



UNITED NATIONS  
UNIVERSITY

GEOTHERMAL TRAINING PROGRAMME



**KenGen**

Kenya Electricity Generating Co., Ltd.

## GEOTHERMAL SYSTEMS IN GLOBAL PERSPECTIVE

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### ABSTRACT

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. Most of the former are related to volcanism (>160 - >300 °C). The latter draw heat from the general heat flow of the crust (just above ambient to >160°C). The temperature range is based on measured values in Iceland. Other subdivisions have been proposed by adding intermediate systems between the two main categories. There are several types in each of the two main groups.

A third category constitutes the so called hot dry rock. The thermal resource there is abnormally hot, usually intrusive rock of very low permeability.

### 1. 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.

#### 1.1 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.

#### 1.2 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 1). Recharge 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 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 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.

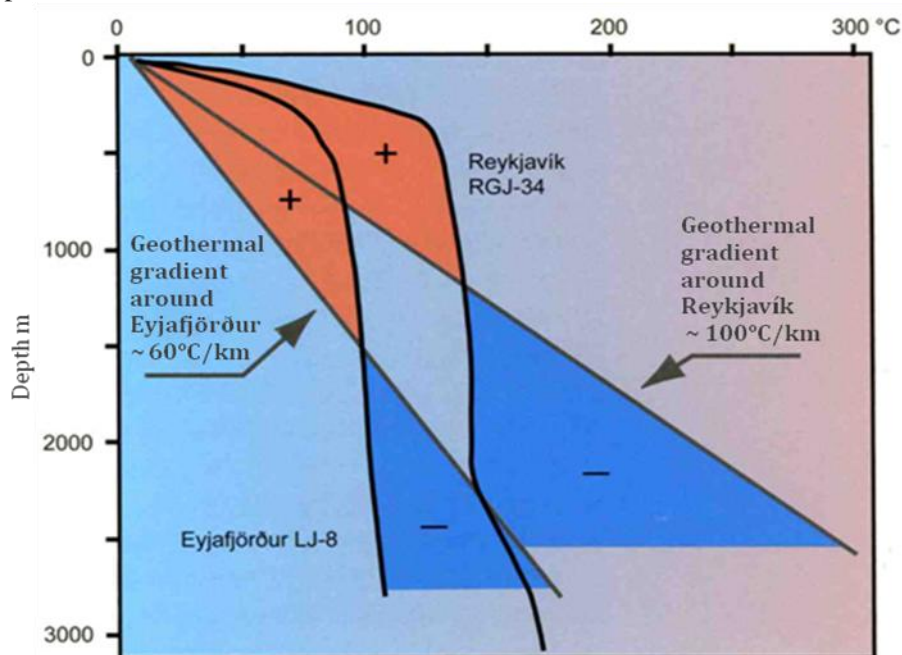


FIGURE 1: Reykjavík and Akureyri, Iceland. Bold lines show actual reservoir temperature, 130-140°C for Reykjavík, 90-95°C for Akureyri. Water transports heat from deep levels, thus cooling the rock (heat mining). Shallower levels consequently are heated up

### 1.3 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.

### 1.4 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 2). 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.

### 1.5 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 faults systems (Figure 3). 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.

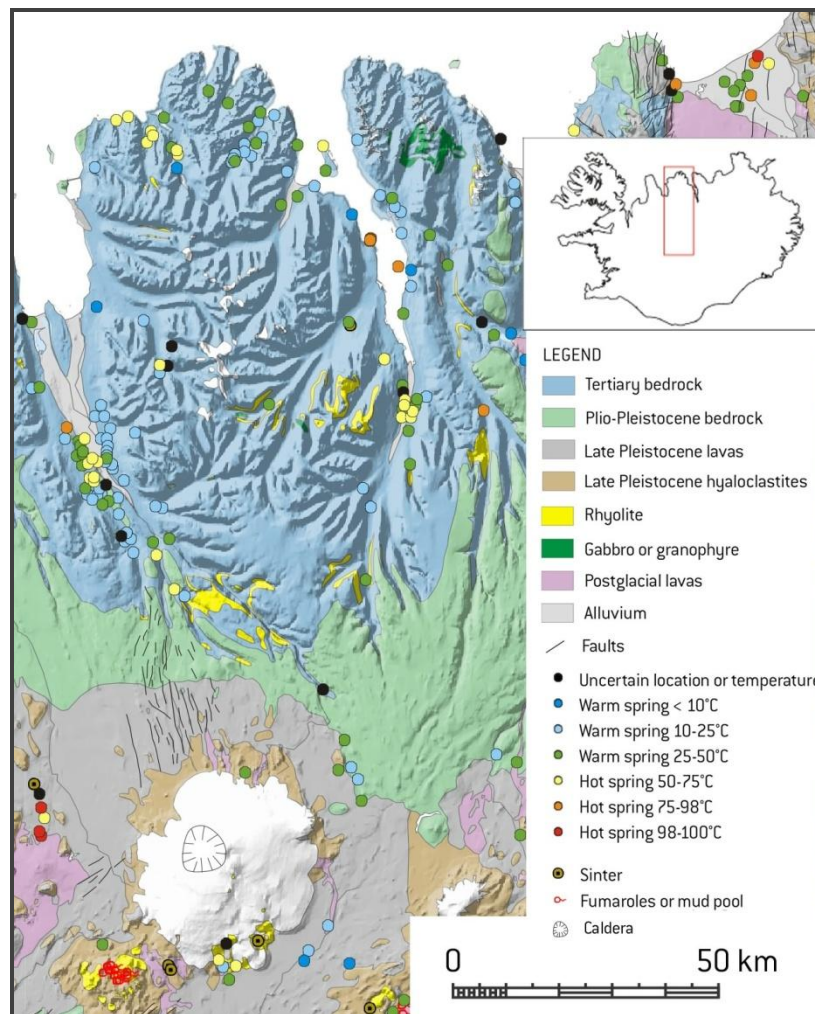


FIGURE 2: Hofsjökull volcano in central Iceland. A fissure swarm extends about 90 km to the NNW from it. Fissure eruptions occur along the first 30 km (proximal part). Faults and fissures extend another 60 km beyond with numerous hot springs in valleys eroded into 7-8Ma basalts (distal part)

## 2. 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.

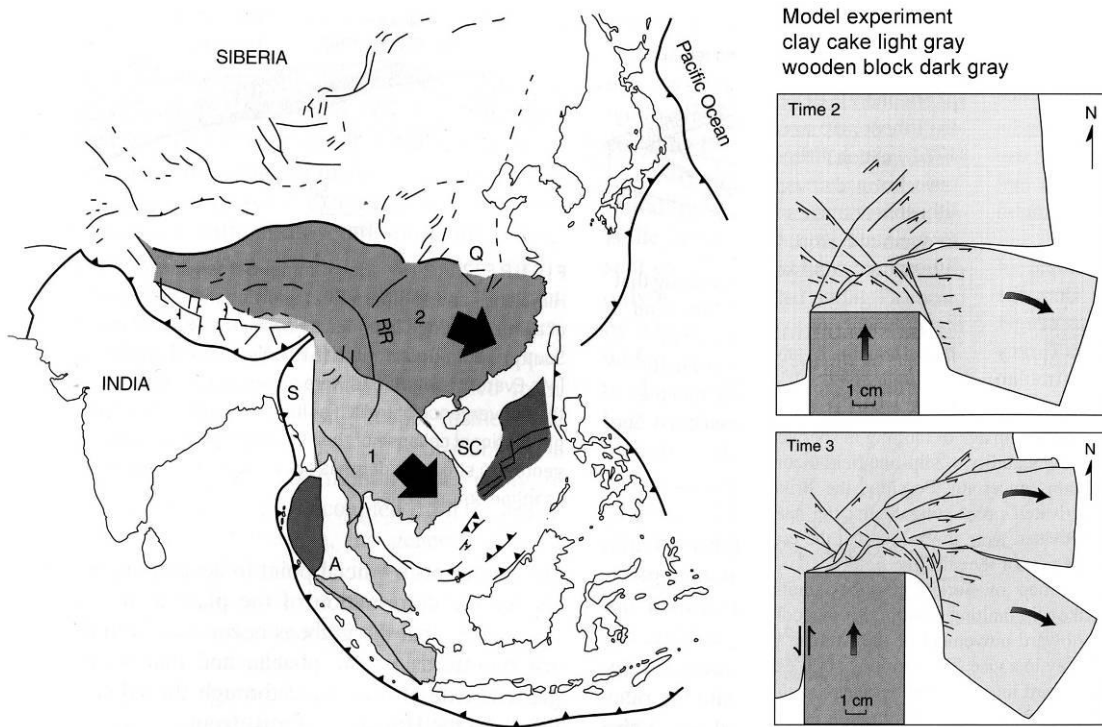


FIGURE 3: Tectonics of SE-Asia showing eastward escape of large crustal blocks along major strike-skip faults as suggested by Tapponier et al. (1982). Model for comparison (from Pluijm and Marshak 2004)

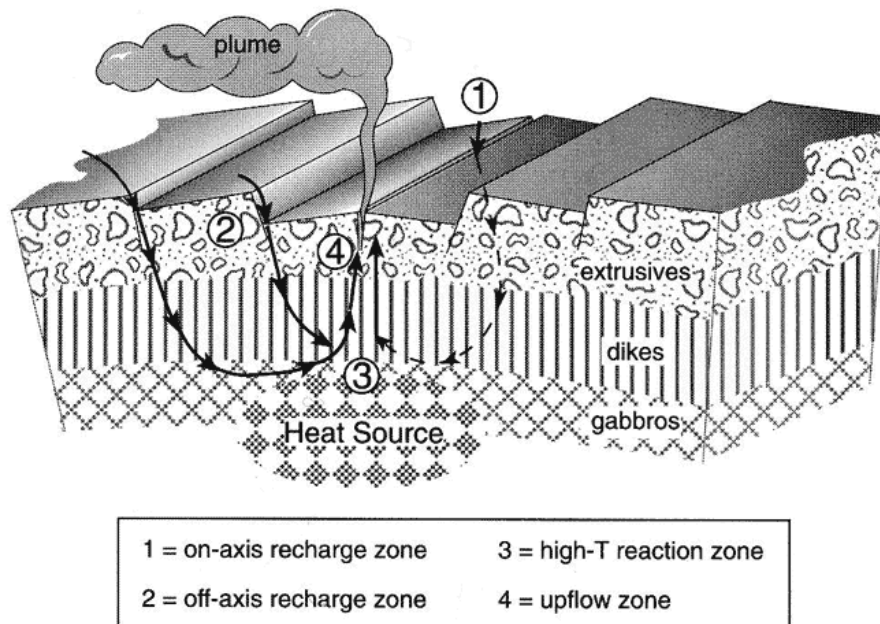


FIGURE 4: Schematic illustration of a black smoker geothermal system. Depth of circulation is about 3-4 km (Encyclopedia of Volcanoes 2000)

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.

## 2.1 Rift zone regime

### 2.1.1 Mid ocean ridges

Mid ocean ridges (black smokers) (Figure 4). 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).

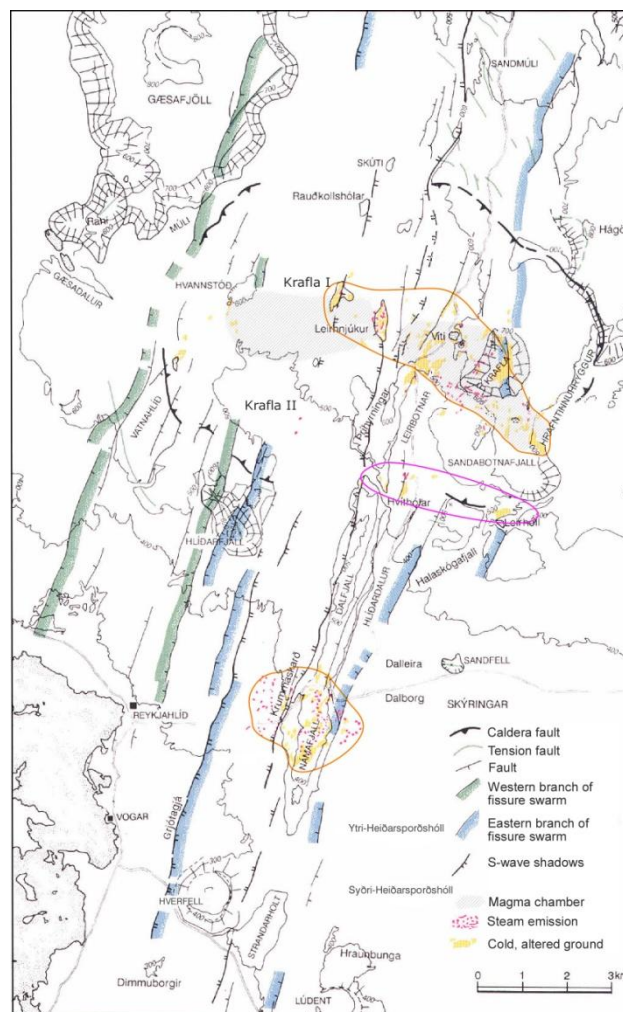


FIGURE 5: Central part of Krafla volcanic system showing caldera and fissure swarms which traverse it. The Krafla caldera hosts a geothermal system. It has a magma chamber (S-wave shadow) at 3-7 km depth. A second geothermal area at Námafjall on the fissure swarm 7 km south of Krafla is located where basaltic fissure eruptions concentrate

### 2.1.2 Supramarine oceanic rifts: Iceland

Geothermal systems develop at high volcanic foci of elongated volcanic systems (Figure 5). 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.

### 2.1.3 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 6).

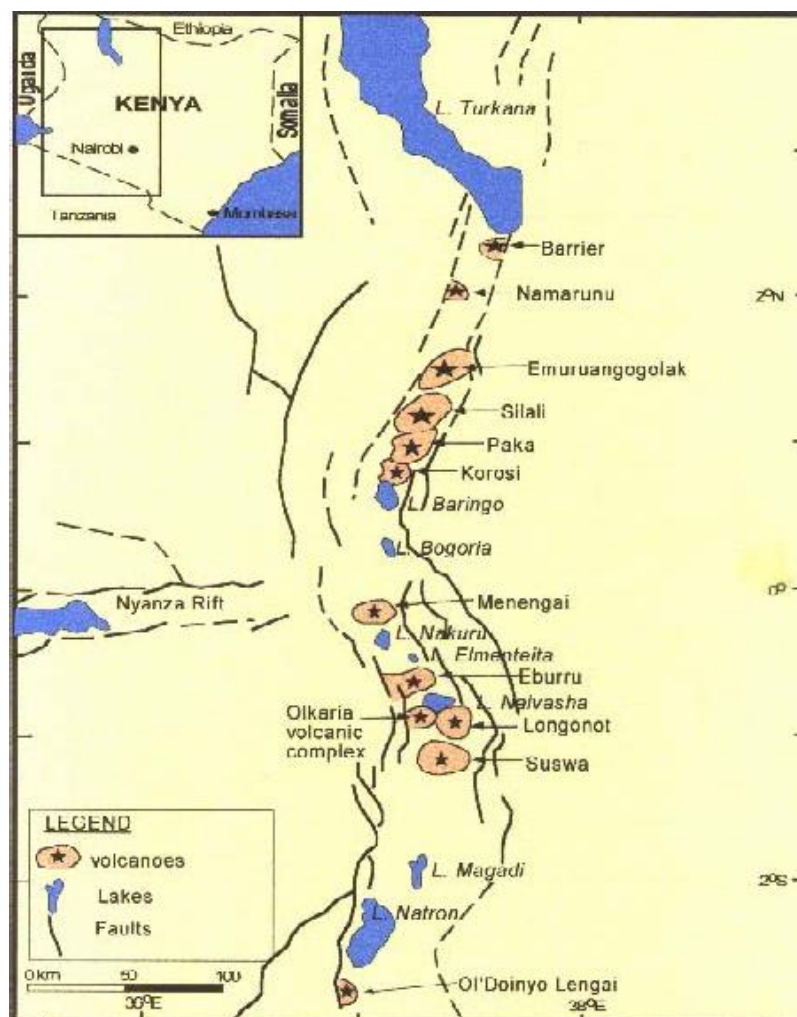


FIGURE 6: Apex of Kenya Rift domal uplift with two volcanically active rift branches and a third E-W branch dying. Stratovolcanoes are shown. Fissure swarms have not been identified as integral parts of volcanic systems (Mwawongo 2004)

## 2.2 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.

### 2.2.1 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.

### 2.2.2 Flank zone volcanism

Flank zone volcanism (Iceland, Azores) (Figure 7) 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.

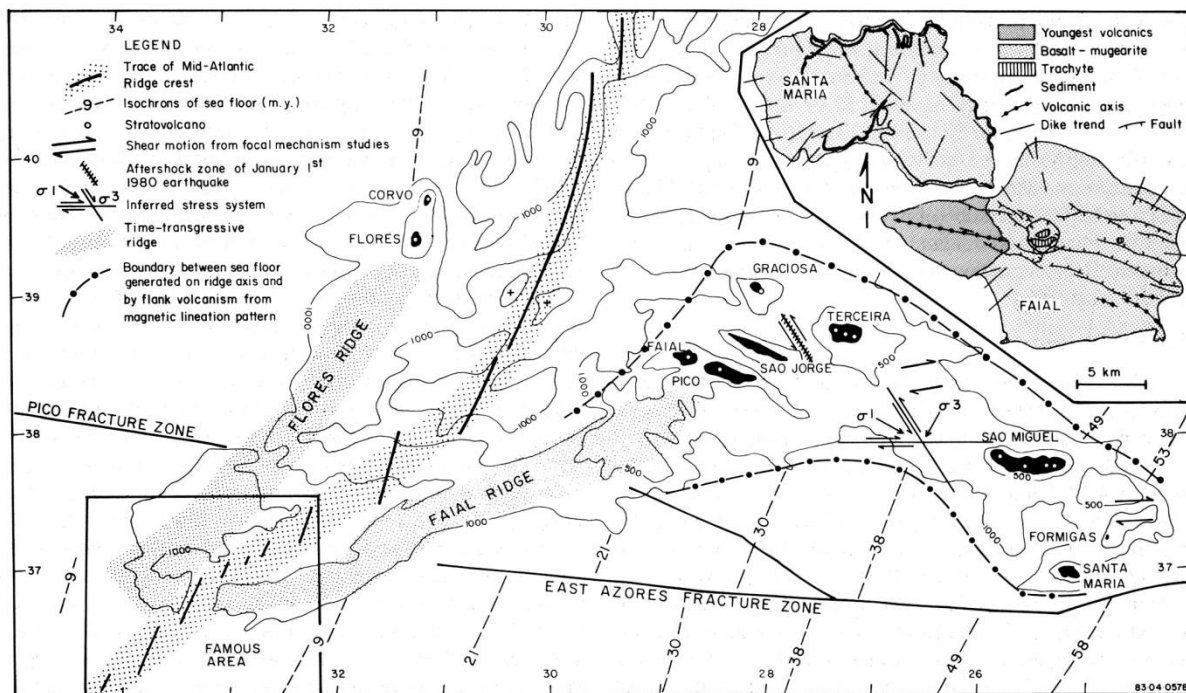


FIGURE 7: High-temperature geothermal fields on the Azores Islands are related to flank zone volcanism north of the Azores Fracture Zones. They developed in caldera regions of stratovolcanoes. Prominent fissure swarms formed in the direction of max. stress

## 2.3 Compressional regime

Compressional regimes are the most common type of high temperature geothermal fields, globally. The tectonic environment is variable (Circum Pacific Belt) (paragraphs 2.3.1-2.3.3 are from Cas and Wright 1995).

### 2.3.1 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 8). 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).

### 2.3.2 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<sup>2</sup>, at 15 km intervals. Volcanic field is comparable in size to Yellowstone also as regards geothermal output. Corresponding magma “intrusion” rates are 1.9 m<sup>3</sup>/s (Yellowstone) and 1.7 m<sup>3</sup>/s (Taupo) (Taupo and Yellowstone comparison from Wilson et al. 1984).

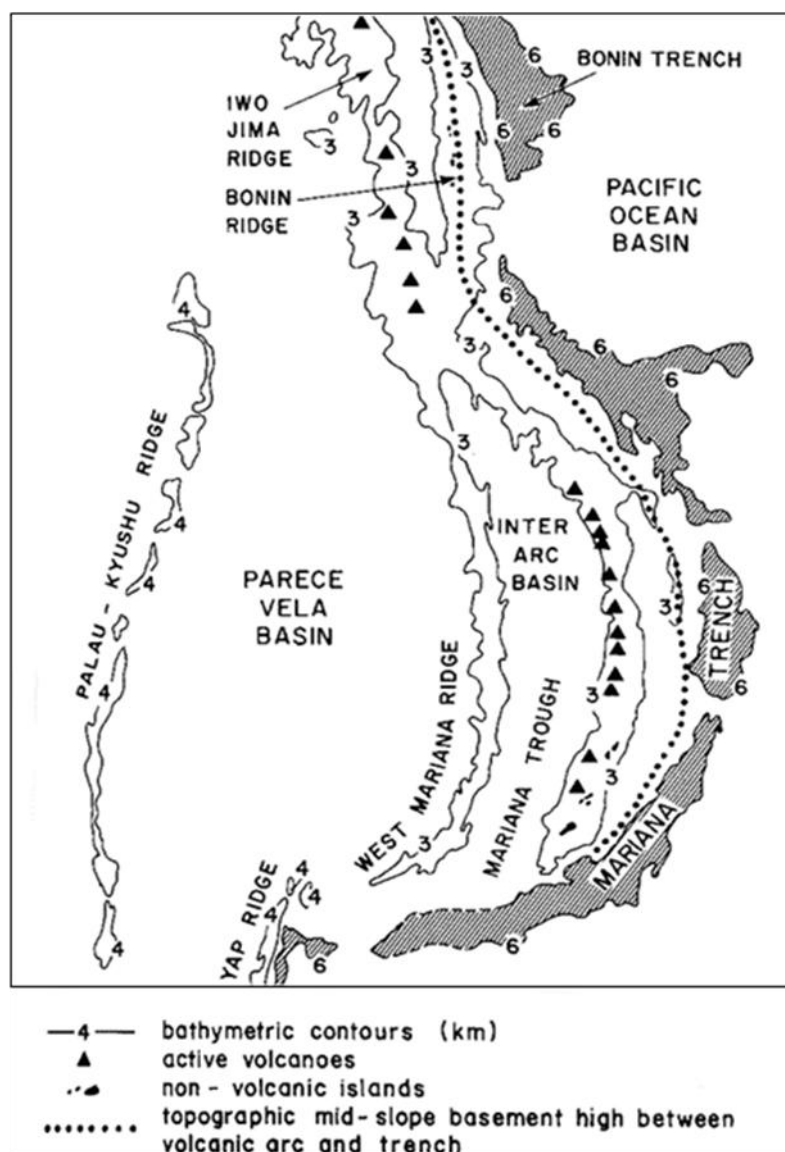


FIGURE 8: Example of a young island arc with inter arc basin and remnant arc. Evolved arcs develop from repeated splitting, crustal thickening and remelting. At the same time the volcanic products evolve from basaltic to acid (Cas and Wright 1995)



### 2.3.3 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<sup>3</sup> erupted in 260 A.D.) and contemporaneous granitoids (batholiths).

### 2.3.4 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.

## 3. 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.

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