



GEOTHERMAL SYSTEMS IN GLOBAL PERSPECTIVE

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ABSTRACT

Geothermal systems are classified in three main categories: (a) volcanic geothermal 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 preferably of high geothermal gradient, (c) sedimentary systems with permeable layers at great depth (2-5 km), including geo-pressured systems often found in conjunction with oil resources.

Some 50 years ago geothermal fields were divided into high- and low- temperature fields or areas. This division was based on (arbitrarily) inferred temperature at 1 km depth. It was soon realized that most of the former are related to volcanism (>160 - >300 °C) (category a) and that the latter draw heat from the general heat flow of the crust (just above ambient to >160°C) (categories b and c). The temperature range given here is based on values measured in boreholes in Iceland or silica and gas geothermometry. Other subdivisions have been proposed by adding an intermediate group between the two main ones. There are several types in each of the two main groups. They are described below, emphasizing the geological control.

A fourth category constitutes the so called hot dry rock. The thermal resource there is abnormally hot, usually intrusive rock of very low permeability and not harnessable so far.

1. INTRODUCTION

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 or enthalpy, physical state, 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 (Bödvarsson, 1964; Axelsson and Gunnlaugsson, 2000)

| | | |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Low-temperature (LT) systems with reservoir temperature at 1 km depth below 150°C. Often characterized by hot or boiling springs. | Low-enthalpy geothermal systems with reservoir fluid enthalpies less than 800 kJ/kg, corresponding to temperatures less than about 190°C. | 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. |
| Medium-temperature (MT) systems with reservoir temperature at 1 km depth between 150- 200°C. | | Two-phase geothermal reservoirs where steam and water co-exist and the temperature and pressure follow the boiling point curve. |
| 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. | High-enthalpy geothermal systems with reservoir fluid enthalpies greater than 800 kJ/kg. | Vapour-dominated geothermal systems where temperature is at, or above, the boiling point at the prevailing pressure and the steam phase controls the pressure in the reservoir. Some liquid water may be present. |

The three main types of geothermal systems which concern us here, based on their nature and geological settings are:

- 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 (Figure 1). They are most often situated inside, or close to, volcanic complexes at or near plate boundaries or hot spots. Permeable fractures and fault zones but also permeable strata such as sediments, ignimbrites or lavas control the flow of water in volcanic geothermal systems.

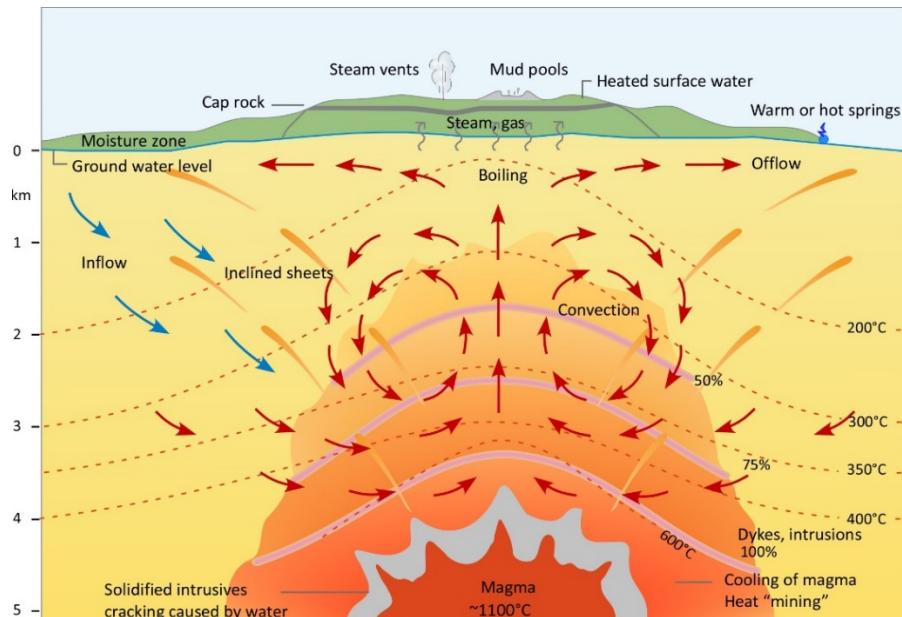


FIGURE 1: Simplified model of a high-temperature geothermal system

- B. In *convective systems* the heat source is the hot crust at depth in tectonically active areas, preferably with above average heat-flow (Figure 2). Here the geothermal water has circulated to considerable depth ($> 1 \text{ km}$), through mostly vertical fractures, to extract the heat from the rocks.

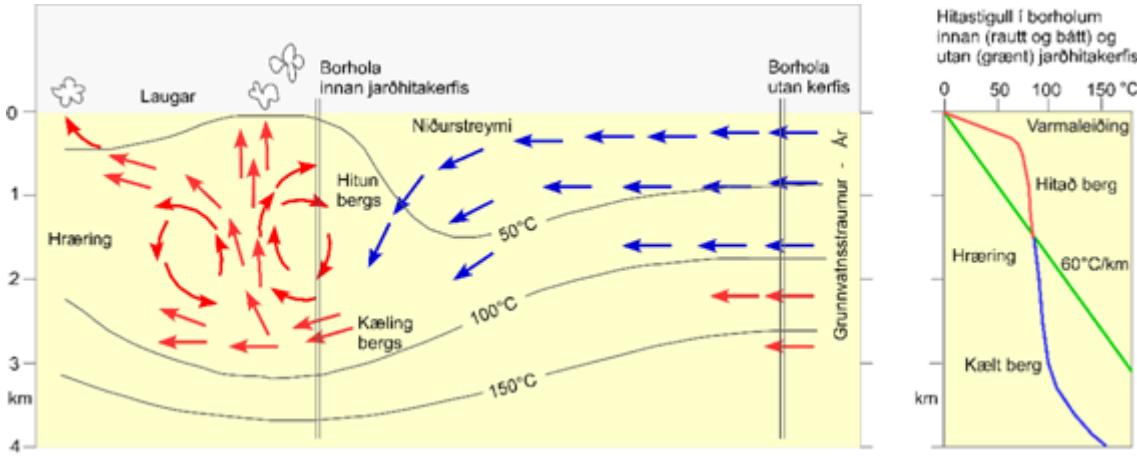


FIGURE 2: Main features of a low temperature fracture controlled geothermal system.
Note bulging down of isotherms at depth. The section is drawn along a leaky fissure.

- C. Sedimentary geothermal systems are probably the most common type worldwide. We are concerned here with such that occur in the sediment filled parts of the East African Rift. They occur mainly in the Western Rift, but locally also in the Eastern Rift where volcanism was sparse.

2. LOW-TEMPERATURE GEOTHERMAL FIELDS

They depend on the regional geothermal gradient, permeability (primary or secondary) of the rock and depth of circulation if such exists.

2.1 Sedimentary basins

Sedimentary basins are layered sequences of permeable (limestone, sandstone) and impermeable strata (shale or mudstone) which alternate. Water is interstitial water, commonly a brine, formerly thought to be of connate origin. Temperature is variable, depending on depth of permeable rocks in basin. Examples are the Molasse basin north of the Alps, the Paris basin, the Hungarian basin and the sediment filled Rhine graben. Those are of different origin and the heat flow differs widely. Natural circulation of the geothermal fluid is minimal. Reinjection is needed to dispose of water after passing through heat exchangers. Doublette boreholes are needed.

2.2 Fracture or fault controlled convection systems

In fracture or fault controlled convection systems circulation may be deep or shallow. Heat is transported by water from base area of system to its upper zone (Figure 3). Recharge comes from precipitation. Water is generally low in TDS but may be high in sediment filled rift zones. 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.

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 contributes to an effective fracture volume. Release joints and tension fractures have a relatively high effective fracture volume contrary to compression fractures. Water contained in matrix pores and microfractures is inaccessible in case of low-temperature geothermal exploitation. Pressure decrease due to drawdown in high-temperature reservoirs may cause pore and microfracture water to boil and hence contribute to the available part of the resource.

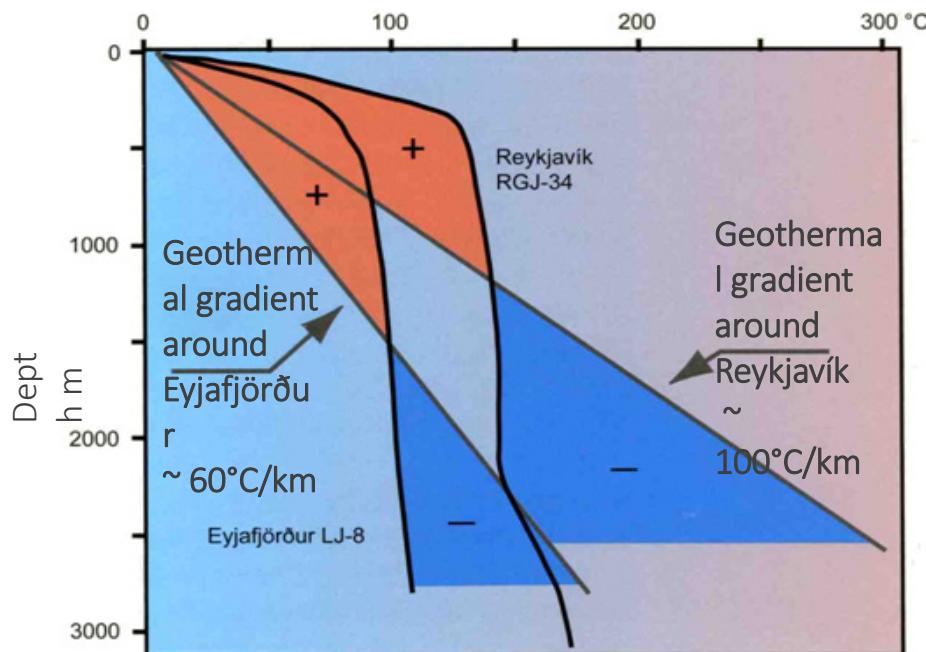


FIGURE 3: Reykjavík and Akureyri, Iceland. Bold lines show actual reservoir temperature, 130-140°C for Reykjavík, 90-95°C for Akureyri. Water transports heat from deep levels, thus cooling the rock (heat mining). Shallower levels consequently are heated up.

2.3 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.

2.4 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.

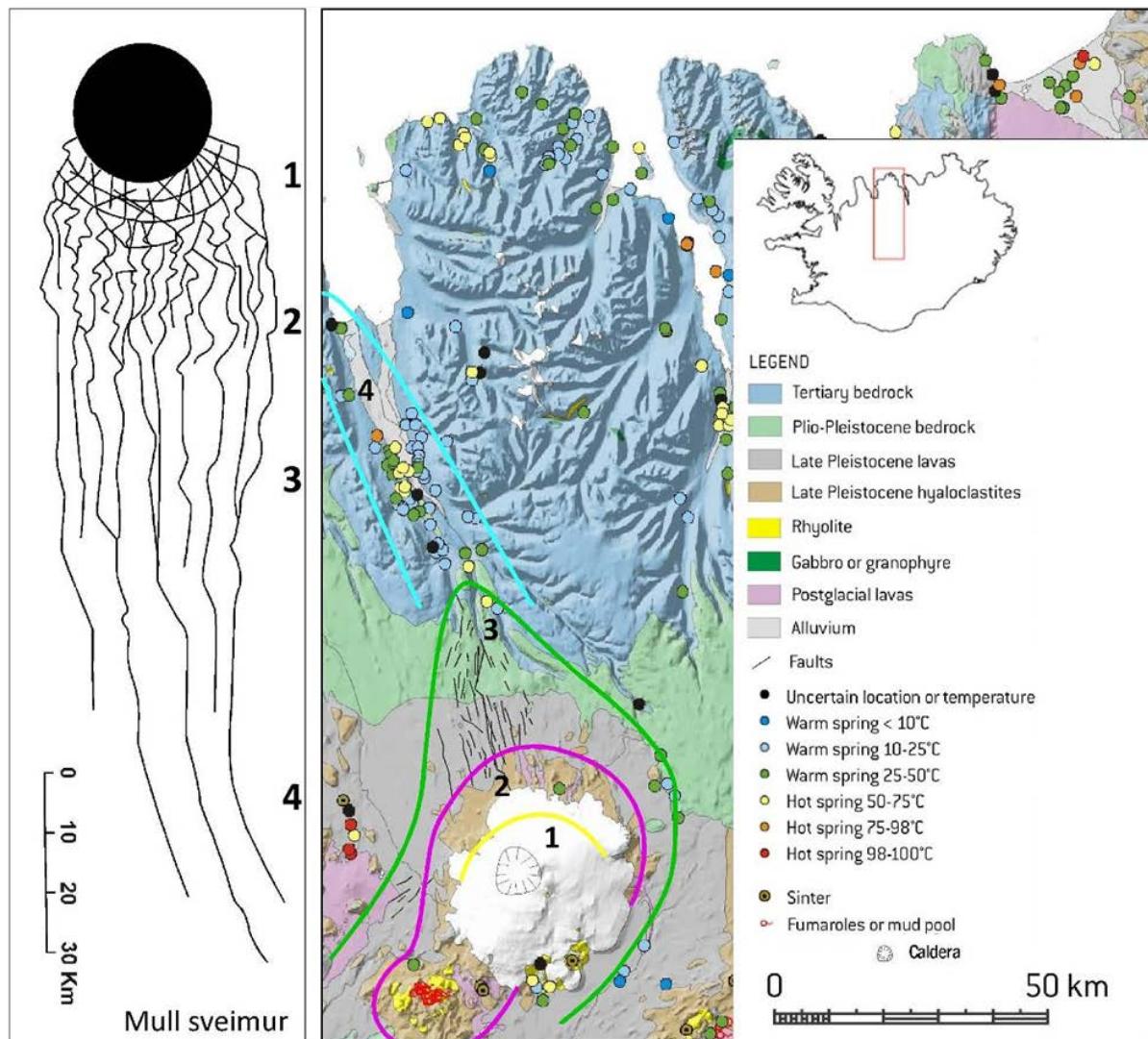


FIGURE 4: Hofsjökull volcanic system in central Iceland. A fissure system extends about 100 km to the NNW from the central volcano covered by glacier (area 1). Densely spaced fissure eruptions occur along the next 20 km (area 2), followed by faults, fissures and stray fissure eruptions for another 30 km (area 3). The distal part of the system (area 4) has narrow, cm-scale fissures, clearly visible in the south of the area, but only occasionally further away. Linearly arranged hot springs indicate fissure control. It is thought that dykes expelled from a magmatic source under Hofsjökull underlie the whole system, becoming deeper with distance and branching towards its end. These would cause fracturing and create permeability in an otherwise rather impermeable rock sequence, made of 7-8 Ma basalts.

2.5 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.

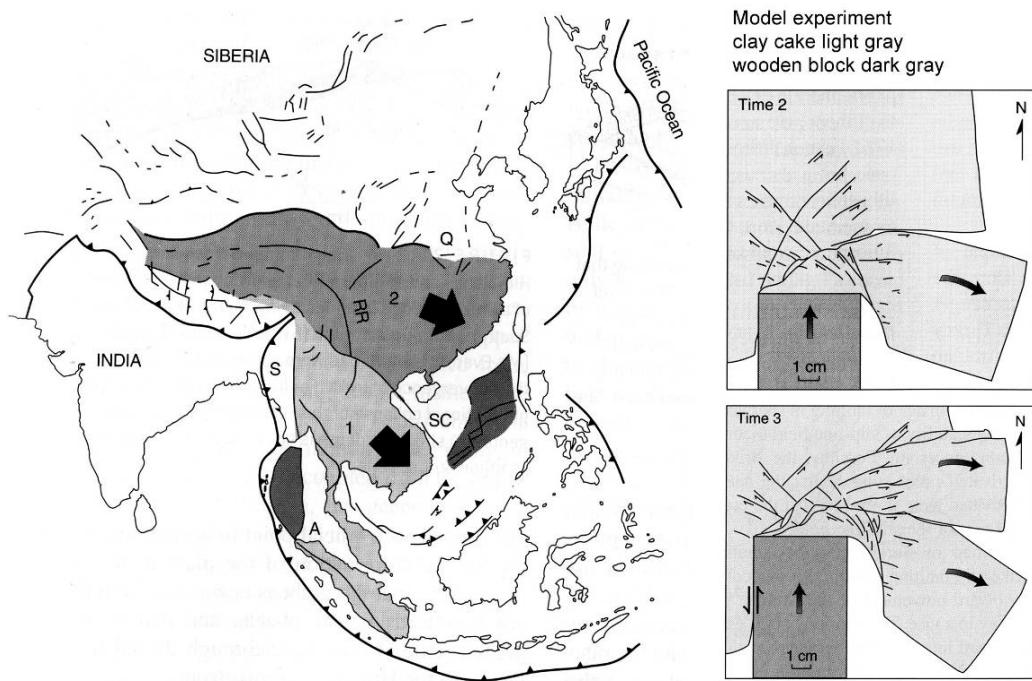


FIGURE 5: Tectonics of SE-Asia showing eastward escape of large crustal blocks along major strike-slip faults as suggested by Tapponier et al. (1982). Model for comparison (from Pluim and Marshak 2004).

3. HIGH-TEMPERATURE GEOTHERMAL FIELDS

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 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 stratabound 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 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 manifest by increased steam flow from hot ground and fumaroles and locally also by new steam emanations from fissures.

3.1 Rift zone regime

3.1.1 Mid ocean ridges

Mid ocean ridges (black smokers) (Figure 6). 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. It is all buried in sediment except latest Pleistocene volcanics (Salton Buttes).

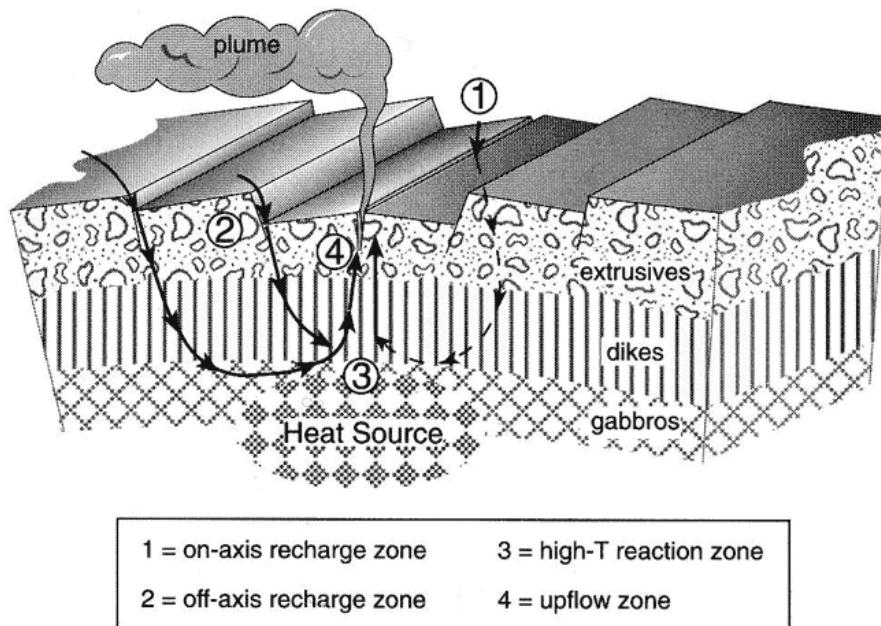


FIGURE 6: Schematic illustration of a black smoker geothermal system.
Depth of circulation is about 3-4 km (Sigurdsson et al., 1999).

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 low viscosity due to an exceptionally powerful mantle plume.

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 8).

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 the 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.

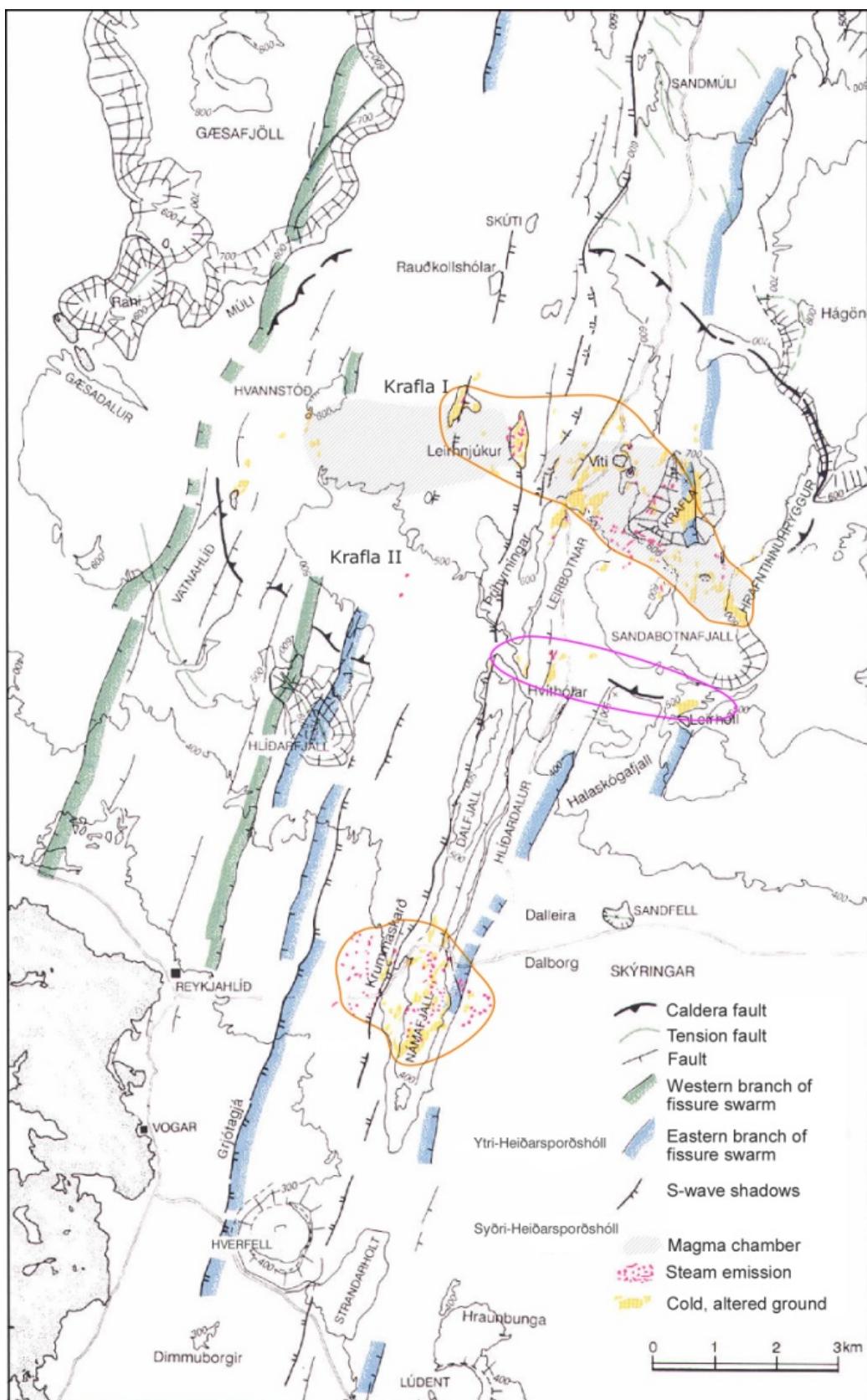


FIGURE 7: Central part of Krafla volcanic system showing caldera and fissure swarms which transect it. The Krafla caldera hosts a geothermal system. It has a magma chamber (S-wave shadow) at 3-7 km depth. A second geothermal area at Námafjall on the fissure swarm 7 km south of Krafla is located where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

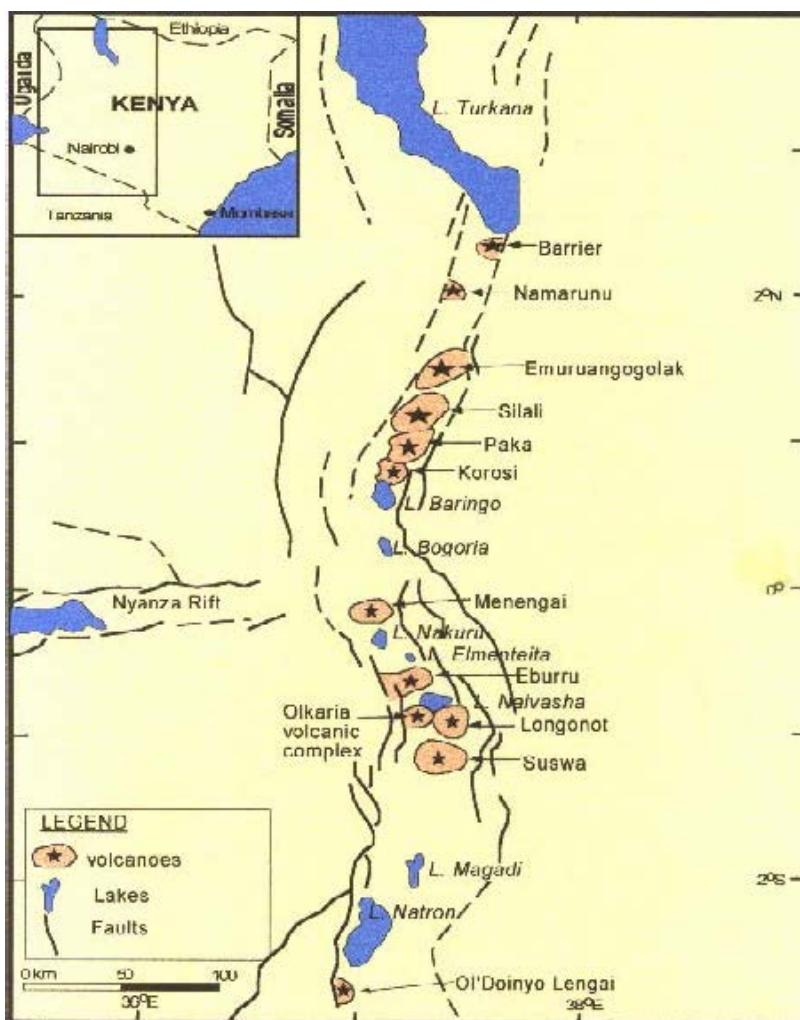


FIGURE 8: Apex of Kenya Rift domal uplift with two volcanically active rift branches and a third E-W branch dying. Stratovolcanoes are shown. Fissure swarms have partly been identified as integral parts of volcanic systems (Mwawongo, 2004).

3.2.2 Flank zone volcanism

Flank zone volcanism (Iceland, Azores) (Figure 9) is characterized by alkalic rocks of deeper mantle origin than tholeiites. Both in Iceland and the Azores they occur where fracture zones intersect hot spots. Shear stresses prevail.

3.3 Compressional regime

Compressional regimes are the most common type of high temperature geothermal fields, globally. The tectonic environment is variable (Circum Pacific Belt) (paragraphs 3.3.1-3.3.3 are from Cas and Wright (1995). The main types are mentioned below.

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 10). 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).

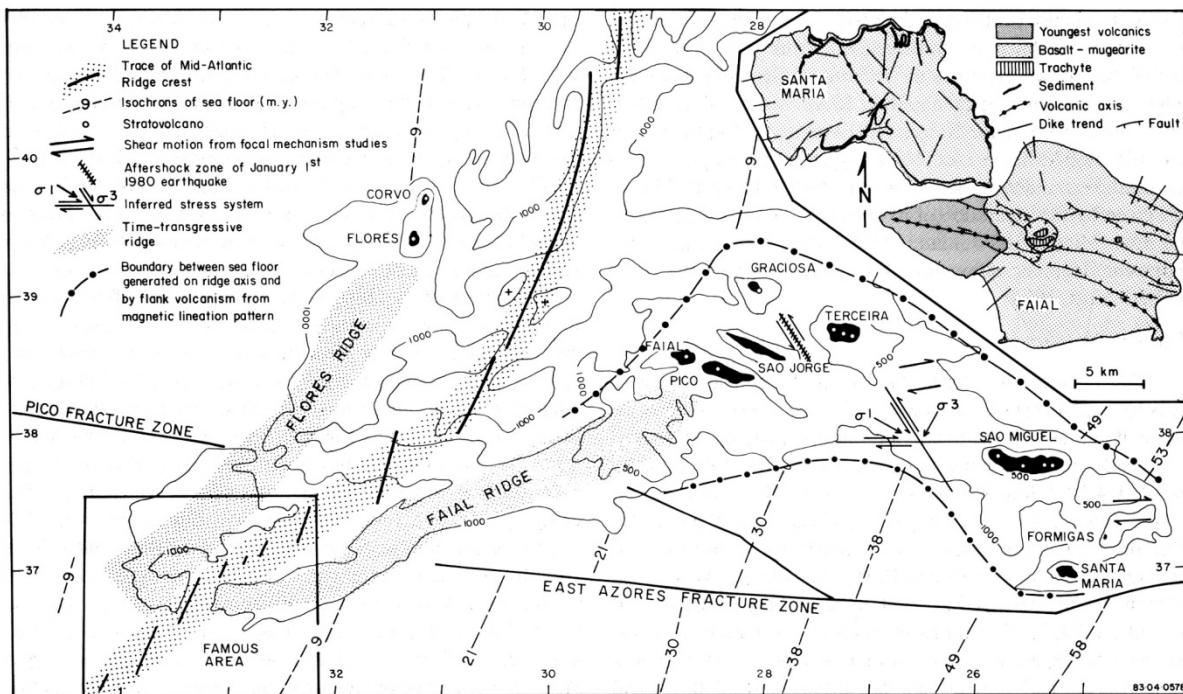


FIGURE 9: High-temperature geothermal fields on the Azores Islands are related to flank zone volcanism north of the Azores Fracture Zones. They developed in caldera regions of stratovolcanoes. Prominent fissure swarms formed in the direction of max. stress.

3.3.2 Micro-continental arc volcanoes

Micro-continental arc volcanoes, such as in Japan, New Zealand and 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 $>220^{\circ}\text{C}$. Average size is 12 km^2 , at 15 km intervals. The entire volcanic field is comparable in size to Yellowstone also as regards geothermal output. 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 GEOTHERMAL RESOURCE

This 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 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, but so far of limited use. Ambitious hot dry rock projects are still under way.

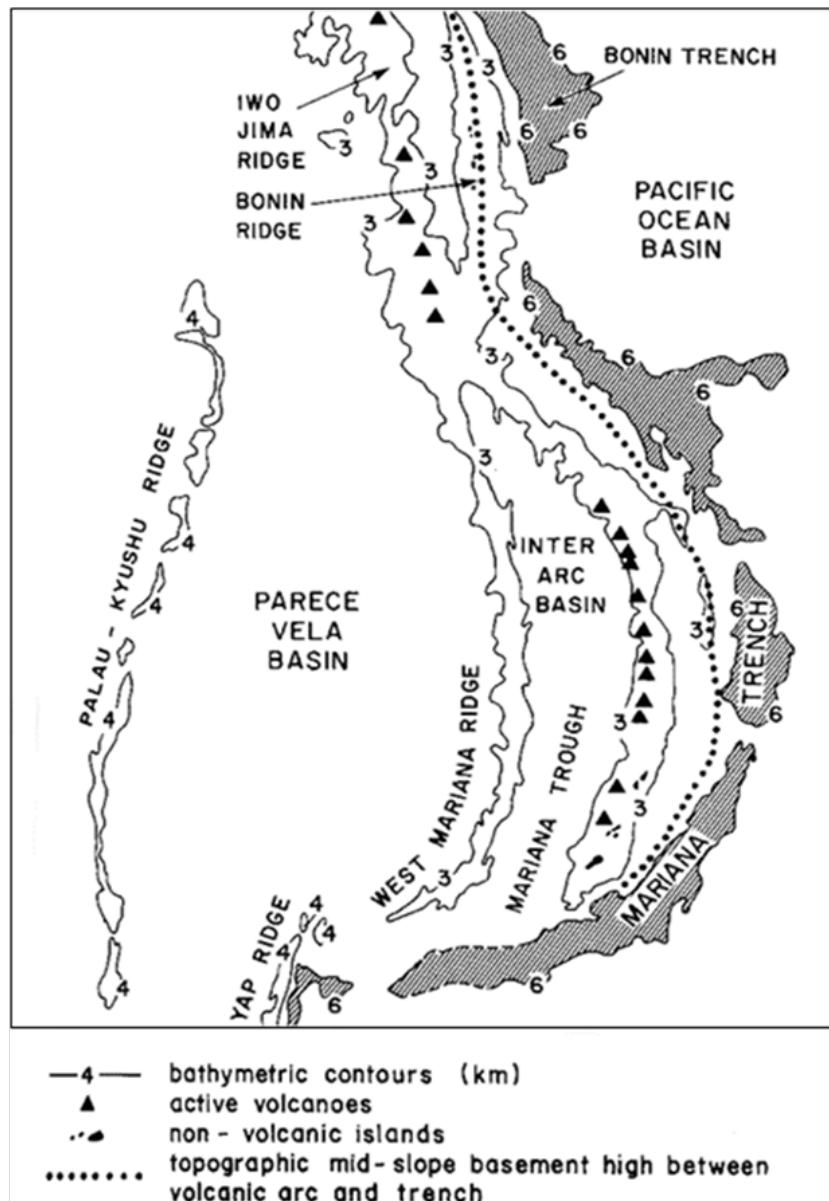


FIGURE 10: Example of a young island arc with inter arc basin and remnant arc. Evolved arcs develop from repeated splitting, crustal thickening and remelting. At the same time the volcanic products evolve from basaltic to acid (Cas and Wright, 1995).

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