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GEOTHERMAL SYSTEMS IN GLOBAL PERSPECTIVE

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ABSTRACT

Geothermal resources are distributed throughout the world. They are classified in various ways on the basis of heat source, heat transfer, reservoir temperature, physical state, utilization and geological settings. Common classification of geothermal systems is: (a) volcanic systems with the heat source being hot intrusions or magma chambers in the crust, (b) convective systems with deep water circulation in tectonically active areas of high geothermal gradient, (c) conductive sedimentary systems with permeable layers at great depth (2-5 km), (d) geo-pressured systems often in conjunction with oil resources, (e) hot dry rock or EGS systems where abnormally hot masses of low permeability rocks are found at drillable depths, (f) shallow resources in normal geothermal gradient areas utilized with ground-source heat pump applications. In most of these classes the energy transport medium is the water within the geothermal system and such systems are therefore called hydrothermal systems, exceptions being the EGS systems and the shallow, ground-source heat pump resources. The geothermal systems are suitable for various applications depending on the reservoir temperature and fluid type. The hot volcanic systems are utilized primarily for electric power generation and the lower temperature systems for space heating and other direct uses.

Some 50 years ago a classification was proposed in which geothermal fields in Iceland were divided into high- and low-temperature hydrothermal fields or areas. This division was based on (arbitrarily) inferred temperature at 1 km depth, high temperature fields where a temperature of 200°C is reached at 1 km depth and low temperature fields where temperature is below 150°C in the uppermost km. The HT-fields are all related to volcanism whereas the LT-fields draw heat from the general heat content of the crust and the heat flow through the crust. Other temperature subdivisions have been proposed by adding intermediate or medium temperature systems in-between the two main categories. There are several types of systems in each of the two main groups.

1. INTRODUCTION

The words *geothermal energy* refer to the thermal energy contained within the earth. Nowadays we use the word, however, for that part of the earth's heat that we can recover from the ground primarily through boreholes and exploit for various purposes. Geothermal resources are found throughout the world but exploitable geothermal systems are mainly found in regions of normal or abnormally high geothermal gradients. Even though the greatest concentration of geothermal energy is associated with the Earth´s plate boundaries, geothermal energy may be found in most countries and exploitation of geothermal systems in normal and low geothermal gradient areas has been gaining momentum during the last decade. The geothermal potential is though highly concentrated in volcanic regions, but may also be found as warm ground water in sedimentary formations world-wide and the flux of heat to the surface is, in most regions of the world, sufficiently high to be utilized for house heating using shallow boreholes and ground source heat pumps. In many cases geothermal energy is found in populated, or easily accessible, areas. But geothermal activity is also found at great depth on the ocean floor, in mountainous regions and under glaciers and ice caps. Numerous geothermal systems probably still remain to be discovered, since many systems have no surface activity. Some of these are, however, slowly being discovered. The following definitions are used here:

- *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.
- *Geothermal System* refers to all parts of the hydrological system involved, including the recharge zone, all subsurface parts and the outflow of the system.
- *Geothermal Reservoir* indicates the hot and permeable part of a geothermal system that may be directly exploited. For spontaneous discharge to be possible geothermal reservoirs must also be pressurized, either artesian or through boiling.

Geothermal systems and reservoirs are classified on the basis of different aspects, such as reservoir temperature, enthalpy, physical state or their nature and geological setting. Table 1 summarizes classifications based on the first three aspects.

TABLE 1: Classifications of geothermal systems on the basis of temperature, enthalpy and physical state (Bodvarsson, 1964; Axelsson and Gunnlaugsson, 2000)

<table>
<tr><td>Low-temperature (LT) systems with reservoir temperature at 1 km depth below 150°C. Often characterized by hot or boiling springs.</td><td rowspan="2">Low-enthalpy geothermal systems with reservoir fluid enthalpies less than 800 kJ/kg, corresponding to temperatures less than about 190ºC.</td><td rowspan="2">Liquid-dominated geothermal reservoirs with the water temperature at, or below, the boiling point at the prevailing pressure and the water phase controls the pressure in the reservoir. Some steam may be present.</td></tr>
<tr><td>Medium-temperature (MT) systems with reservoir temperature at 1 km depth between 150- 200°C.</td></tr>
<tr><td rowspan="2">High-temperature (HT) systems with reservoir temperature at 1 km depth above 200°C. Characterized by fumaroles, steam vents, mud pools and highly altered ground.</td><td rowspan="2">High-enthalpy geothermal systems with reservoir fluid enthalpies greater than 800 kJ/kg.</td><td>Two-phase geothermal reservoirs where steam and water co-exist and the temperature and pressure follow the boiling point curve.</td></tr>
<tr><td>Vapour-dominated reservoirs where temperature is at, or above, boiling at the prevailing pressure and the steam phase controls the pressure in the reservoir. Some liquid water may be present.</td></tr>
</table>

Geothermal systems may also be classified based on their nature and geological settings as:

A. *Volcanic geothermal systems* are in one way or another associated with volcanic activity. The heat sources for such systems are hot intrusions or magma. They are most often situated inside, or close to, volcanic complexes such as calderas, most of them at plate boundaries but some in hot spot areas. Permeable fractures and fault zones mostly control the flow of water in volcanic systems.

B. In *convective facture controlled systems* the heat source is the hot crust at depth in tectonically active areas, with above average heat-flow. Here the geothermal water has circulated to considerable depth (> 1 km), through mostly vertical fractures, to mine the heat from the rocks.
C. *Sedimentary geothermal systems* are found in many of the major sedimentary basins of the world. These systems owe their existence to the occurrence of permeable sedimentary layers at great depths (> 1 km) and above average geothermal gradients (> 30ºC/km). These systems are conductive in nature rather than convective, even though fractures and faults play a role in some cases. Some convective systems (B) may, however, be embedded in sedimentary rocks.
D. *Geo-pressured systems* are analogous to geo-pressured oil and gas reservoirs where fluid caught in stratigraphic traps may have pressures close to lithostatic values. Such systems are generally fairly deep; hence, they are categorized as geothermal.
E. *Hot dry rock (HDR) or enhanced (engineered) geothermal systems (EGS)* consist of volumes of rock that have been heated to useful temperatures by volcanism or abnormally high heat flow, but have low permeability or are virtually impermeable. Therefore, they cannot be exploited in a conventional way. However, experiments have been conducted in a number of locations to use hydro-fracturing to try to create artificial reservoirs in such systems, or to enhance already existent fracture networks. Such systems will mostly be used through production/reinjection doublets.
F. *Shallow resources* refer to the normal heat flux through near surface formations and the thermal energy stored in the rocks and warm groundwater systems near the surface of the Earth's crust. Recent developments in the application of ground source heat pumps have opened up a new dimension in utilizing these resources.

The classification of geothermal systems into low temperature (LT) and high temperature (HT) is commonly used in Iceland and dates back some 50 years. It should be pointed out that hardly any geothermal systems in Iceland fall in-between 150 and 200ºC reservoir temperature, i.e. in the MT range. The few ones are declining volcanic geothermal systems, on their flanks or in the outflow zone. Different parts of geothermal systems may be in different physical states and geothermal reservoirs may also evolve from one state to another. As an example a liquid-dominated reservoir may evolve into a two-phase reservoir when pressure declines in the system as a result of production. Steam caps may also evolve in geothermal systems as a result of lowered pressure. Low-temperature systems are always liquid-dominated, but high-temperature systems can either be liquid-dominated, two-phase or vapour-dominated.

In the following chapters we will look in more details at the various types of low and high temperature geothermal fields in the word. We will start by dividing them in low and high temperature fields and then into sub types based on the geological settings.

2. LOW-TEMPERATURE GEOTHERMAL SYSTEMS

Low temperature geothermal activity is spread over most of the Earth, and low temperature fields are found in various geological settings. They are divided into several types as described below but primarily they depend primarily on the regional geothermal gradient, permeability (primary or secondary) of the rock and depth of circulation if such exists.

2.1 Shallow systems

Shallow resources refer to the normal heat flux through near surface rock formation and the thermal energy stored in these and warm ground water systems near surface of the Earth. The heat flux varies from place to place over the surface of the Earth. The average value is about 60 mW/m^2, which corresponds to an average geothermal gradient of ~30°C/km. Geothermal resources could earlier only be utilized economically in regions of abnormally high heat flow. This has changed and recent developments in application of ground source heat pumps have opened up new frontiers in utilizing shallow geothermal resources in areas of normal or even subnormal geothermal gradient using boreholes in the depth range of few tens of meters to few hundreds of meters and downhole heat exchangers. The feasibility of this utilization has also changed due to governmental actions i.e. subsidy programmes and green tariffs and there are examples where ground source heat pumps are utilizing up 2 km deep wells in a normal gradient areas, where the bottom hole temperature is therefore only 60°C.

2.2 Sedimentary systems

Sedimentary geothermal systems are found in many of the major sedimentary basins of the world. Sedimentary basins are layered sequences of permeable (limestone, sandstone) and impermeable strata (shale or mudstone) which alternate. Water is interstitial water, commonly brine, formerly thought to be of connate origin. Temperature is variable, depending on depth of permeable rocks in basin. These systems owe their existence to the permeable sedimentary layers at great depth (>1 km), often above average geothermal gradients (>30°C/km) due to radiogenic heat sources in the shallow crust or tectonic uplifting (folding) in the region or for other reasons. These systems are conductive in nature rather than convective, even though fractures and faults play a role in some cases (Figure 1). Some convective systems may, however, be embedded in sedimentary rocks. Examples of geothermal systems in sedimentary basins are the Molasse basin north of the Alps, the Paris basin, the Pannonian basin, the Great Artesian Basin in Australia, the sediment filled Rhine graben and several basins in China to mention only few. These systems are of different origin and the heat flow differs widely. The depth to useful temperatures may vary from 1 up to 5 km. The fluid salinity is also different from relatively fresh water to high salinity brine (250,000 ppm). Natural recharge of the geothermal fluid is minimal and reinjection is needed to maintain reservoir pressure and is often a mandatory way to dispose of the geothermal water after passing through heat exchangers. Doublets (production-injection) boreholes are commonly used.

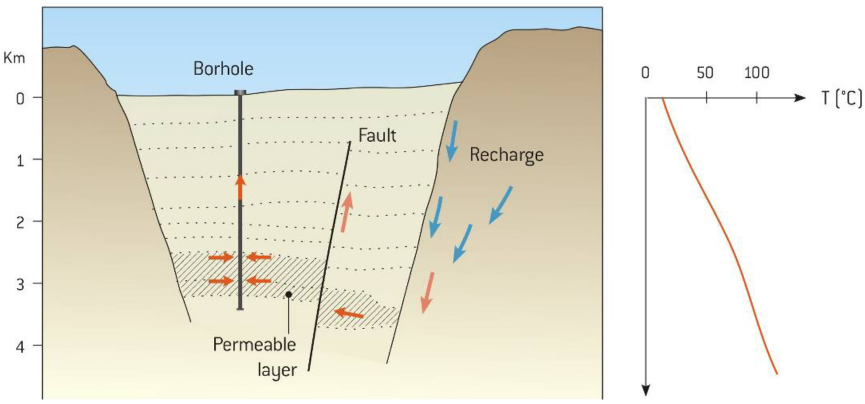

FIGURE 1: Schematic figure of a sedimentary basin with a geothermal reservoir at 2- 4 km depth. The temperature profile to the left shows a typical sedimentary geothermal gradient profile

Some sedimentary basins contain sedimentary rocks with pore pressure exceeding the normal hydrostatic pressure gradient. These systems are classified as geo-pressured geothermal systems. They are confined and analogous to geo-pressured oil and gas reservoirs where fluid caught in stratigraphic traps may have pressures close to lithostatic values. Such systems are fairly deep; hence they are categorized as geo-pressured geothermal systems. The known geo-pressure systems are found in conjunction with oil exploration. The most intensively explored geo-pressured geothermal sedimentary basin is in the northern part of the Gulf of Mexico and in Europe in Hungary. Geo-pressured geothermal fields have not yet been exploited.

2.3 Fracture or fault controlled convection systems

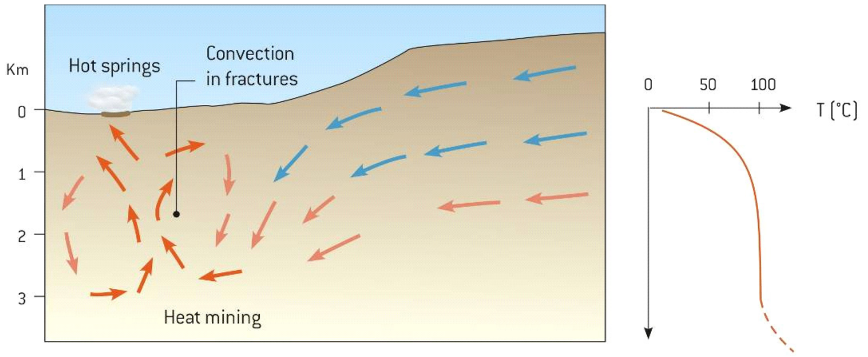

FIGURE 2: A conceptual model of fractured low temperature convective system. The temperature profile to the right represents the temperature in the central part of the convective reservoir

In fracture or fault controlled convection systems circulation may be deep or shallow. The recharge water is rain from mountainous areas some distance from the geothermal field that flows as ground water stream towards a permeable fracture area where fluid convection mines heat from the deeper parts of the geothermal field (Figure 2). The convecting water picks up heat at depth (cools the formations) and transports the heat from base area of the system to upper parts of the reservoir (Figure 2 and 3). The reservoir water is generally low in TDS but may be high in sediment filled rift zones or in coastal areas. Temperature is anywhere from little above ambient to 160°C depending on depth of circulation. Highly fractured ground hosts relatively cold systems. High discharge (such as over 100 l/s) of >100°C water from a single fault would suggest transient character. Temperature inversion commonly occurs in open, fracture controlled geothermal systems as hot water flows or spreads laterally in the near-surface part of the fractures. These low temperature systems are common in Iceland as in other tectonically active countries.

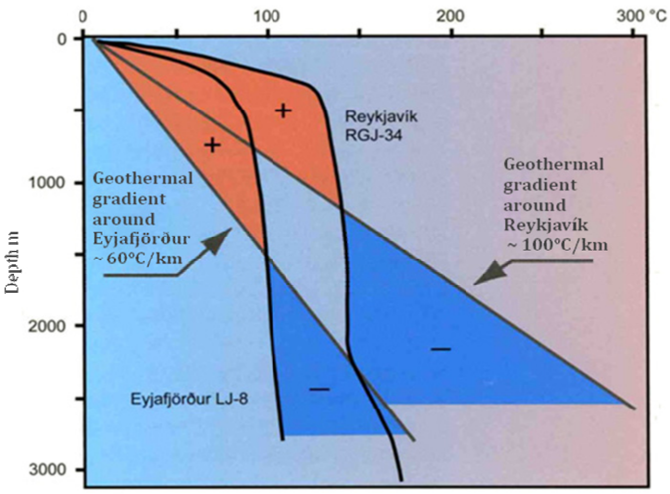

FIGURE 3: Reykjavík and Akureyri, Iceland. Bold lines show actual reservoir temperature, 130-140°C for Reykjavík, 90-95°C for Akureyri. Water transports heat from deep levels, thus cooling the rock (heat mining). Shallower levels consequently are heated up

Fracture permeability is dependent on the type of rock. Fracture-friendly rocks are hard and „non-yielding“, such as igneous rock (basalt, andesite and intrusive rock) and also granite, gneiss, quartzite, also limestone and indurate sandstone. Fracture-unfriendly are claystone, shale and the like which react to rock stress by plastic deformation. Only a part of the fractures contribute to an effective fracture volume. Release joints and tension fractures have a relatively high effective fracture volume contrary to compressional fractures. Water contained in matrix pores and micro-fractures is inaccessible in case of low-temperature geothermal exploitation. Pressure decrease due to drawdown in high-temperature reservoirs may cause pore and micro-fracture water to boil and hence contribute to the available part of the resource.

2.4 Off-flow from volcanic (high-temperature) geothermal systems

Systems with off-flow from volcanic (high-temperature) geothermal areas include groundwater heated by contact with hot ground and/or mixing of deep reservoir water with local ground water. Commonly inversion of temperature is found and in some cases deposits of travertine occur, especially where the geothermal system is on the decline. Aquifers may be either stratabound or fracture related. Temperature decreases with distance from the source region. Depending on the temperature in the uppermost kilometre, the outflow systems are classified as low temperature systems but close to the volcanic areas the temperature may exceed 150°C at 1 km thus lifting it to medium temperature system (MT).

2.5 Distal part of fissure swarms via their laterally injected dyke swarms

Fissure swarms of volcanic origin pass downwards into dyke swarms. These may extend into the marginal blocks of the rift zones and create secondary permeability within them and thus pathways for deep circulation (Figure 4). The proximal parts of fissure swarms are located within the rift zones (actually defining them), usually in areas of thick young volcanics of high permeability and sediments. Surface manifestations may be scarce under such conditions, but at deep levels (below 1-1.5 km) conditions for a geothermal system may exist.

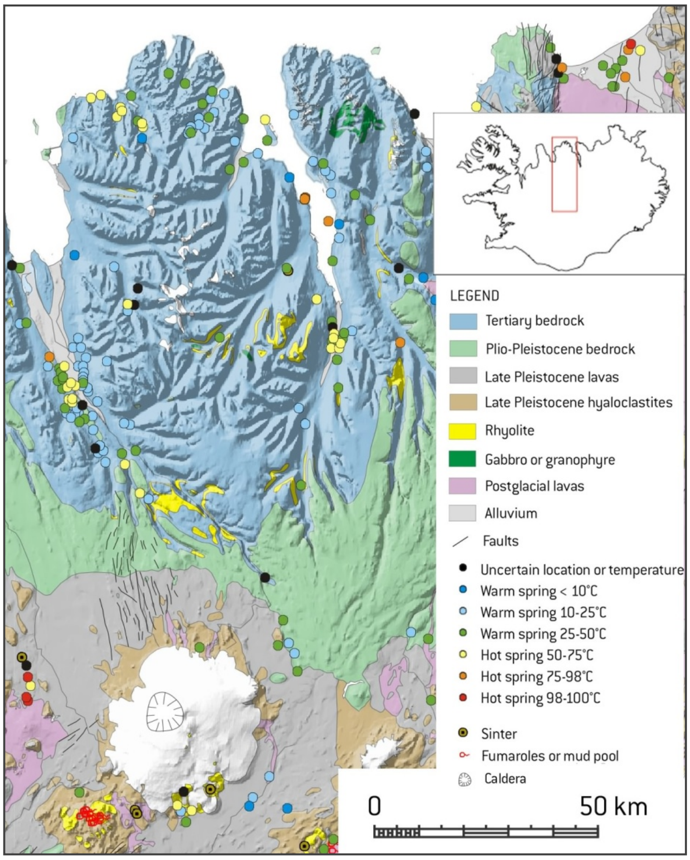

FIGURE 4: Hofsjökull volcano in central Iceland. A fissure swarm extends about 90 km to the NNW from it. Fissure eruptions occur along the first 30 km (proximal part). Faults and fissures extend another 60 km beyond with numerous hot springs in valleys eroded into 7-8Ma basalts (distal part)

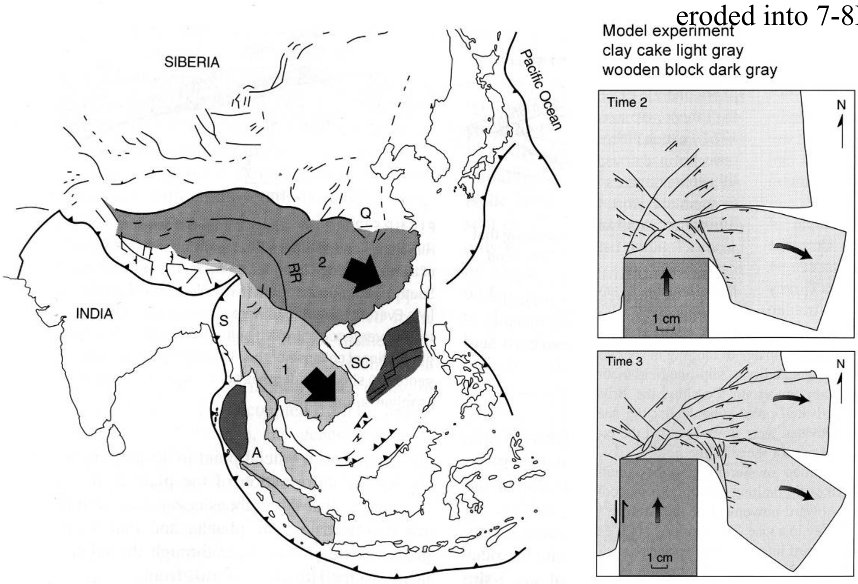

FIGURE 5: Tectonics of SE-Asia showing eastward escape of large crustal blocks along major strike-slip faults as suggested by Tapponier et al. (1982). Model for comparison (from Pluijm and Marshak 2004)

2.6 Active fracture zones on land

Active fracture zones on land host some of the richest low-temperature geothermal resources (China, South Iceland). In China enormous deformation zones have developed due to collision of India with Asia. The collision gives rise to lateral escape of China to the east along left lateral transcurrent fault systems (Figure 5). In Iceland the South Iceland Seismic Zone (left lateral) connects between offset spreading centres. It hosts about 30% of Iceland´s low-temperature geothermal resources.

3. HIGH-TEMPERATURE GEOTHERMAL SYSTEMS

These are volcanic/intrusive in origin as regards occurrence and heat source. Most magma does not reach the surface but heats large regions of underground rock. Most active fields are of Pliocene to Recent age. Young batholiths at relatively shallow depth may still be hot. Rapid removal of uppermost overburden helps to get near to them. Aquifers are strata-bound and or fracture controlled. The high-temperature geothermal fields occur in different types of geological settings, most of them at plate boundaries, but also in continental rifts and in hot spot environments.

High temperature geothermal systems are water dominated, but often vapour dominated to a varying depth if the reservoir is boiling. Induced steam zone may develop as production proceeds. This is a corollary of drawdown in a boiling reservoir as characterize most of the high-temperature geothermal fields. A shallow steam zone may thus thicken by hundreds of metres if recharge is limited. The volume increase from water to steam under conditions such as prevail at shallow depth may be on the order of 50 fold with a corresponding pressure increase. This is manifested by increased steam flow from hot ground and fumaroles and locally also by new steam emanations from fissures.

3.1 Rift zone regimes

3.1.1 Mid ocean ridges

The mid oceanic ridges comprise over 50,000 km long continuous volcanic zone on the ocean floor. Hot springs at great depths on the mid-oceanic ridges are known as "black smokers" (Figure 6). They are the surface activity on the ocean bottom of geothermal systems under the ocean floor. The knowledge on these systems is limited but the Asal system in Djibouti may be the closest supramarine analogue. At slow spreading ridges as in Djibouti, high viscosity asthenosphere causes rift valley to form with uplifted, outwardly dipping flanks. Salton Sea California is also on a ridge crest, which is all buried in sediment except latest Pleistocene volcanics (Salton Buttes).

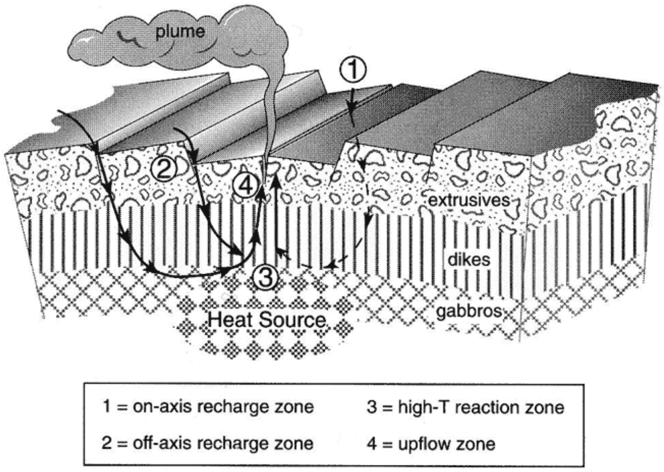

FIGURE 6: Schematic illustration of a black smoker geothermal system. Depth of circulation is about 3-4 km (Encyclopedia of Volcanoes, 2000)

3.1.2 Supramarine oceanic rifts: Iceland

Geothermal systems develop at high volcanic foci of elongated volcanic systems (Figure 7). In Iceland the flanks of the rift dip inwardly, i.e. towards the rift zone, as at fast spreading oceanic ridges (such as the East Pacific Rise). This is because the asthenosphere is hot and of lower viscosity due to an exceptionally powerful mantle plume. The reservoir fluid is of meteoric or seawater origin depending on the relative distance to the ocean shores and the heat source is magmatic intrusions at depth and sometimes a magma chamber exists in the roots of the volcanic system (Figure 8).

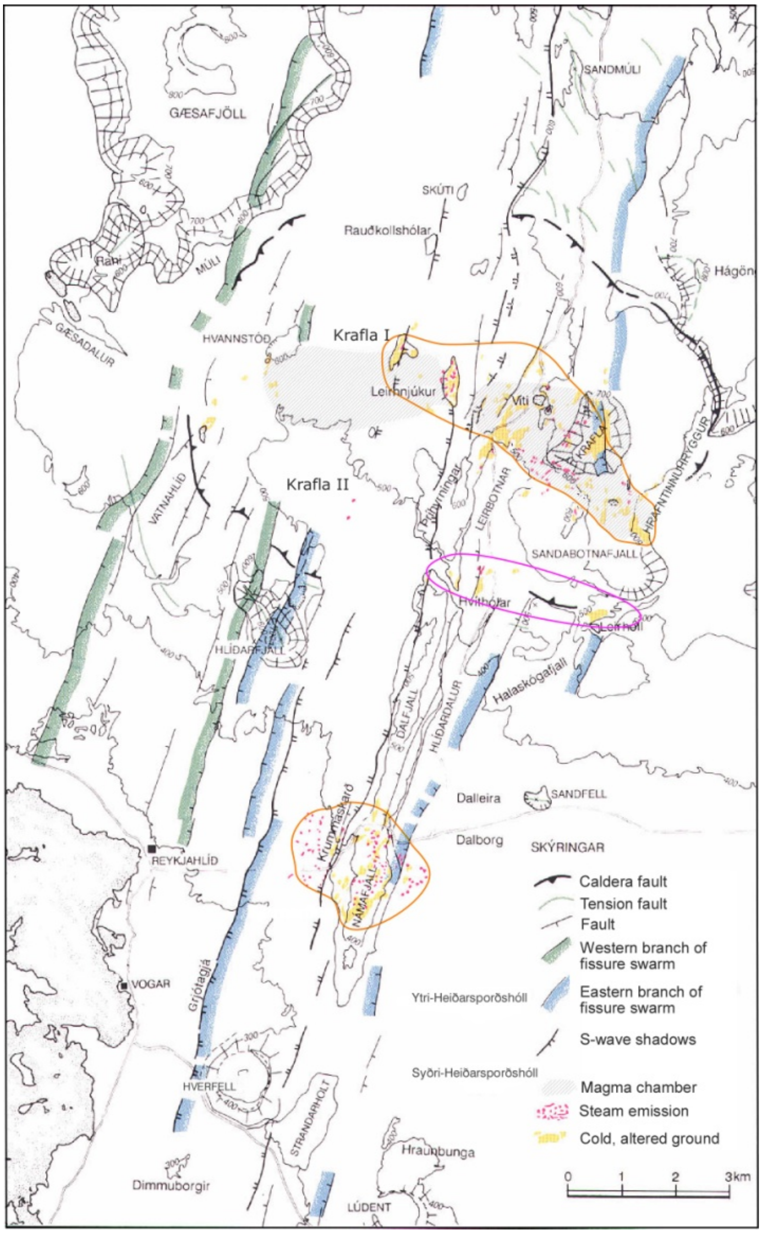

FIGURE 7: Central part of Krafla volcanic system showing caldera and fissure swarms which transect it. The Krafla caldera hosts a geothermal system. It has a magma chamber (S-wave shadow) at 3-7 km depth. A second geothermal area at Námafjall on the fissure swarm 7 km south of Krafla is located where basaltic fissure eruptions concentrate

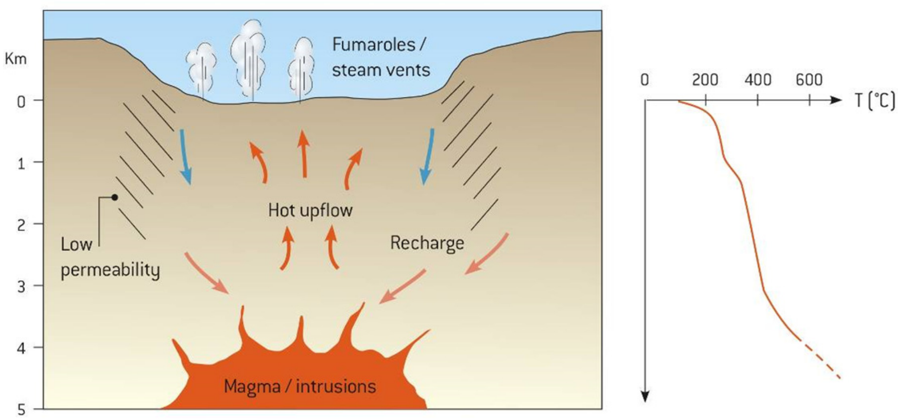

FIGURE 8: Conceptual model of a high temperature field within a rifting volcanic system. The temperature profile to the right represents the central part of the model

3.1.3 Continental rifts: East Africa

The East African rift valleys, exclusive of the Western Rift, are at the apex of two domal uplifts. They developed from stray stratovolcanoes (Mt Elgon, Mt. Kenya, both at the southern dome) to a later stage rift valley with elongated volcanic systems on their floor. Again the geothermal systems formed in areas of high volcanic production, i.e. in the core areas of the volcanoes (Figure 9).

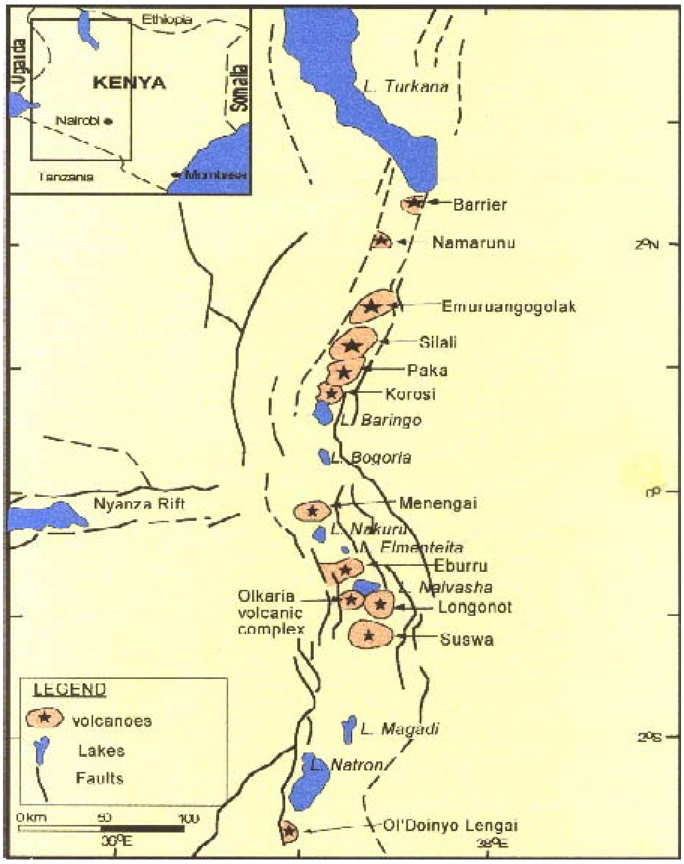

FIGURE 9: Apex of Kenya Rift domal uplift with two volcanically active rift branches and a third E-W branch dying. Stratovolcanoes are shown. Fissure swarms have not been identified as integral parts of volcanic systems (Mwawongo 2004)

3.2 Hotspot volcanism

Hotspot volcanism is off, sometimes far off, from spreading centres. Two examples will be mentioned one located on oceanic crust the other on continental crust. Both have a hot spot track associated with them.

3.2.1 Hawaii and Yellowstone

At Hawaii basaltic shield volcanoes begin on top of a mantel plume, and are carried off from plume centre as the plate passes over it. Geothermal systems may develop at apex of the volcanoes and also on their associated fissure swarms in areas of local concentrations of dykes.

Yellowstone is the world's largest rhyolite volcano. A huge, composite caldera has formed in it following major ignimbrite eruptions. Rhyolite volcanoes generally contain little other than rhyolite the low density rock type possibly forming a volcanic shadow zone, impenetrable for heavier less silicic melts. Near-surface intrusions (magma chambers) of rhyolite magma at depth below these long-lived centres promote very active geothermal systems.

3.2.2 Flank zone volcanism

Flank zone volcanism occurs far off from oceanic ridge crests. It is characterized by alkalic rocks of deeper mantle origin than tholeiites. The Azores are an example of this (Figure 10). There the flank zone volcanism occurs where fracture zones intersect hot spots. In Iceland the Snæfellsnes Peninsula is an example. Shear stresses prevail in these regions.

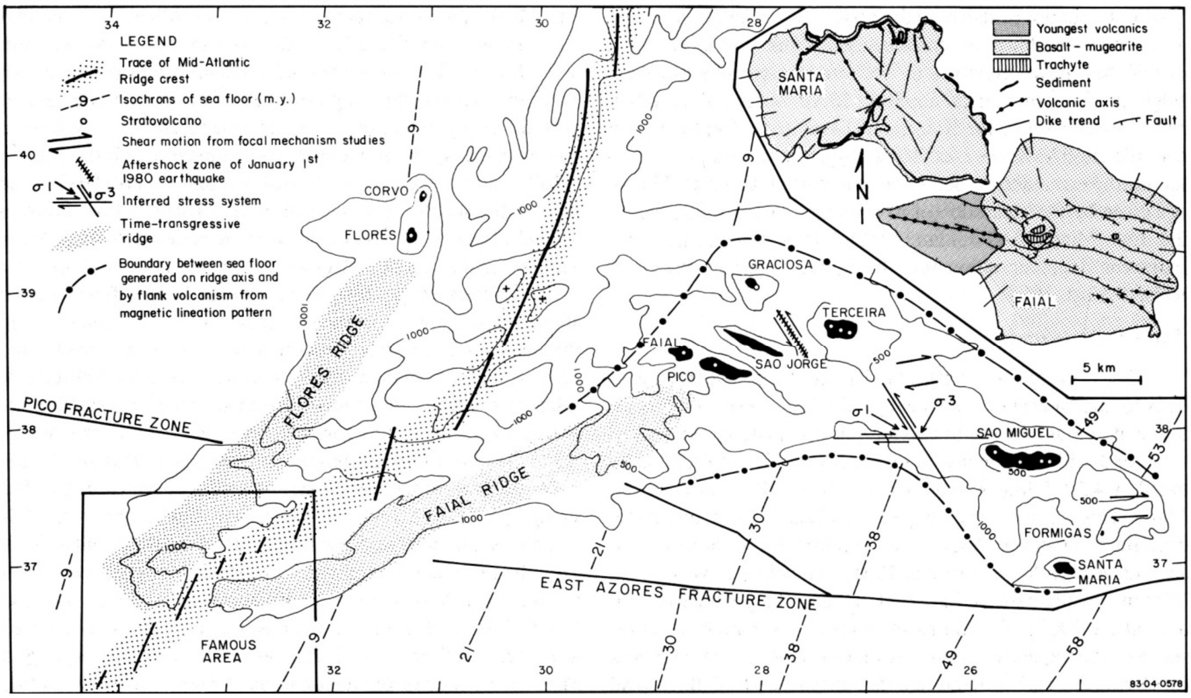

FIGURE 10: High-temperature geothermal fields on the Azores Islands are related to flank zone volcanism north of the Azores Fracture Zones. They developed in caldera regions of stratovolcanoes. Prominent fissure swarms formed in the direction of maximum stress

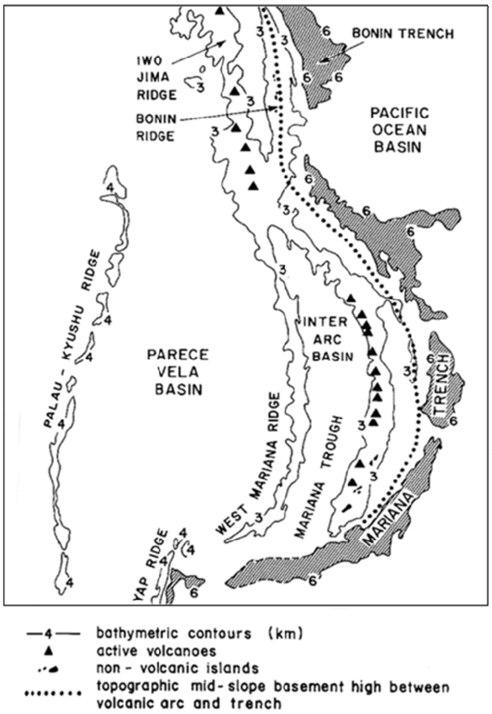

FIGURE 11: Example of a young island arc with inter arc basin and remnant arc. Evolved arcs develop from repeated splitting, crustal thickening and re-melting. At the same time the volcanic products evolve from basaltic to acid (Cas and Wright 1995)

3.3 Compressional regimes

Compressional regimes are the most common type of high temperature geothermal fields, globally. The tectonic environment is, however, variable (Circum Pacific Ring of Fire) (paragraphs 3.3.1-3.3.3; are from Cas and Wright (1995).

3.3.1 Young island arc volcanoes and inter arc basins

Young island arc volcanoes and inter arc basins are such as occur in the Marianas, Tonga-Kermadec, the Philippines, the West Indies (Figure 11). Successive splitting and ocean-ward migration of the frontal half of the arc block creates new inter-arc basins. Rock types mainly comprise basalt and basaltic andesite (island arc tholeiite).

3.3.2 Micro-continental arc volcanoes

Micro-continental arc-volcanoes are found in Japan, in New Zealand and in Indonesia. Arc-block is wider and is thicker than in young island arcs. Magmatic products are much more silicic. Calc-alkaline rocks are prominent. Taupo Volcanic Zone in New Zealand has erupted mainly rhyolite during the last 1 m. y. There are 15 harnessable geothermal fields with reservoir temperatures >220°C. Average size is 12 km², at 15 km intervals. The entire volcanic field is comparable in size to Yellowstone also as regards geothermal output. To maintain it the corresponding magma "intrusion" rates are 1.9 m^3/s (Yellowstone) and 1.7 m^3/s (Taupo) (Taupo and Yellowstone comparison from Wilson et al. 1984).

3.3.3 Continental margin arc volcanism

Continental margin arc volcanism, such as in the Andes and the Cascades. Magmatism takes place upon a wholly sialic, continental type crust, up to 60 km thick. The proportion of silicic volcanics is high, including huge ignimbrites (Ilopango, El Salvador: 40 km^3 erupted in 260 A.D.) and contemporaneous granitoids (batholiths).

3.3.4 Batholith driven geothermal systems

Batholith (pluton) driven geothermal systems, such as in Larderello in Italy and Geysers in California, are both vapour dominated. The geothermal resource is primarily found in the enveloping sedimentary strata.

4. HOT DRY ROCK OR ENHANCHED GEOTHERMAL RESOURCES

Hot dry rock (HDR) or enhanced (engineered) geothermal systems (EGS) consist of volumes of rock that have been heated to useful temperatures or abnormally high heat flow, but have low permeability or are virtually impermeable. They may be regarded as a downward extension of the batholith driven systems, the thermal resource being the cooling pluton itself. Permeability of the rock is very low but fracture permeability is induced by injecting cold water under high pressure into the hot part of it. Natural fractures and fissures are supposed to widen and new flow paths be created. Shortcuts tend to occur between injection and production boreholes. The heat source is vast and several experiments have been conducted in a number of locations to use hydro-fracturing to create or enhance permeability and hence create what we could call an artificial geothermal reservoir. Such systems will mostly be used through production/reinjections doubles. The best known of these experiments are the Fenton Hill project in the Jemez Mountains, New Mexico and the Soultz project in the Rhine graben near the border of France to Germany. These projects demonstrated that it is possible to create such artificial reservoirs. In the Fenton Hill project a small geothermal power unit was actually operated on steam from the reservoir for a short period of time in the 1970ties and in Soultz, a 1.9 MW ORC power plant has been in operation since June, 2008. The production cost of energy HDR/EGS systems are, however, still much higher than electricity from conventional geothermal resources but there are hopes that the production cost can be lowered and ambitious EGS projects are now underway in Australia.

5. SUMMARY AND DISCUSSION

In this paper we have discussed various types of geothermal systems. True to the Icelandic traditions we have focused the discussion on the two categories that we divide our geothermal systems into, i.e. *low temperature fields*, where temperature at 1 km depth is below 150°C and *high temperature fields*, where the reservoir temperature at 2 km exceeds 200°C. Very few Icelandic geothermal fields have reservoir temperatures in the obvious temperature gap in this definition but those few are sometimes called medium temperature fields. Each of these two types can be divided into several subgroups based on the regional geological setting of the geothermal field.

The sub classification used in this paper is to divide the low temperature system into:

A. *Shallow resources* refer to the normal heat flux through near surface formations and the thermal energy stored in the rocks and warm groundwater systems near the surface of the Earth's crust.

B. *Sedimentary low temperature systems* are found in many of the major sedimentary basins of the world.
C. *Geo-pressured systems* are also sedimentary systems but are often categorized as a special class due to their similarities to geo-pressured oil and gas reservoirs where fluid caught in stratigraphic traps may have pressures close to lithostatic values.
D. In *convective low temperature systems* the heat source is the hot crust at depth in tectonically active areas, with above average heat-flow. Here the geothermal water has circulated to considerable depth (> 1 km), through mostly vertical fractures, to mine the heat from the rocks.

The high temperature fields are without exception found in the volcanically active areas of the Earth. They are therefore also categorized as: *Volcanic geothermal systems,* and the sub classification applied here is to look at the tectonics and volcanism in the regions of the geothermal activity. These are:

E. *Rift zone regime geothermal systems* are located in volcanic systems on the mid ocean ridges, on the supra-marine rifts or in continental rifts, most on plate boundaries where the tectonic plates are moving apart. The geothermal systems are in one way or another associated with the volcanic activity. The host rock is usually igneous and the permeability fracture dominated.
F. *Hotspot volcanism* is accompanied by geothermal activity and the heat source is magmatic intrusions, derived from the mantel plume underneath.
G. *Compression regions,* where oceanic plates collide with continental plates forming subduction zones. The collision creates various volcanic arcs on the continental side; narrow islands arcs; micro-continental arcs and continental margin arcs.

The low temperature activity is spread over most of the Earth. The exploitation has, however, been mostly in areas of normal to abnormally high geothermal gradient areas where geothermal systems of category (B) and (D) are found. Sedimentary systems (B) are for example found in France, Eastern Europe and throughout China. Low temperature systems of the convection type (B) are found in Iceland, USA and in China. Improved ground source heat pump technology has increased drastically the exploitation of shallow resources (A). Typical examples of geo-pressured systems (C) are found in the Northern Gulf of Mexico Basin in the U.S.A., both offshore and onshore. Their exploitation is, however, very limited.

Numerous volcanic geothermal systems are found in the rift zones (E) and the compressive regions (C) of the world, for example in The Pacific Ring of Fire, in countries like New Zealand, The Philippines, Indonesia, Japan, USA and Central and South America and in East Africa, Iceland and Italy. Geothermal systems related to hot spot volcanism (F) are found on Hawaii and the Azores and in Yellowstone and in Iceland.

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