WESTERN PACIFIC
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Introduction to Geothermal Geological Principles

Module 3

Contents

1. Introduction

The principal role of geology in geothermal exploration is to obtain as much information as practical on:

- The lithology of the anticipated reservoir.
- The nature of hydrothermal alteration of the reservoir rocks, and hence the nature of the fluids which were responsible for it. If the alteration exposed on the surface indicates temperatures over 100°C, or there are disequilibrium assemblages present, then there has been some erosion of the system, which can affect the hydrological model and also the interpretation of the geophysics.
- Permeability controls in the anticipated reservoir, and hence the location of permeable zones.
- Possible heat source of the system, any indications of active volcanism, and some idea of the age of the system.
- Assessment of geological risk to the project such as volcanic, seismic, and slope stability.

During development of the resource the same topics are addressed, but at a greater level of detail and with less uncertainty.

Although most of the surface geological data are collected prior to drilling, and most of the subsurface data during the development drilling phase, the geologist's task does not stop when the power plant is commissioned. There will be a continuing need to have input to the conceptual resource model as it develops in response to production, to interpret the results of reservoir monitoring (*e.g.* subsidence), and to guide the course of on-going resource management, most particularly the drilling of make up wells.

2. Lithology and Stratigraphy

Points to consider when studying the lithology and stratigraphy of a geothermal area include the following:

- Are there thick volcanic sequences that could constitute a geothermal reservoir?
- How deep is crystalline basement?
- Are there any limestones or marbles?
- Are there any clay-rich young sediments such as lake beds which could constitute aquicludes?
- Are there any clay-rich low-temperature altered or weathered volcanics which could cause drilling problems?
- Are there any non-geothermal related low resistivity units such as clay-rich lake beds or marine sediments that could complicate the interpretation of resistivity surveys?

The degree to which it is possible to erect a meaningful stratigraphy in a geothermal reservoir is quite variable. If the rocks are mainly sedimentary and undeformed, it can be quite straightforward. If they are mainly volcanic it may be very difficult due to a lack of marker horizons and because they were not necessarily deposited in any simple layered sequence. Use of volcanic facies models can overcome these difficulties and provide a tool to predict sequences in undrilled parts of a field. Metamorphic sequences can be more difficult to deal with but can generally be treated as basement units. Nevertheless, if it is possible to develop a stratigraphy it can become a powerful predictive tool to place the lithologies that might be encountered during drilling into context. This is most important in establishing major structural breaks in the field or identifying hydrological controls within the field.

3. Hydrothermal Alteration

Hydrothermal fluids can have various effects on the reservoir rocks: existing minerals can be dissolved, new minerals can be deposited in fractures and pores in the rocks, or the existing minerals can be replaced by other minerals in a process of hydrothermal alteration. All of these processes usually occur together. The new minerals that are formed, whether by deposition in cavities or by replacement, are called secondary minerals.

The geologist studies the effects of hydrothermal fluids on the reservoir rocks. By an understanding of the physical and chemical processes that take place in hydrothermal systems, and by knowing something about the mineral temperature and chemical stability ranges, he can predict the nature of the reservoir fluids while a well is being drilled. This is very valuable, as in this way cool or acid zones can be avoided by casing them out. He may also be able to recognise whether alteration is current or relict (fossil). If there is extensive fossil alteration then the geophysical models of the field will have to be adjusted accordingly.

As well as the study of individual secondary minerals, geologists recognise that certain minerals often occur together, forming distinctive mineral assemblages. Where the minerals can all form in a consistent temperature and chemical range, we have an *equilibrium assemblage*. Minerals that should not, on chemical or thermodynamic grounds, occur together, may form a *dis-equilibrium assemblage*. Note however, that many mineral reactions are quite sluggish, and minerals can form or persist metastably, thus forming apparent dis-equilibrium assemblages. The common mineral assemblages found in hydrothermal systems are described in Appendix 2. The names for these assemblages are mainly derived from economic mineral deposits.

The degree (intensity) and nature (rank) of alteration caused by hydrothermal fluids is controlled by two conflicting factors (*Figure 1*). On the one hand, most chemical reactions proceed more rapidly at high temperatures, and the fluids are more mobile. Therefore, more rapid alteration is to be expected at depth. In contrast, at near-magmatic temperatures, the fluid, being basically of magmatic origin, is close to being in equilibrium with igneous rocks and hence there is little reaction between the rock and the fluid.

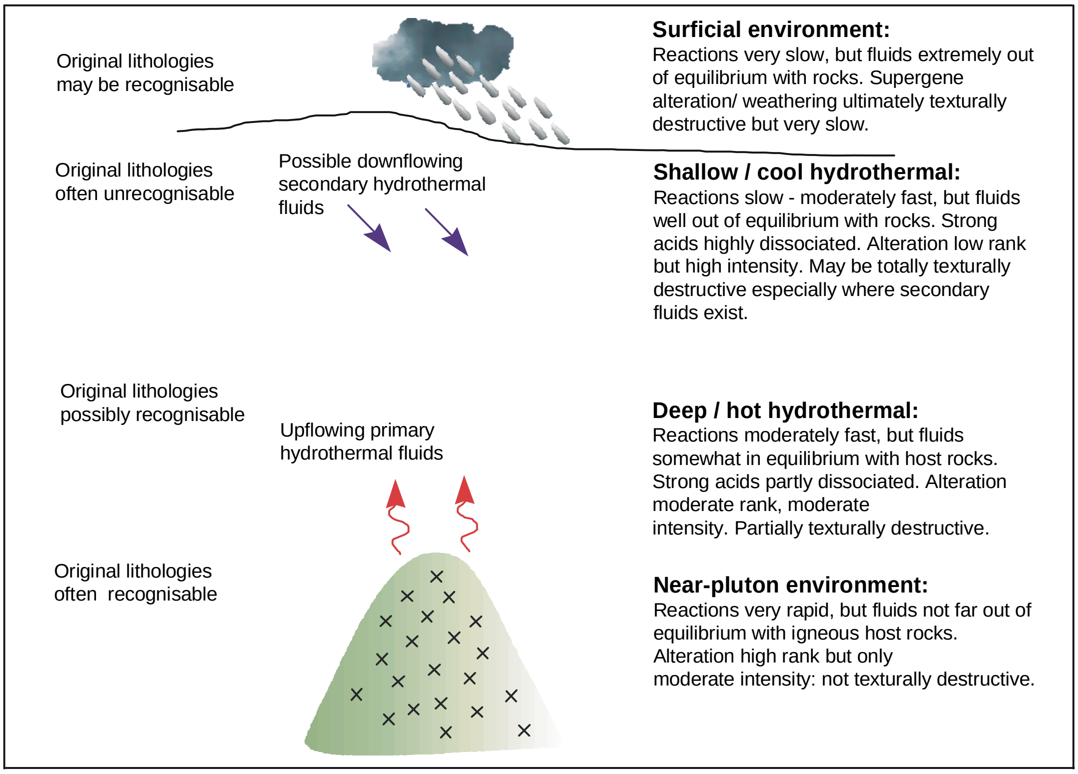

Figure 1 Variations in alteration style and intensity with depth and temperature in volcanic terrains.

Furthermore, species such as HCl are much less dissociated in aqueous solution at high temperatures which means that the effective acidity is less than their concentration would lead one to expect.

These effects were quantified for the reaction of carbonic acid with rhyolite by Bischoff and Rosenbauer (1996). They found that the degree of reaction was greatest at 150 -200 °C. The extent of alteration at 200°C was 27 times as great as at 350°C. At lower temperatures the rates of reaction were too slow to be effective:

Table 1 Rates of reaction for carbonic acid/rhyolite

Temperature °C	Time
300	Minutes
200	One day
100	4000 days (~ 11 years)
50	1000 years

The time given is that required for reaction to proceed to 50 % of saturation (after Bischoff and Rosenbauer 1996). There is therefore limited potential for alteration of the intrusive that forms the heat source to a hydrothermal system, or igneous host rocks at high temperatures. Near-intrusive alteration is restricted to a certain amount of hydration and potassium and silica metasomatism, giving K-feldspar and biotite. (This is not of course the case if the host rocks have a different composition.) As the fluid cools, becomes diluted with more groundwater, and becomes modified through reactions, it gets further and further out of equilibrium with the host rocks. So, while the rate of reaction may be slower, it can have a greater effect on the mineralogy of the rocks. In general, the process is one of removing ferromagnesian cations and replacing them with alkalis, along with silica addition, hydration, and a variable amount of carbonation and sulphidation. As the temperature drops, the Na/K ratio of the fluid rises, and that of the rock correspondingly falls.

This process leads to a systematic zonation of alteration in the hydrothermal system (Appendix 3).

3.1 Hydrothermal Processes and Their Effects on Fluid and Mineral Compositions

The following processes which occur in hydrothermal systems can cause changes in the composition of the fluids and leave their record in the rocks:

- **Conductive Heating**: Heating without significant change of bulk composition of the rock is the process of contact metamorphism. Since most host rocks in hydrothermal system are of igneous composition, simple heating may produce few recognisable changes. It is more apparent when rocks of other composition are heated, for example when limestones are heated to form skarn marbles. Contact metamorphism without significant metasomatism through fluid interaction is rare in hydrothermal systems, as it requires high temperatures and low permeability.
- **Conductive Cooling**: Cooling of fluids will cause some secondary minerals to deposit, but it is not a very effective concentration mechanism since the rate of heat loss is slow, and hence takes place over a large area. It will not change the bulk composition of the fluids except due to loss of solutes to deposited minerals.

  Note that some important minerals, such as anhydrite, have retrograde solubility. That is to say, they are more soluble at lower temperatures.
- **Evaporation**: This is more effective as a means of concentrating materials in solution, but is not very effective in producing large zones of concentrated deposition, since the energy requirements are high. Flashing a fluid at 240°C down to atmospheric pressure (*i.e.* to 100°C) will cause only about one-fifth of it to be lost as steam, so the degree of concentration is small. More prolonged evaporation at the surface, in hot pools, can cause sinters to form. Hotter fluids will deposit siliceous sinters, whereas cooler fluids will usually deposit calcareous sinters, or travertine. Recognition of these can be helpful in determining if a hydrothermal system has undergone recent changes in activity. For example, fossil sinter terraces may show that a system has been hotter in the past.

- **Water-Rock Interaction**: In most hydrothermal systems the fluids are not greatly out of equilibrium with the host rock. There is a tendency for alteration to produce lower-temperature and hydrated phases, but not large shifts in *fluid* composition through water-rock interaction. An important exception is when hydrothermal fluids encounter calcareous rocks. Another exception is high-sulphidation systems, where the fluid has a different, more aggressive composition.
- **Fluid Mixing**: This has contrasting effects. Mixing of a hot hydrothermal fluid with cold groundwater will both dilute the solutes and cool the fluid. For most potential precipitates the cooling effect dominates, but not by much. Thus this will cause some mineral deposition. However, change of pH due to fluid mixing will have a much greater effect. Particularly important is where secondary hydrothermal fluids, which can be of a highly acidic nature mix back into the stream of upflowing primary near-neutral hydrothermal fluid. This can cause the deposition of minerals such as anhydrite, which can have important hydrological effects on the system by forming an aquiclude.
- **Fluid Boiling**: Once again, this has contrasting effects. The concentrating effect of evaporation, and cooling by loss of energy, does promote mineral deposition. The loss of gas is much more important. Removal of only 1% of the water as steam will be accompanied by loss of most of the dissolved gases from solution (the exact amount depends on the temperature and pH) (*Figure 2*). The situation is complicated by associated pH changes: the effect of CO_2 and H_2S loss causes the fluid to become more alkaline. But overall the combination of these factors means that boiling produces dramatic changes in composition of both the volatile phase (steam plus gas) and the residual brine, which becomes more concentrated in most solutes. There is potential for significant water-rock interaction and mineral deposition. Hence certain mineral phases can from mineralogical indicators of boiling. This is important for recognising two-phase or vapour-dominated zones during drilling.

The study of hydrothermal minerals is part of the science of petrology.

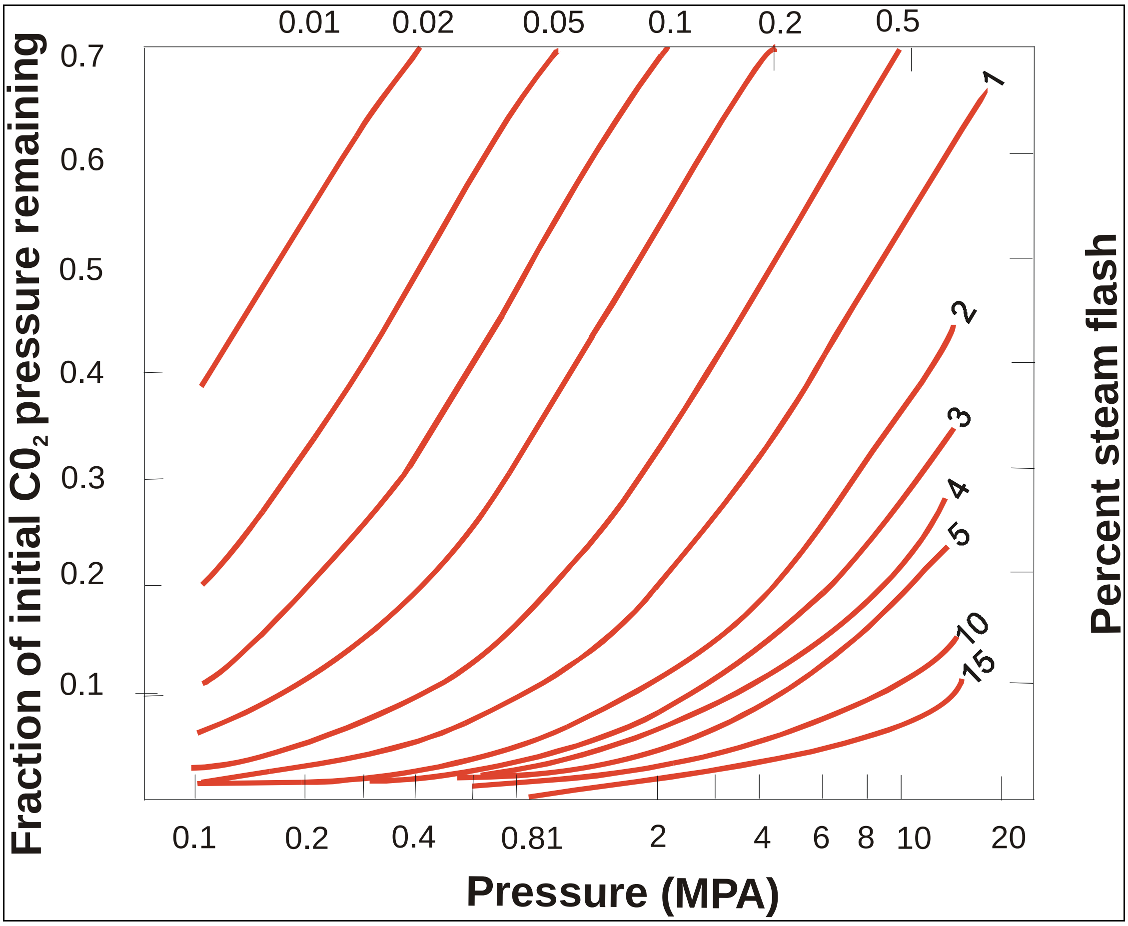

Figure 2 Pressure, as a function of flash fraction and steam partial pressure (from Michels 1981).

4. Permeability Controls in Hydrothermal Systems

The objective of this section is to identify which are the most important types of permeability for fluid flow in geothermal systems, and hence see how an understanding of the geometric relations of permeable zones might be used to predict their location both to understand the hydrology of the system and define drilling targets.

4.1 Sources of Permeability

4.1.1 Primary Permeability

Massive volcanic rocks are the most common host rocks for geothermal systems. The sources of primary permeability in these rocks are (*Figure 3*):

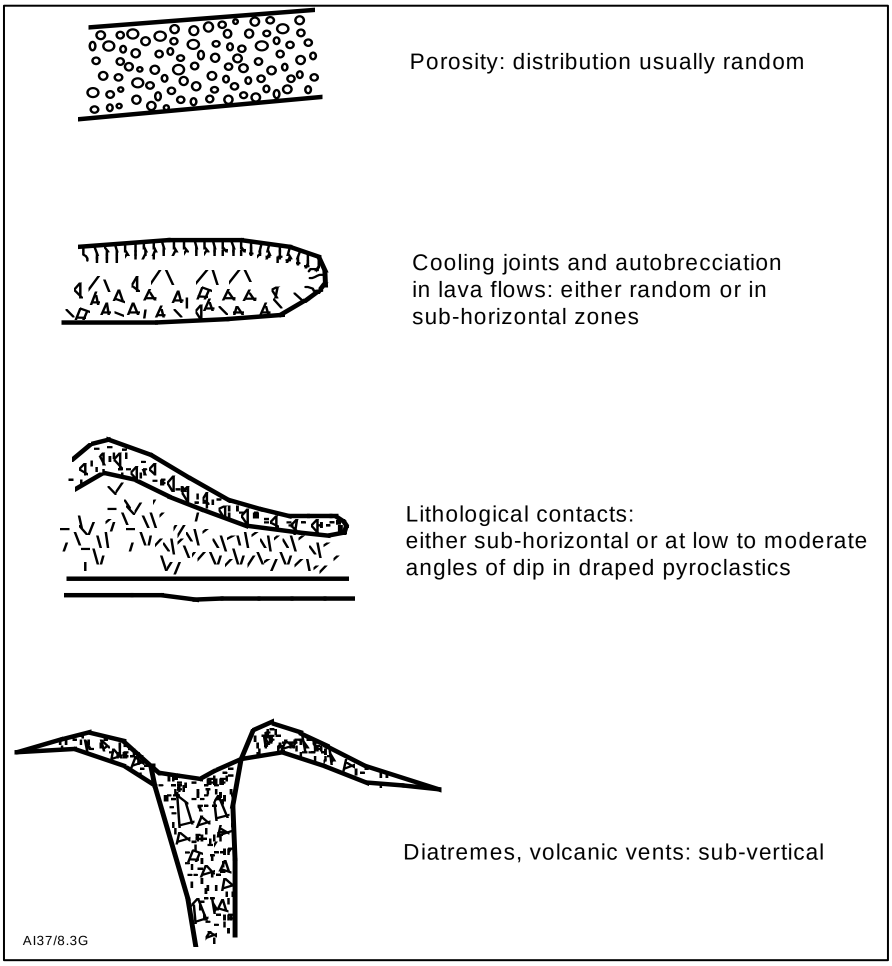

Figure 3 Primary permeability in volcanic rocks.

- **Primary pores**: These have very little effect on the permeability of the rock as a whole unless they are well connected. In most rocks they add little to the permeability. We must distinguish between porosity and permeability. Porosity is important for fluid storage, and hence the long term producibility of the resource, but unless it is connected it does not contribute to bulk permeability. There are exceptional rocks where it does matter, *e.g.* pumice.
- **Cooling joints**: In lava flows and welded pyroclastics these may form zones of permeability, *e.g.* columnar joints in the middle of lava flows or pyroclastic cooling units. These zones of permeability will originally be sub-horizontal.
- **Autobreccias**: These form zones of permeability at the tops bottoms and sides of lava flows, particularly if they are silicic. Hence they will be mainly horizontal permeable features with some limited vertical permeability at the edges of flows.
- **Lithologic contacts**. Weathering surfaces and basal conglomerates and breccias may form permeable zones. These zones of permeability will generally originally be sub-horizontal, but some air-fall pyroclastics can be draped over pre-existing terrain at quite steep angles of dip: 20° is not uncommon. In plutonic or hypabyssal rocks, the contacts are just as likely to be vertical as horizontal (or anything in between.
- **Volcanic vent structures:** These are a special case of autobrecciation. They are generally sub-vertical (*Figure 4*).

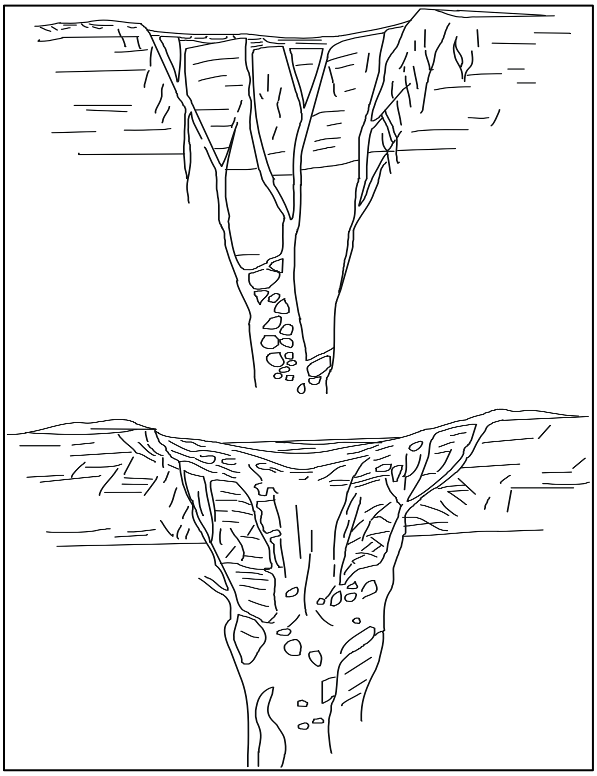

Figure 4 Examples of maar/diatremes

In volcaniclastics and sediments, the degree of permeability will depend on the grain size, the degree of sorting and packing. Tuffs, for example, may be quite permeable or quite impermeable. Such rocks may also have a large surface area per volume, and hence be prone to alteration. Large vertical eruptive vents (*e.g.* diatremes) are a special case of highly permeable primary channels in volcanic terrains.

4.1.2 Secondary Permeability

In the typical island arc setting, the main sources of secondary permeability are (*Figure 5*):

- **Intrusion margins**: Plutonic, or hypabyssal rocks, can be permeable at their margins due to a combination of thermal stressing and hydrofracturing as a result of a release of fluid from the intrusives. The geometry of the permeable zone will follow that of the intrusive resulting in significant variation in their geometry but the most common are near vertical zones associated with dykes and domes and ridges associated with a stock or series of stocks.
- **Rock Dissolution**: Except in special cases, such as limestones, or with acid fluids, this is a relatively minor source of permeability in volcanic terrains. It is however very important for the formation of oil reservoirs. In contrast, permeability reduction by deposition of secondary minerals is a very important process in controlling the hydrology of hydrothermal systems.
- **Tectonism**: Faulting and related fracturing. Both normal and reverse faults can produce large fracture zones, since lateral stresses are often high. In plate-margin settings, repeated movement on faults is the norm. Once a fault is created, it is easier for it to move again that for a new fracture to form in response to accumulating stress. This is the "Andersonian" faulting principle. Slightly misdirected stress will therefore enhance permeability as open space is created in order to accommodate this. Conversely permeability can be lowered in some situations and consistently high permeability cannot be assumed to exist all along a fault. Strike-slip faults usually are less permeable because shearing produces comminuted rock particles that tend to fill any open spaces produced by the juxtaposition of non-parallel rock faces. However, associated normal faults and tensional gashes associated with strike-slip faulting are important sources of permeability.
- **"Hydrothermal" Brecciation**: This will take place when the fluid pressure in a rock exceeds the sum of the minimum principal stress, plus the tensile strength. Two different mechanisms produce hydrofracturing at depth in geothermal fields. The first is where fluid at near lithostatic pressures is released from an intrusive and it hydrofractures the solid part of the intrusive and surrounding rocks. This process is important at depth for creating pathways to channel fluid through and transfer heat from an intrusive. The second process is where tectonic movement creates open space by pulling apart the rocks. The minimum principal stress is effectively reduced resulting in the fluid pressure producing a network of fractures in the surrounding rocks with some of them imploding into the open space. The drop in pressure as fluid expands into the open space causes violently boiling and upward transport of brecciated rock further fracturing the already broken rock and the sides of the open fracture. This process is important in creating wide zones of brecciation around a fault, giving it much greater permeability than a simple planar fracture (*Figure 6*).

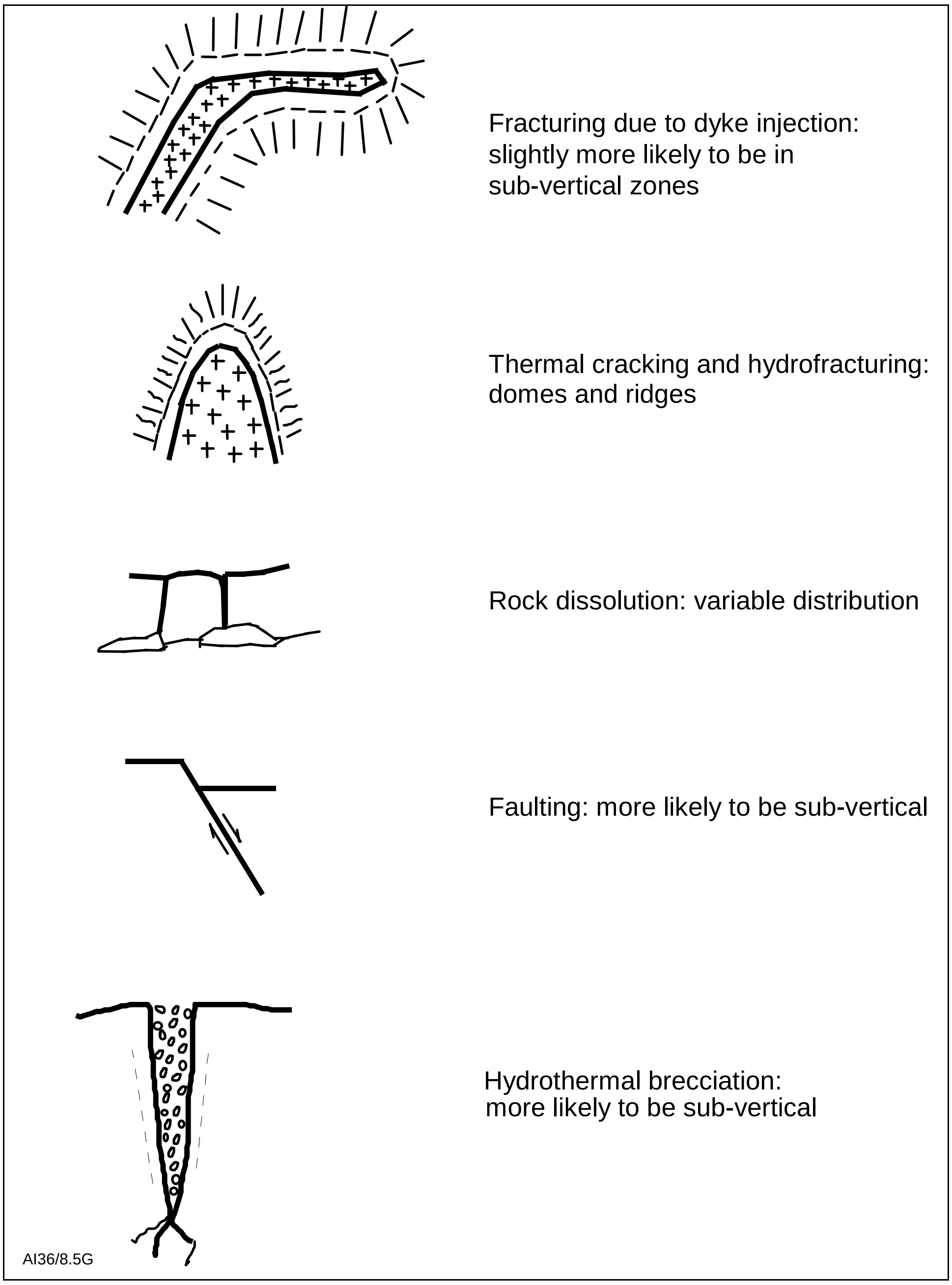

Figure 5 Secondary permeability in volcanic rocks

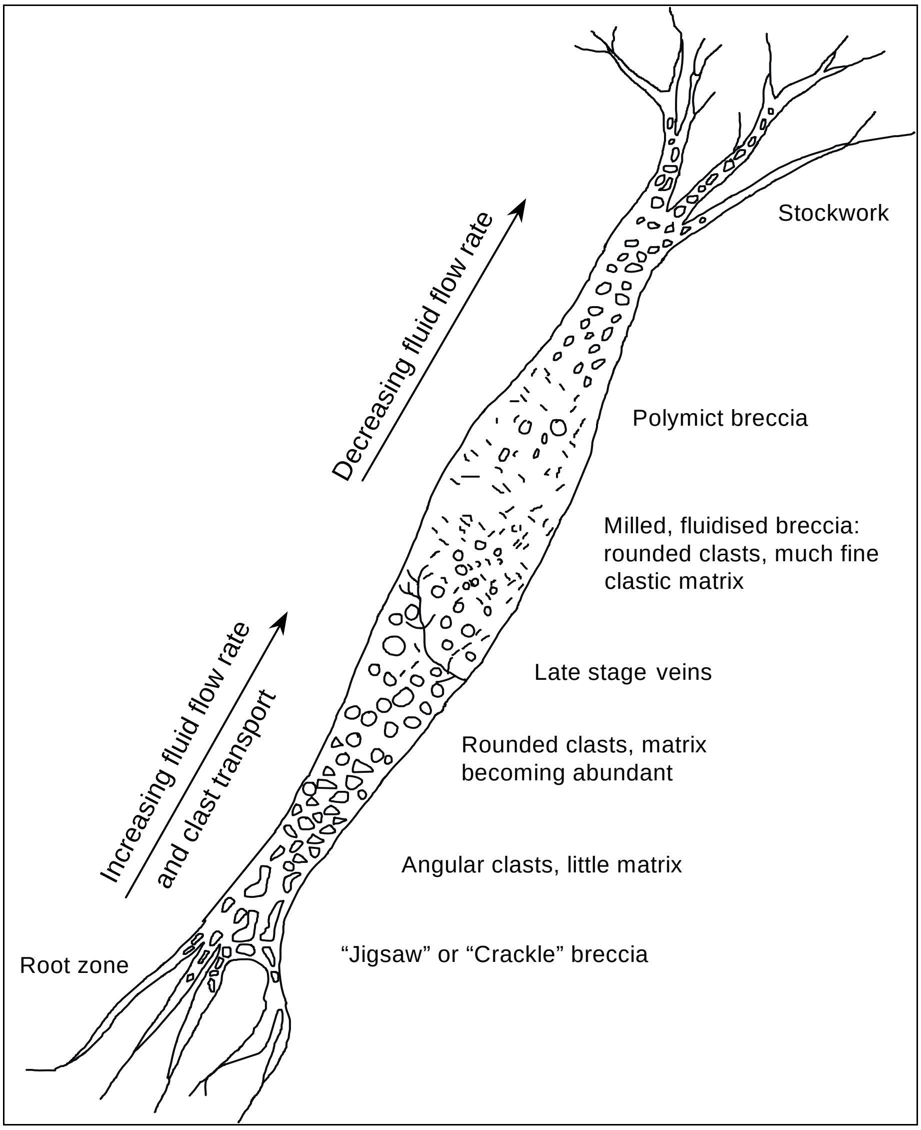

Figure 6 Idealised development of hydrothermal vein and breccias

Hydrothermal fracturing, and hydrothermal eruptions if the fluids can vent to the surface, may be cyclic in hydrothermal systems due to silica sealing (*Figure 7*).

Silica is more soluble at higher than lower temperatures, and the different silica polymorphs have different solubility. Hydrothermal fluids become saturated with quartz at depth. As they flow upwards and cool they become super-saturated and so deposit silica. Because of the kinetics of silica deposition, amorphous silica is usually the solubility-controlling phase at shallow levels (*Figure 8*). This tends to seal the top of hydrothermal systems.

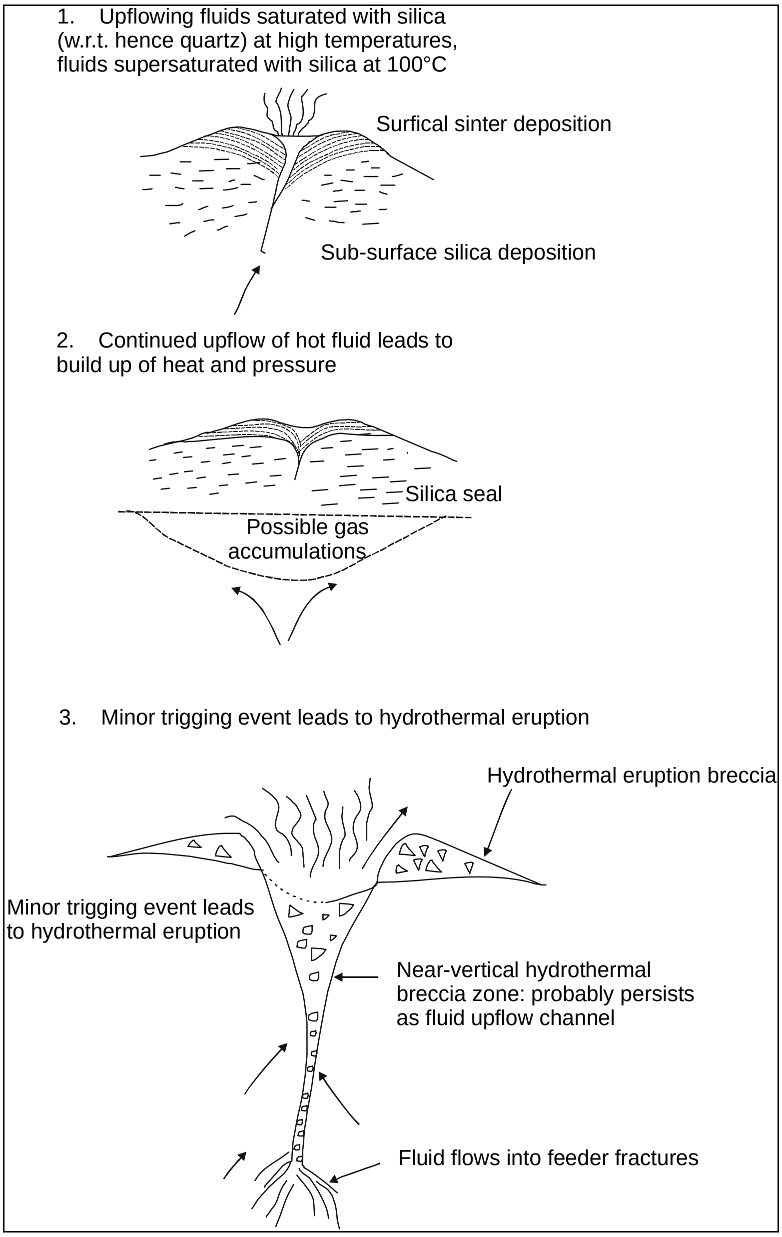

Figure 7 Mechanism for cyclic, shallow focus hydrothermal eruptions

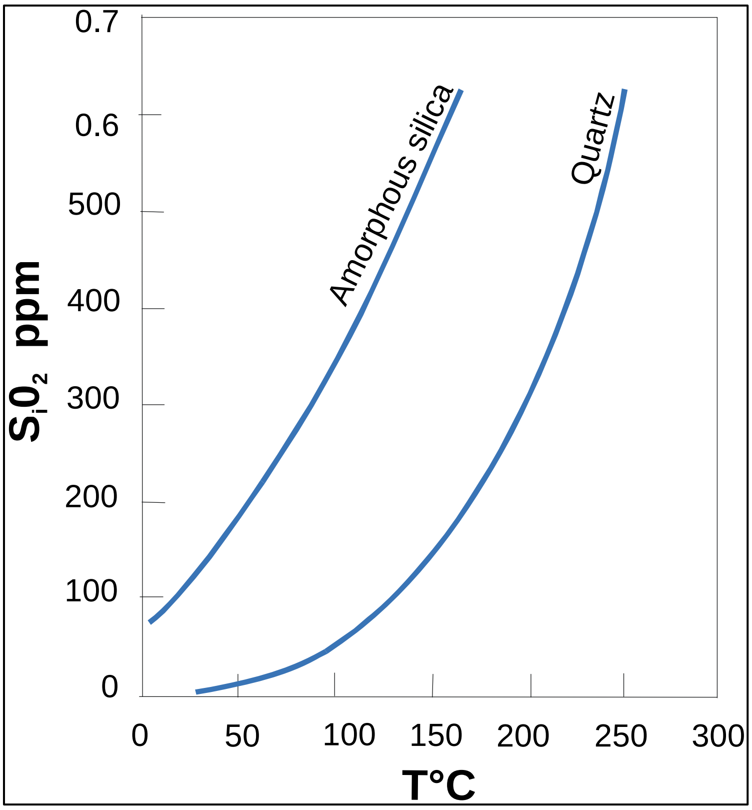

Figure 8 The solubility of amorphous silica in comparison to a solution initially saturated with quartz at high temperature which has cooled by boiling without loss of silica

The continued upflow of hot fluid, and the accumulation of gas at the top beneath the seal, allow heat and pressure to build up to the point where fracturing occurs. The host fluid can then flash into the open space created. If the fluid reaches the surface, a hydrothermal eruption will result. At depth, the feeder channels will be hydrothermal breccia zones. These can also form entirely sub-surface. It is not necessary for the fluid to vent to the surface, merely into a lower-pressure area.

A common misconception is that fluid pressures in a hydrothermal system must exceed lithostatic for hydrothermal brecciation to occur (*e.g.* Hedenquist and Henley 1985, Nelson and Giles 1985). This is incorrect. For a fracture to open at depth, only the least principal stress, plus the tensile strength of the rock must be exceeded. Except in regions of unusual tectonic stress, at the depths that we are talking about, one of the horizontal components of stress will usually be less than the vertical stress, which will approximate lithostatic. Commonly the least compressive stress will follow the rule:

$$U_h = \frac{U_v V}{1-V}$$

Where U_h is the least compressive stress, U_v is the lithostatic load and V = Poisson's ratio, commonly around 0.2 to 0.3 (Fyfe *et al.* 1978). Furthermore, the tensile strength of jointed or fractured rocks may be very low. Hence fractures will be opened when fluid pressures exceed a critical pressure that may be substantially less than lithostatic. Since the least principal stress is commonly horizontal, fractures will open perpendicular to this; that is to say in a vertical plane.

Accumulation of exsolved gas beneath a temporary capping layer of hydrothermally altered material may assist with fracturing, which can then be initiated by some small disturbance such as a minor seismic shock, earth tides, atmospheric pressure changes or other climatic events, or geomorphic processes. Once a fracture has been opened from a high pressure area at depth to a lower pressure area above, fluid flashing can occur. This progressively unloads the fluid column, causing geysering, which will continue until the supply of fluid is exhausted.

The conditions for hydrothermal brecciation are set up by the steady accumulation of heat, fluid and pressure. It is released when a fracture opens. Once the local fluid source is exhausted, or the rock is locally cooled to the point where the fluid no longer boils, eruption ceases. Heat and pressure can then build up again: perhaps for a hundred years or so. Note that the energy throughput of a typical hydrothermal system is adequate to allow quite frequent hydrothermal eruption events. Enough thermal energy passes through a large hydrothermal system to explosively shift of the order of 100,000 m^3 of rock per day: the same amount as would be extracted in a large mine.

Tectonism and hydrothermal brecciation go hand in glove: one may initiate the other; the same zones tend to remain as foci for repeated episodes of brecciation of both types. It is often not clear whether any particular event is strictly tectonic or strictly hydrothermal. To some extent the distinction is artificial. Tectonic forces create a state of stress; within which fracturing may be induced as increasing fluid pressures reduce the effective confining stress, as so movement results.

4.2 Relative Importance of Primary and Secondary Permeability to Fluid Flow

In active hydrothermal systems exploited for energy generation primary permeability is generally much less significant than secondary permeability. This is basically because the fractures created by secondary processes tend to be larger, and more continuous, than those created by primary processes. The ability of a fracture to transmit fluid varies at about the fourth power of the width of the fracture (depending on the shape, surface roughness, temperature *etc*.). Thus a few big fractures are much more important than many little ones. This has serious implications for well targeting: a well which intersects a major permeable zone may have an injectivity or productivity 100 times as great as one which does not within the same reservoir.

With time, hydrothermal mineral deposition tends to block primary permeable channels. Secondary channels keep being rejuvenated, whereas primary ones do not.

Secondary permeability-creating processes are more likely to produce permeable channels with a high angle of dip, whereas many primary zones of permeability are comparatively flat-lying (*i.e.* effectively stratigraphically controlled). Near-vertical channels are more effective in connecting zones of different hydraulic pressures, and hence inducing fluid flow.

Reservoir engineering tells us that *overall* horizontal permeability is usually much greater than vertical permeability in geothermal reservoirs. This does not necessarily mean, however, that it is due to particular *layers* of high horizontal permeability. A planar, near vertical fault zone will provide good horizontal permeability (along the plane) as well as vertically. In this case the horizontal component of permeability will be markedly anisotropic, and this is what has been revealed by tracer tests in many reservoirs.

4.3 Locations and Orientation of Zones of Secondary Permeability

Primary zones of permeability, as mentioned, can have any orientation, but other things being equal are more often near-horizontal. Secondary permeability channels tend to be more nearly vertical. This is because of the relative stresses in a typical volcanic belt.

In the back-arc situation, stresses will be extensional, and simple gravity faults at angles in the range 60-75° dip will result, depending on the rock properties. More often in plate-margin volcanic belts, forces will have a strong lateral component, and are often compressional. This means that both the least and greatest principal stress will be horizontal. Thus hydrofracturing will result in near-vertical normal fractures. The fractures created become the pathways for the hydrothermal fluids, thus forming the typical near-vertical hydrothermal veins. Similarly, rupture in response to tectonic stress, that is to say faulting, may be expressed as a series of conjugate shears with a high angle of dip, or often an en-echelon structure of large scale tension gashes (*Figure 9*).

Tensional gashes need not have a surface expression and can only be targeted indirectly. They are usually found between two strike slip faults, running diagonally between them in opposite directions for sinistral and dextral faults. Therefore, where two strike-slip faults are found, directional wells can be targeted at right angles to the appropriate diagonal and good permeability found. This should be the case in Sumatra in particular.

The situation with both horizontal stresses exceeding vertical (*Figure 10*), which is common at depth in metamorphic zones, is not common at comparatively shallow levels at tectonic plate boundaries, which is where magmatic-related geothermal systems occur. Thus low-angle fractures are not so common in this setting, except perhaps in response to removal of lithostatic load during the erosional unroofing of plutons.

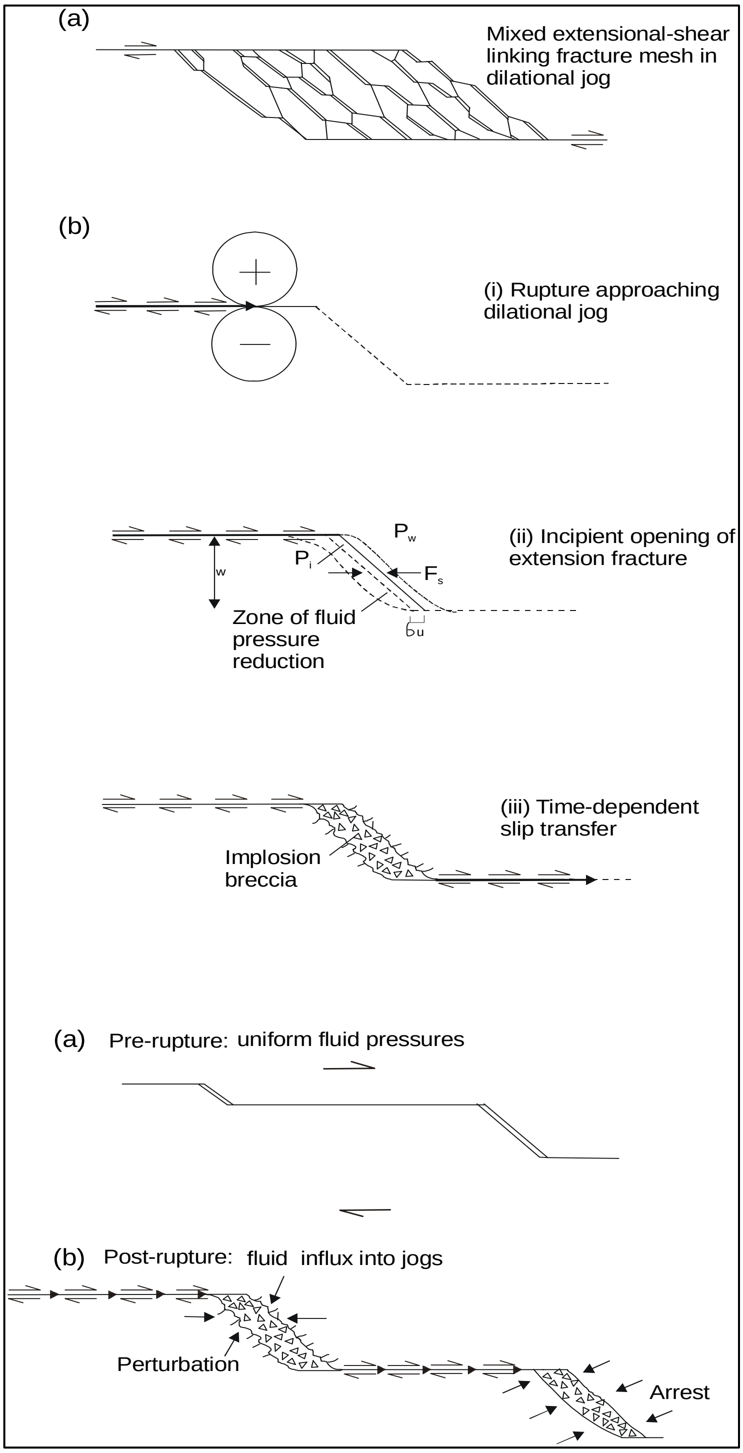

Figure 9 Schematic representation of dilational fault jogs (idealised as single extension fractures) causing rupture perturbation and arrest along a strike-slip fault (from Sibson 1985, 1987).

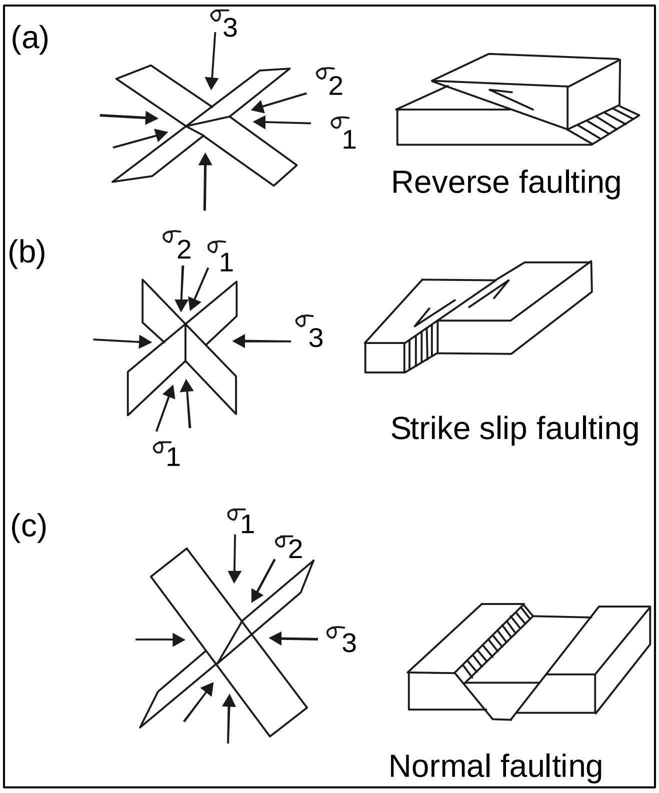

Figure 10 Initial stress distribution causing faulting: σ_1 = maximum, σ_2 = mean, σ_1 = minimum (compressive) stress (after Hills 1964).

4.4 Variations in Permeability with Depth

The vertical zone at which economic geothermal fluids occur is controlled to a large extent by the nature of the boiling-point for depth curve for water and the economics of drilling. But there are some general mechanical considerations that also play a role, and mean that some levels in a hydrothermal system are more likely to have extensive permeable zones than others. Let us look at the mechanics of a typical hydrothermal system from the bottom up (*Figure 11*).

Much of the information on permeability comes from drilling for geothermal energy in active hydrothermal systems. As the technology improved, geothermal wells were drilled deeper and deeper, into hotter and hotter conditions. Thus the energy output of the wells became greater. But this process led to diminishing returns, and not just due to the greater friction within deeper wells. Below a depth of about 2500 m in typical active hydrothermal systems in andesitic terrain, experience in geothermal drilling has shown that permeabilities are usually not consistently as high as at shallower levels. Experience has shown that the best wells for energy extraction often penetrate zones in the temperature range 260 - 300°C, rather than higher temperatures. The answer to this puzzle is to be found in the rate of plastic deformation of common minerals at these temperatures. Above about 320°C, both quartz and feldspar (which make up the bulk of the reservoir rocks) will deform sufficiently rapidly that fractures either do not occur, or become healed within a short time in comparison to the rate of stress accumulation due to tectonic plate movement. Thus major permeability is short-lived.

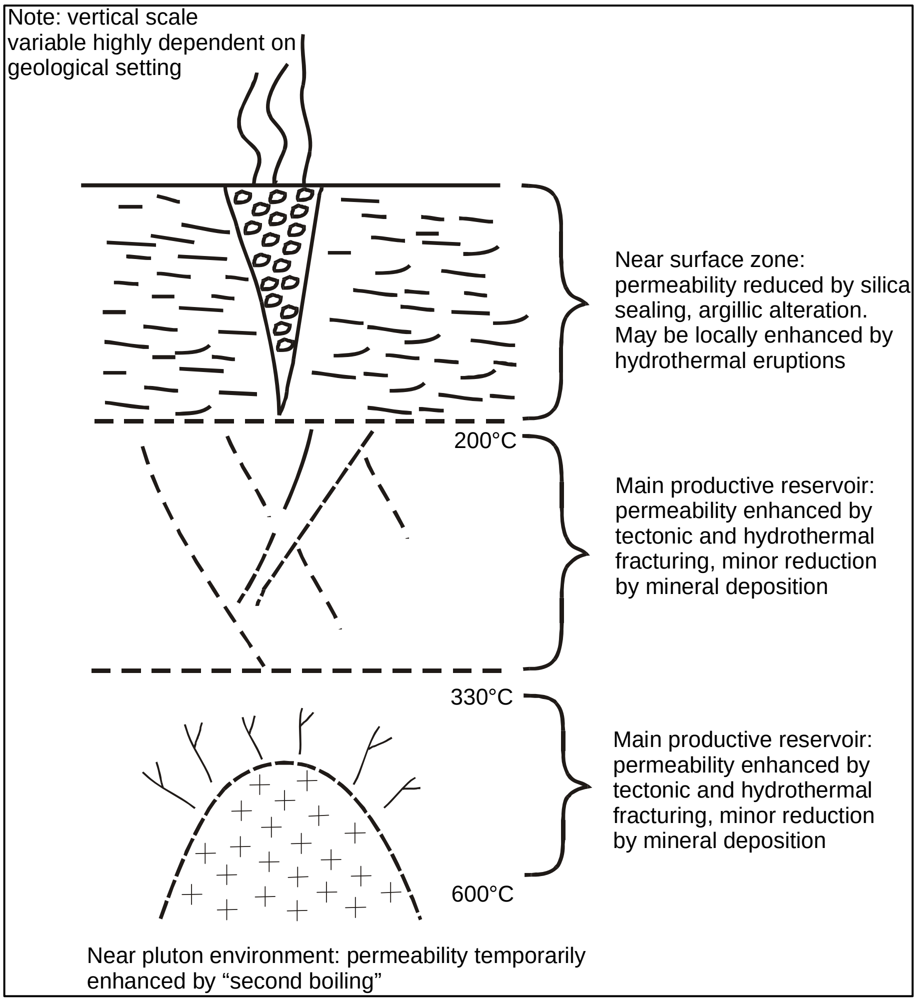

Figure 11 Vertical permeability distribution in hydrothermal systems

The same phenomenon is well known to structural geologists working in metamorphic terrains, who refer to this as the "quartz-feldspar brittle-ductile transition", and set the temperature limit at about the same level (320-340°C). But in metamorphic zones, the much smaller geothermal gradient means that this transition occurs much deeper: many kilometres, where pressures are also much greater. In hydrothermal systems the transition zone is much closer to the surface. This is also reflected in the depth limit of small earthquakes: it is well known that the number of micro-earthquakes drops off below the transition zone (10-15 km in continental crust). Active hydrothermal systems are often quite aseismic compared to the surrounding areas.

Another factor causing a decrease in permeability at depth is silica deposition. Late-stage magmatic and hydrothermal fluids are usually close to saturated with silica, simply because they are in equilibrium with silica-containing rocks. But the solubility of silica depends both on the temperatures and the fluid state. Supercritical fluids can contain much more silica in solution than sub-critical water (*Figure 12*). Thus if fluid cools from near-magmatic supercritical temperatures down to subcritical, it becomes silica supersaturated and quartz is deposited. We cannot put a single figure on the temperature of this process, since the critical point for water solution is so dependent on the concentration of dissolved solutes. But at some level around a cooling pluton, there will be a zone where silica tends to deposit and reduce permeability. This tends to keep separate the near-pluton magmatic fluid and the overlying freely-convecting fluid which is largely of meteoric origin.

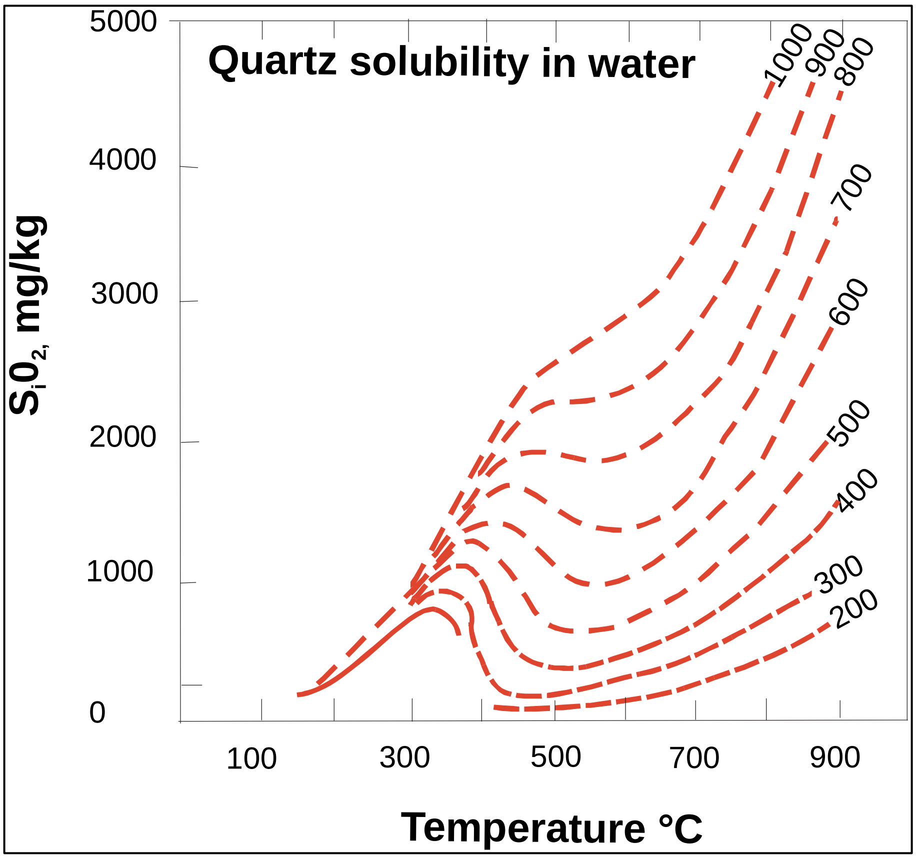

Figure 12 Calculated solubilities of quartz in water up to 900 °C at the indicated pressures in bars (after Fournier 1985)

These effects are accentuated by the properties of water at high temperatures. At high temperatures water has very low viscosity. In that respect it more resembles a gas than the fluid we are familiar with, and so can penetrate even tiny fractures readily. But it also has very low density, so a large volume of fluid moving through the rock is in effect providing a relatively small mass for chemical reaction and mineralisation. This is not true for the hyper-saline brines formed in the near-intrusive environment by phase separation on depressurisation. They are very dense and may in fact be too dense to convect.

Permeability within the deeper part of the geothermal environment is therefore short-lived. Permeability can be created by faulting, by intrusions, by hydrofracturing, or thermal cracking, but it does not remain open indefinitely.

Moving up the hydrothermal system, the zone from 300 to 240°C, corresponding to perhaps 1 to 3 kilometres depth, is often found to be very permeable. The rocks are strong enough that fractures can be formed, and cool enough that they do not rapidly heal.

The zone above 1000 m depth, that is to say from a level of 240-260° C up to ambient conditions at the surface, is where vigorous hydrothermal brecciation, possibly leading to surficial hydrothermal eruptions, is most probable. The reason for this is easily seen from the boiling-point for depth curve: the *relative* pressure gradient is much greater near to the surface. It is within this zone that gas can separate and accumulate to set up the conditions for triggering hydrothermal eruptions.

This is also the level at which a hydrothermal system in high elevation terrain may become stratified, with layers of different chemistry developing. This in turn can lead to permeability reductions due to secondary mineral deposition. So the overall effect is probably to focus the most important fluid flow in relatively few channels.

We now have a picture of what the target zones for geothermal production will be. In a typical geothermal reservoir there will be a general level at which temperatures are high enough for production, and fracture permeability is most likely. Within this sub-horizontal zone, at a scale of individual well production, the most productive zones will tend to be steeply-dipping structures.

The need for permeability to be constantly rejuvenated means that the most productive zones will be concentrated on major structural channels. This will especially apply to any lateral outflow zones, simply because the available fluid is potentially spread over a much wider area. It is important to appreciate the scale of such structures. Experience shows that major faults can often be traced over 1 to 5 km, and sometimes three times as far.