenomena.

The *subduction* of a cold tectonic plate in the hot asthenoshere (case of convergent boundaries) creates positive thermal conditions above the lower parts of the overriding plate. This plate is descending with an angle of 30-35° creating the Benioff zone. Above the boundary and within a vertical range of 150-200 km the area experiences volcanism of andesite type. The magma ascends towards the sur-face creating sometimes volcanoes. How-ever, in most cases the magma does not reach the surface and, instead, it creates underground plutonic penetrations of granitic-dioritic composition. These areas form the **volcanic island arcs** or the **Cordilleras**, where huge quantities of interior thermal energy are transferred close to the surface.

When two tectonic plates crush together, further behind the crush area the extension tectonics can create magma conditions in the Earth crust. More often though, these tectonics facilitate the uprise of deep hot fluids, thus creating a positive thermal anomaly. The extremely impressive geothermal fields of Central Italy and Tibet can be possibly attributed to such magmatism.

Another anatectic magmatism is created from transform boundaries associated with deep and long transcurrent faults. The result is identical: alkali type magmas, rising asthenosphere facilitating the ascend of hot underground fluids (e.g. Turkey, California, Venezuela).

Another mechanism that creates exceptionally favourable geothermal conditions deals with magmatism occurring within continental or oceanic plates, known as *hot spot magmatism* or *thermal swells*. Volcanoes are created on the ocean floors and on continental environments, respectively, matching usually a straight line. These straight-line volcanoes, such as the Hawaii Island complex, and the Jos area in Nigeria are formed in territories where neither faults nor fractures do exist

The creation of positive thermal anomalies can be favoured either by transfer of huge quantities of heat through molten rocks or small quantities from the upwelling motion of magmatic gases and, generally, of “young” magmatic fluids. This transfer takes place through small fractures of rocks overlying magma chamber. Finally, there are areas displaying above normal heat flow densities which are a consequence of crest thinning due to tectonic plate movement. These areas correspond to *continental grabens*, such as the Rhine River rift valley and the Pannonian plain depression.

1.7. Heat Flow Values

It has been established that the average value of heat flow in both continental and oceanic crust ranges from 60 to 100 mW/m^2. Pollack et al. (1993) provide the most recent published compilation of surface heat flow measurements. The mean continental thermal flow is estimated at 65±1,6 mW/m^2, while that of the oceanic crust is 101±2,2 mW/m^2. Europe’s average heat flow is estimated at 62 mW/m^2. Certainly, heat flow densities are area specific. The lowest rates in Europe have been recorded in Scandinavia (25 mW/m^2) and the highest in Southern Europe; in Central Italy the maximum figure reaches 680 mW/m^2.

In general, with respect to continental regions, lower than average heat flow values are noticed for Precambrian shields, normal for Postcambrian regions, above average for regions exhibiting Cenozoic volcanic activities, while significantly higher than average in regions evidencing recent or active volcanic activity or plutonism. It is obvious that heat flow measurements do not include monitoring in already explored and validated geothermal regions.

Summing up, high heat flows relate primarily to magmatism and secondarily to hydrothermal circulation, while tectonics, lithology, and stratigraphy also influence heat flow, at a lesser degree though. Nevertheless, some local surface conditions may also affect measured heat flow densities, such as the convective circulation of hot ground water in large horizontal or water permeable formations, in wide and open faults, etc.

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Chapter 2

DEFINITION AND CLASSIFICATION OF GEOTHERMAL RESOURCES

Michael Fytikas, Pierre Ungemach

2.1 Definition of Geothermal Resources and Reserves

Geothermal resources are the quantities of thermal energy stored between the earth's surface and an accessible depth, so that they can be retrieved by drilling with modern technology at a competitive cost with regards to conventional energy sources. The geothermal potential involves both the natural steam and the thermal waters (surface or ground), as well as the heat of geological formations whose temperature is higher than the yearly average temperature of the area.

The exploitation of the geothermal potential is possible in areas where the hot fluids (water, steam and various other gases) rise towards the surface through faults or fractures carrying significant amounts of heat from deeper and hotter parts of the crust. These areas are very often associated with active or, at least, with recent volcanism, as well as with active tectonics. In theory, favourable geothermal areas are also those with higher than average heat flow (60 mW/m^2), or, in other words, with geothermal gradient higher than the average value (30^{o}C/km). The most favourable "geothermal" systems are located at lithospheric plate boundaries, where geothermal gradients are much higher than average.

The existence of a favourable geothermal system is not associated only to thermal anomaly. Other favourable geological conditions must also exist: the geothermal fluids need to be located at relatively shallow depths, to show acceptable physico-chemical characteristics and to exist in adequate quantities. Favourable characteristics, such as porosity and permeability, of the host rock are also required. The thermal energy of the natural fluids depends obviously on their amount and temperature, while their economic feasibility depends on the fluid physico-chemical characteristics and drilling depths.

The term geothermal resources usually refers to *accessible resources*, i.e. the thermal energy stored between the Earth's surface and a specified depth and that can be extracted at a competitive cost (with respect to other conventional or not energy sources), or even the resources that may not economical today but could potentially become accessible sometime in a foreseeable future, i.e. within the next 100 years.

The accessible geothermal resources – as for fossil fuel sources – can be divided into *identified resources* and *unidentified resources* (Figure 2.1). The former, also known as *reserves*, refer to the geothermal energy quantities that exist at known locations, qualities, and quantities or that can be estimated from geologic exploration, which includes exploratory drillings. They represent the part of energy sources quantities for which it has been recognised as available and exploitable. They can be further subdivided into *possible*, *probable* and *proven* resources, thus reflecting varying degrees of geological evidence. Proven resources are those which are retrievable under current prevailing financial and technological standards. Probable resources are those retrievable either from likely geological reservoirs not yet assessed by drilling, or from known reservoirs via novel (and, as a result, more expensive) technologies. Possible resources are those assumed to exist in a priori favourable regions, which, because of insufficient factual evidence cannot be qualified as probable. New geothermal resources are regularly discovered and identified worldwide so that the boundaries between the various types of resources are constantly moving. Ultimately, unidentified resources address expected or/and assumed to exist under similar geologic environments.

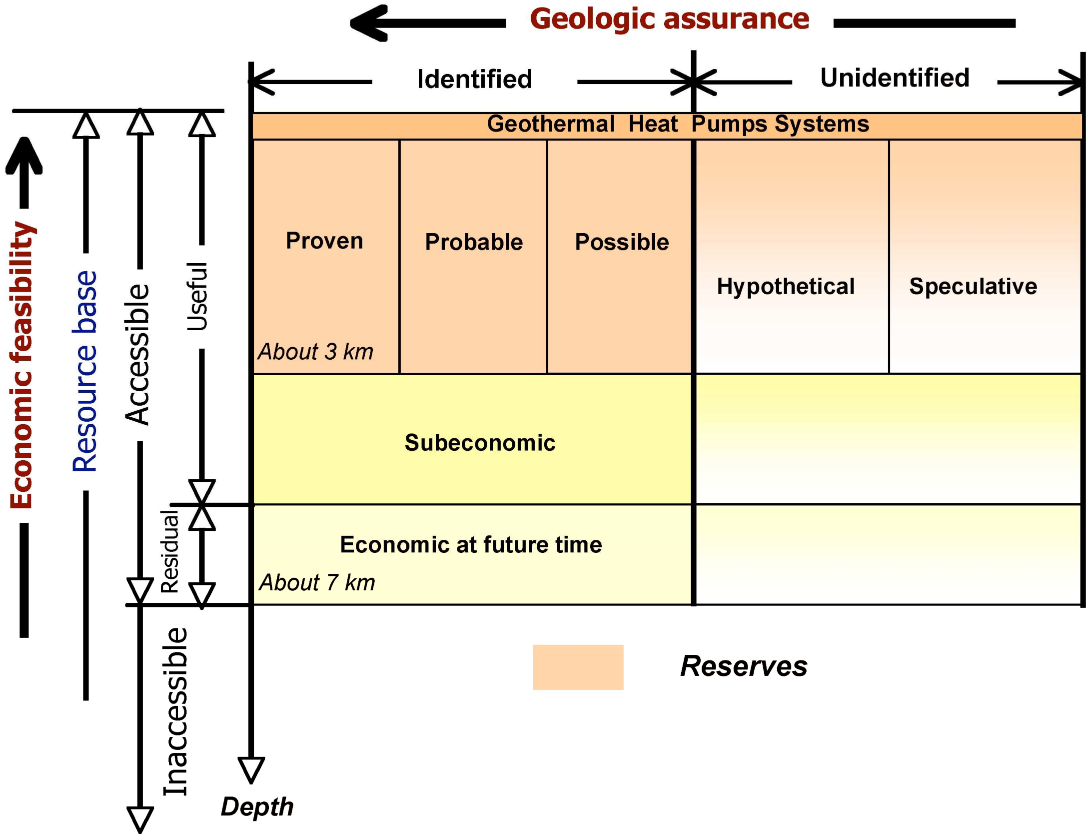

Figure 2.1. A modified McKelvey diagram for the classification of geothermal reserves and resources.

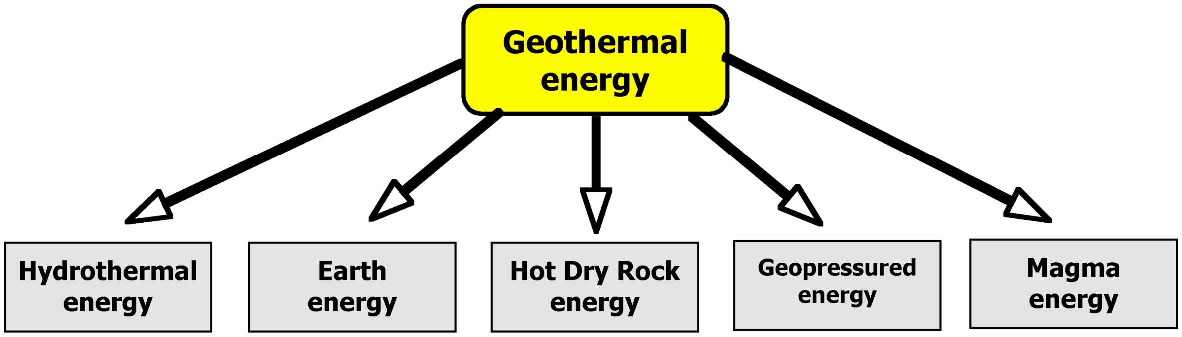

Figure 2.2. Geothermal energy types with decreasing exploitation degree from left to right.

The concept of geothermal resource is of wider significance. It refers to the entire quantity of geothermal energy either known or assumed such, whatever the technologies involved in their exploitation. For instance, various more or less hypothetical resources are known (at depths exceeding 10 km), whose extraction costs stand excessively high. Most of the time, assessing reliable estimates of energy resources (both conventional and geothermal) is a risky exercise, since estimates can fluctuate depending on the information made available through research and experience.

Heat is not the only "geothermal product" that can be extracted from a geothermal system. Other geothermal (by)products include various minerals (e.g. boron or potassium salts, precious metals, etc.) and gases (methane, carbon dioxide) dissolved in the liquid phase. Finally, some geothermal fluids can be utilised further for heat extraction for balneology, irrigation, waste water injection, geothermal heat pumps purposes among others.

2.2 Geothermal Systems Classification

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 host rock, the heat source type and fluid circulation modes within the reservoir. With respect to the geothermal resource type, five systems are usually identified (Fig. 2.2):

a) **Hydrothermal systems or resources** address the natural thermal fluids, which are hosted in one or more reservoirs. These are heated up from a heat source and occasionally appear at the earth surface in the form of thermal manifestations. This category is often synonymous of geothermal energy since it represents today the largest fraction of energy extracted from the earth. These systems are also called *convective systems* or *dynamic systems*, since convection is primarily the heat transfer driving mechanism. Of course, some *conductive* or *static systems* also exist, heated by conduction; they consist mainly of slightly saline waters trapped at depths of 2-4 km, with temperatures in the 60-150°C range. A typical example such systems may be found in the Pannonian basin.

b) A promising geothermal sector includes the so-called **shallow geothermal systems**, which represents the energy stored (as water, soil and rock) in the uppermost 200 m of the subsoil. This energy can be reclaimed thanks to available heating/ cooling heat pumps technology.

c) G**eopressured systems,** which consist of trapped hot saline fluids under high nearing lithostatic pressures, contain high concentrations of dissolved methane. These systems are confined by impermeable rocks and their pressures greatly exceed the hydrostatic figures. They can be classified as static systems.

d) **Hot dry rock resources** deal with the heat available in rocks at depths of 3 to 10 km, whenever there exists no natural fluid circulation and heat carrier to sustain surface heat recovery. This thermal energy can be harnessed by means of water injection and thermosyphon enhanced water injection.

e) **Magma systems** refer to heat extraction from molten rock accessed via appropriate frontier drilling technology in areas displaying active volcanism.

Hydrothermal systems are usually classified as either *vapour-dominated systems* or *water-dominated systems*. The former are systems which host superheated vapour, used exclusively for power generation, while the latter address hot water.

The most common criterion for hydrothermal system classification is based on *geothermal fluid enthalpy* (i.e. ΔH), since fluids convey heat from deep seated hot rocks to surface. ΔH expresses the energy content of the fluid, and is roughly proportional to their temperature. Therefore, geothermal resources are more often classified, for practical reasons, and somewhat arbitrarily, as *low, moderate* and *high enthalpy* or *temperature fluids* (Table 2.1). High-enthalpy include fluids, the tempe-rature of which exceeds 150°C; medium-enthalpy fluids exhibits temperatures ranging from 90 to 150ºC; low-enthalpy fluid temperature stands below 90°C. Use of binary power conversion cycles (known as Organic

Rankine Cycle, ORC) make it possible to use organic fluids at temperatures, as low as 85ºC. Classification of low enthalpy fluids is supported by the fact that geothermal fields at such temperatures are plentiful and can be exploited for a variety of direct uses. The above classification by all means is arbitrary; as a result many modifications or alternative classifications have been suggested in the geothermal literature (Nicholson, 1993; Dickson & Fanelli, 1995).

Table 2.1 Classification of geothermal systems

System type	**Characteristic**	**Temperature (°C)**
1. HYDROTHERMAL		
1a. Convective systems	Permeable formations with natural circulation	
A) *Vapour dominated*	Closed convective systems, vapours trapped due to impermeable cap-rock, >200ºC, up to 1.5-km depth	~240
B) *Water dominated*		
i) High temperature	Closed or open convective systems to a depth of 3 km	> 150
ii) Medium temperature	Almost horizontal aquifers with hot water circulation under pressure	90-150
iii) Low temperature	As before, lower water temperature, hydrostatic pressure or slightly increased, in areas with normal heat flow.	< 90
1b. Conductive systems	Impermeable formations with high porosity and permeability, depths 1-3 km, trapped waters	60-150
2. EARTH ENERGY	At depths from 1 m to 100 m, with or without water	<40
3. HOT DRY ROCK ENERGY	Impermeable rock formations without natural circulation. Technical water circulation with at least two drillholes.	
i) High temperature	T>250ºC up to 3 km	>250
ii) Medium-low temperature	T<150ºC up to 3 km	<150
4. GEOPRESSURED ENERGY	Enclosed aquifers under high pressure with high methane content (conductive systems)	150-200
5. MAGMA ENERGY	Temperature >500ºC at a depth of a few kilometers due to molten rock intrusions	>500

Water dominated systems are of more common occurrence. Depending the temperature and pressure conditions, they can produce either *hot water* (at temperatures <100ºC) or a *two-phase mixture* of water and vapour. The heat source is provided by molten or recently solidified rocks that lye at depths between 3 and 10 km. Heat transfer is achieved by ground water convection. Isotopic studies have proven that the most of the produced water and vapour is of meteoric or surface origin. The circulating waters are usually enriched in NaCl and other elements, with a simultaneous reduction of certain element concentrations, such as Mg. Pressures and temperatures of most water dominated systems remain within the boiling vs depth curve.

A water dominated system of low or medium temperature is of economic interest for direct uses when reservoir depths stand below 2 km, productivity in excess of 30 kg/s, and salinity relatively low (less than 50 g/l). The most well known geothermal systems exploited for direct uses are located in the Paris basin (in France), in the Pannonian basin (in Hungary) and in the in the Po valley (in Italy).

Approximately 90% of the exploited hydrothermal systems (with regards to reco-

vered heat) are medium and high enthalpy water dominated fields (Barbier, 2002).
These waters contain large quantities of dissolved salts (from 1 to 350 g/l), whose thermochemistry usually causes scaling and corrosion shortcomings.

In vapour dominated systems, water and vapours coexist in the reservoir, even though at the surface the only superheated steam is produced, together with small quantities of non-condensable gases. These systems are of generally rare occurrence, with only fields recorded and exploited to date; however some of them have been exploited for electric power generation, such as Larderello (Italy), the Geysers (USA), Matsukawa (Japan), Kamojang and Darajat (Indonesia) and Los Azufres (Mexico). Due to natural convection, high salinity waters usually rise up to a depth where evaporation takes place. The resulting steam moves upwards through fractures and may become superheated through further contact to hot rocks. It is believed that in such systems rocks exhibit limited permeability, since in any other circumstances waters from nearby formations would obviously flood the reservoir. Reservoir temperatures and enthalpies, reservoir conditions of geothermal fluids in water- and vapour-dominated fields vary significantly. Typical values are listed in table 2.2.

Table 2.2. Reservoir temperature and fluid enthalpies of high-temperature geothermal fiedls (Barbier, 2002).

Geothermal field	Reservoir temperature, °C (maximum temperature, °C)	Maximum enthalpy (kJ/kg)
Vapour-dominated systems		
The Geysers (U.S.A.)	237 (310)	3000
Larderello (Italy)	200 (420)	3100
Monte Amiata (Italy)	170 (344)	2600
Matsukawa (Japan)	220	
Kamojang (Indonesia)	175 (248)	2780
Water-dominated systems		
Wairakei (New Zealand)	230 (290)	1175
Broadlands (New Zealand)	255 (326)	1175
Imperial Valley (U.S.A.)	160 (370)	1000
Cerro Prieto (Mexico)	300 (388)	2430
Los Azufres (Mexico)	175 (300)	2700
Momotombo(Nicaragua)	210 (327)	2700
Tiwi (Philipines)	273 (309)	2800
Hatchobaru (Japan)	250 (308)	2250
Krafla (Iceland)	205 (344)	2680
Milos (Greece)	225 (320)	2600

Alternative classification criteria might be contemplated which relate to the energy (temperature, enthalpy) and utilisation (power, heat) of the geothermal source. They would shape less academic, or at least better targeted, than the sole depth vs geological assurance criterion. The latter, actually, may prove misleading by providing huge recoverable reserve estimates and wishful thinking regarding practical development issues. Fig. 2.4 and 2.5 illustrate two candidate classification nomenclatures.

Fig. 2.3, based on utilisation opportunities, addresses two main, temperature dependant, applications, geoheat and geopower respectively. The border line between electric and non-electric uses, set at 100 – 110 °C, ought to be allowed some flexibility and overlapping regarding process heat and absorption freezing/cooling uses. Given the regional geodynamic context, reservoir temperatures and heat flow densities, expected at economically accessible depths, should enable to reliably assess and rank the resource development objectives.

A similar rationale, suggested by Sanyal (2005), is displayed in Fig. 2.4, a variant of the Mollier diagramme for pure water, which reflects the thermodynamic properties of the reservoir fluid. It is obviously oriented towards high enthalpy, either liquid or vapour dominated, systems eligible to power generation and, occasionally, combined heat and power.

The system nomenclature, portrayed in Fig. 2.4 (pressure, enthalpy, temperature) diagramme, identifies, according to the saturated temperatures of the reservoir, seven categories listed in Table 2.3. Based on these selective guidelines, Sanyal (2005) achieved, for the Western U.S.A., the following reserve assessment (at 2005):

- Class 2 : 200 – 250 MWe
- Class 3 : 400 MWe
- Class 4 : 1200 MWe
- Class 5 : 2000 MWe
- Class 6 : 1000 MWe

Table 2.3. Tentative Geothermal Resource Classification (adapted from Sanyal, 2005).

Class	**Temperature (*) (°C)**	**Fluid State**		**Well Power Rating (MW)**	**Eligible Conversion Cycle**
		Reservoir	**Well head**		
1	< 100	L	L	1 – 10	Heat exchange
2	100 – 180	L	L (pumped) 2 ϕ (self flowing vapour lift)	1 – 5	Binary, Single flash, Dual flash
3	180 – 230	L	2 ϕ	2 – 10	Single flash, Dual flash
4	230 – 300	L, 2 ϕ	2 ϕ, V (**)	5 – 20	Single flash, Dual flash
5	> 300	L, 2 ϕ	2 ϕ, V (***)	10 – 50	Single flash
6	240	V	V	10 – 50	Direct steam expansion
7	> 374	L	2 ϕ	?	?

Symbols: L = liquid; V = vapour; 2 ϕ = two phase.
(*) saturated reservoir temperature
(**) saturated steam
(***) saturated and superheated steam

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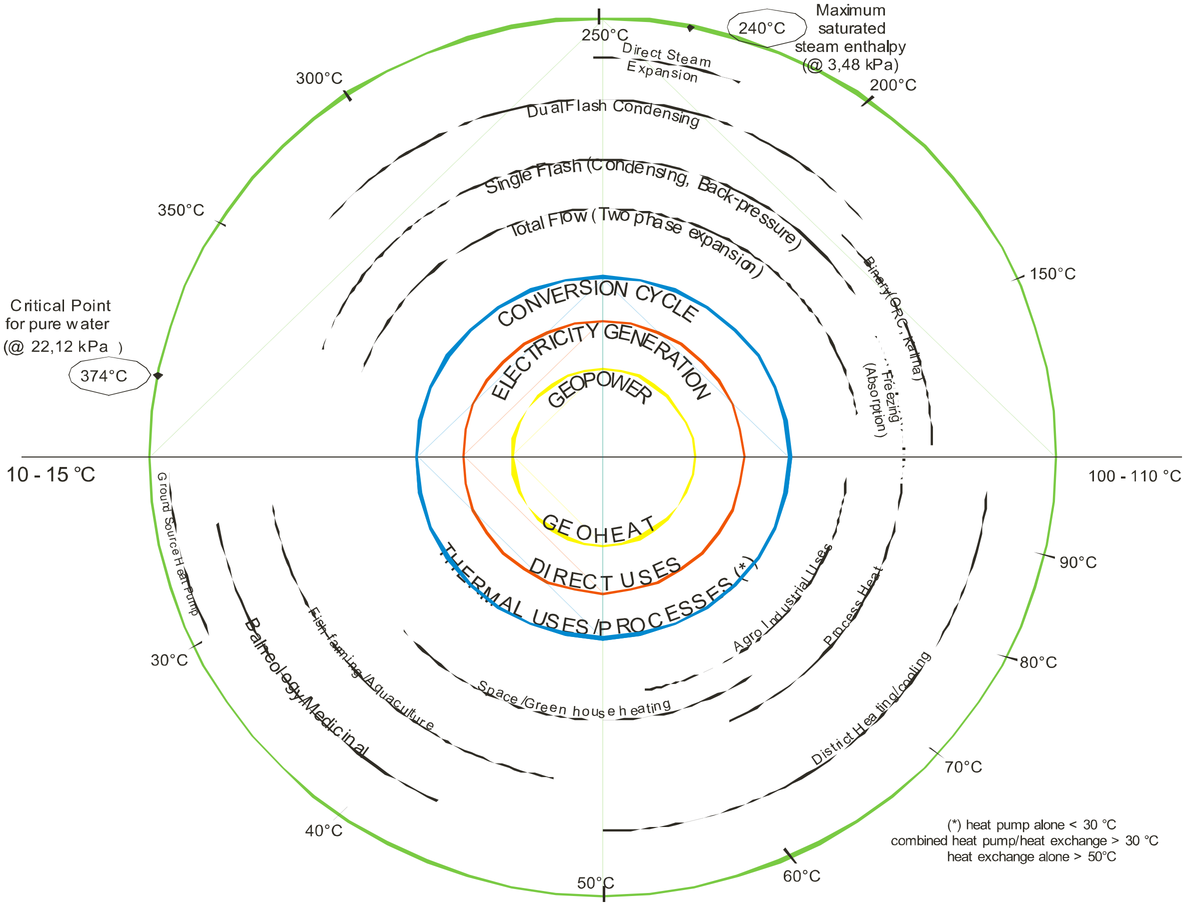
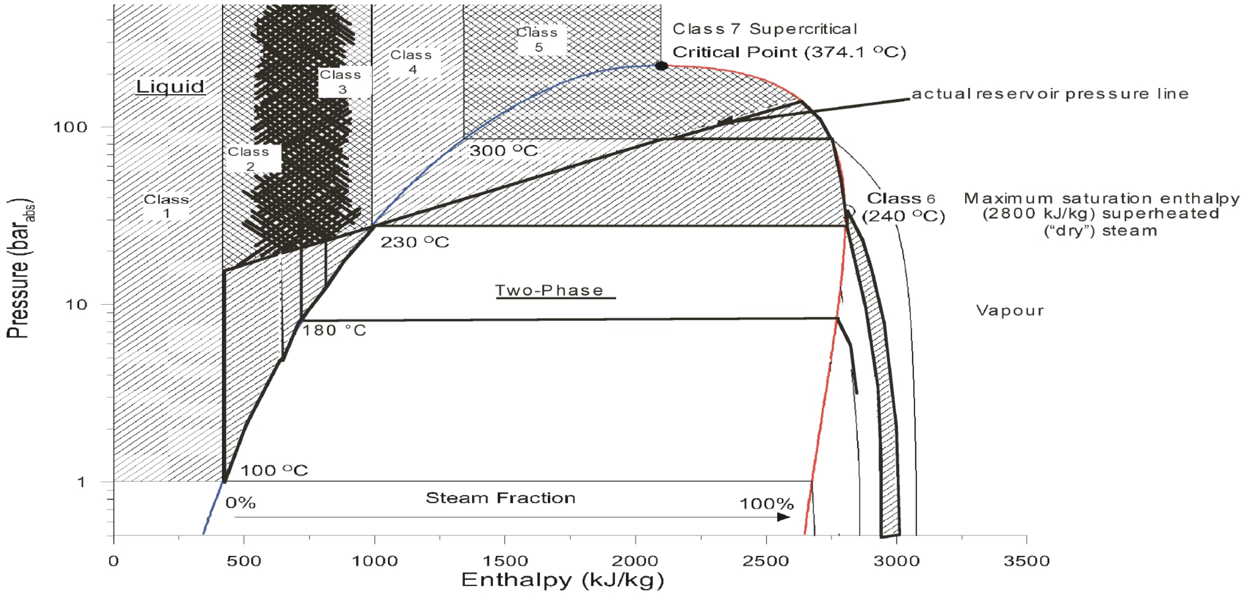


(*) heat pump alone < 30 °C
combined heat pump/heat exchange > 30 °C
heat exchange alone > 50°C

Fig. 2.3. Simplified geothermal utilisation diagramme.



Pressure-Enthalpy-Temperature diagram for pure water

Fig. 2.4. Tentative geothermal system nomenclature based on saturated temperatures (adapted from Sanyal, 2005).