Geothermal and hydrothermal systems

Description: Geothermal and hydrothermal systems are connected with the occurrence of high temperature events and processes. Geothermal systems are those systems where the heat of the Earth is concentrated to the point of potential utility. It is possible to distinguish between active (recent) and fossil systems.

The difference in density between descending cooler fluids and ascending geothermal water is the major driving force of a geothermal system. Generally, terrestrial geothermal systems are described as either convective or advective. Geothermal systems are found in various geological and tectonic environments, but all share certain common features: a heat source (magmatic or volcanic), fluids (water of various origin), permeable flow paths and impermeable boundaries. Geothermal systems are closely linked with the boundaries of tectonic plates – for example the western USA, Iceland, Italy, Japan or New Zealand. Hydrothermal systems are recognised in connection with determination of the origin of deposits formed by high temperature aqueous solutions of magmatic origin.

Various geothermal and hydrothermal systems have been studied to assess the period immediately following the disposal of SNF or HLW in a deep geological repository.

Most deep disposal concepts are limited by a maximum permissible temperature of around 100^0C at the contact between the disposal container and the buffer/backfill material, which is usually based on some form of plastic clay mineral. The reason for this is to avoid the creation of steam and also to minimize the occurrence of degradation effects in the clays (phase transformation, cementation etc).

Most studies have been carried out in connection with the Yucca Mountain Project (Nevada, USA), where it is planned to construct chambers in unsaturated tuffs, and where the disposal concept envisages high temperatures after disposal (currently, two modes are under consideration – a low and a high temperature scenario). The key processes that are expected to occur are boiling of interstitial water and subsequent condensation, together with mineral dissolution and precipitation, both of which will impact upon permeability, fluid flow and transport of radionuclides. Therefore, the main aim of studies of geothermal and hydrothermal analogues (Bechtel, 2002) is to evaluate the behaviour and migration of important elements and radionuclides, the stability of mineral phases (dissolution and precipitation), and the alteration of pores and fractures (effects on permeability) in a high temperature environment. Testing of geochemical models is one of the main tasks, but coupled processes (thermo-hydro-chemo-bio processes) are also examined (conceptual models, model validation).

To date, mostly active systems have been studied (Yellowstone, Island, Wairakei in New Zealand), with less emphasis on fossil systems. Hydrothermal alterations in granitic rocks have also been studied.

Yucca Mountain itself can serve as an example of a fossil geothermal system (Bechtel, 2002). Most zeolitic alteration occurred 13 to 11.3 My, at about the same time as tuff emplacement. After the formation of the major zeolitic horizons, deep-seated hydrothermal activity persisted until 10 My. This activity is known to have been limited to temperatures of 90 - 100^0C because the transformation of sorptive zeolites to non-sorptive minerals is not detectable.

The Paiute Ridge intrusive complex, located 40 km northwest of Yucca Mountain, also represents a fossil system. The complex consists of late Miocene (8.7 My) alkali basalt that was intruded into tuffs. Changes in tuff mineralogy, texture and chemistry, resulting from emplacement of the basalt, has been recognised. The FLOWTRAN model has been applied as an example of a code for simulation of two-phase non-isothermal fluid flow in a variably saturated media for dual and single continuum systems

The most intensively studied geothermal system from the point of view of its use as a natural analogue is Yellowstone, because of the similar mineralogy and chemistry to the rhyolitic tuffs found at Yucca Mountain. Yellowstone is composed of hundreds of thermal features located both within and outside of a 0.6 My old caldera. The most recent eruptive activity at Yellowstone occurred around 70 ky ago. The geothermal system consists of two distinct reservoirs: a liquid-dominated reservoir in the western portion of the caldera and a steam-dominated system in the eastern portion. The Yellowstone system has been intensively studied by U.S. Geological Survey (*http://volcanoes.usgs.gov/yvo/hydro_refs.html*).

Numerous studies have focused on the hydrothermal silica sealing which occurs as a consequence of the cooling of silica-saturated waters, the mixing of fluids with different chemistries and temperatures in excess of 100^{o} C. Porkchop Geyser in particular has been subject of chemical monitoring for over 50 years, due to the presence of significant concentrations of silica in the water (some hundreds of ppm). The evolution of thermal activity, from a quiescent hot spring, to an infrequently geysering pool and finally to a perpetually spouting geyser, has been observed since an earthquake in 1959.

Sealing, as a consequence of dissolution - precipitation processes, has been recorded at boreholes located about 3 km northwest of Old Faithful Geyser. Significant changes in porosity connected with silicification of sediments have been detected. Most fluid flow in the Yellowstone geothermal system is associated with high-permeability features. While the initial permeability distribution is controlled by lithology, subsequent hydrothermal alteration has clearly modified both matrix and fracture permeability. Hydrothermal alteration resulted in the reduction of matrix permeability and focusing of flow along fractures, where multiple pulses of fluid flow and self-sealing have occurred (Bechtel, 2002). Other types of hydrothermal alterations (other than silicification) have been detected - argillitization or zeolitization - with similar impacts on permeability. The Yellowstone system has helped in the validation of geochemical models focused on the prediction of changes in secondary mineral assemblages as a function of temperature, pressure and solution chemistry. Problems in the calculation of disequilibrium processes (usual in hydrothermal systems) and the lack of thermodynamic data for some important mineral phases have been reported.

[The main processes characterized at geothermal systems studied specifically for the purpose of natural analogue or generally for other purposes but the results can be interpreted as natural analogue are further specified in detail (according to Bechtel, 2002).

<u>Fracture-dominated fluid flow</u>

Many geothermal systems have reservoir rocks with relatively low matrix permeabilities, but high overall formation permeabilities, caused by the presence of a high-permeability fractures. Such a system occurs in Dixie Valley (Nevada, USA) where interference and tracer tests were conducted to demonstrate the connectivity of wells via a high-permeability fracture network. Similar features were characterised at the Silangkitang geothermal field (Indonesia) and Wairakei (New Zealand).

Such examples demonstrate the importance of high-permeability fractures for the circulation of fluids. If such faults/fractures are permeable, then they could serve as a fast fluid flow path for infiltrating surface waters reaching the repository horizon, as well as a path for dissolved radionuclides transport from the waste packages down to the water table (by analogy with Yucca Mountain).

<u>Chemical transport in geothermal systems</u>

The transport of chemical species in geothermal systems is linked to advective fluid flow. Chemical constituents of geothermal fluids are commonly used to derive deep reservoir temperatures, identify sources of fluids (magmatic, meteoritic, mixed, etc.) and to monitor important transport processes. Fluid velocities are usually rapid and often faster than chemical equilibration. The chemical composition of geothermal waters is commonly used to determine reservoir temperatures, using a variety of silica and alkali geothermometers. Natural and introduced chemical tracers are used to monitor fluid velocities, estimate flow paths, examine fracture-matrix interaction and identify the sources of fluids within geothermal systems. Such tests and observations have been performed in many geothermal systems - Dixie Valley (Nevada, USA), Wairakei (New Zealand), various Japanese fields and at Bulalo (The Phillippines) where dispersal of injected fluids within reservoir was monitored and high permeability flow paths were identified. Changes in chloride content and fluid enthalpies were used in production wells to identify the contribution of re-injected fluids.

Geothermal boiling and dryout

Many geothermal systems have localized boiling zones resulting from upward flow of high-enthalpy fluids or from depressurization induced by geothermal production. Dryout zones are much less common and are typically associated with the transition between liquid-dominated and steam-dominated geothermal systems. The effects of boiling on fluid chemistry, mineral precipitation and reservoir permeability have been documented for many natural-state and producing geothermal systems. Boiling-water features were studied at Waiotapu (New Zealand), which is the largest of the 20 major geothermal systems located in the Taupo Volcanic Zone on the Northern Island. Surface features include fumaroles and associated acid sulphate springs and numerous chloride, acid sulphate and mixed hot springs. Surprisingly, much higher dissolved silica concentrations were measured there (445 ppm) than is the equilibrium solubility concentration of both quartz and amorphous silica at the pool temperature. This is probably as a consequence of boiling and cooling processes.

Boiling features resulting in substantial increase of total dissolved solids concentrations have been studied in Cerro Prieto (New Mexico, USA). Large decreases (up to 70%) in discharge rates detected from wells have been interpreted as being the result of the precipitation of quartz and calcite, which decreased the permeability of flow zones.

At Yucca Mountain, the impact of boiling on mineral precipitation should be significantly less than observed in most geothermal systems because of the restricted area in which the boiling can occur, the much smaller quantities of water present, and the lower initial concentrations of dissolved silica. Therefore, very minor reduction of fracture porosity is predicted for the Yucca Mountain system, resulting in a negligible reduction in fracture permeability. Dryout features have been characterized in the Karaha-Telaga Bodas geothermal system (Indonesia). Such dryout zones could develop in the rock mass around the potential repository drifts at Yucca Mountain as the waste packages transfer their heat to the surrounding environment (but only in the high temperature scenario). Predicted processes are actually the precipitation of minerals in fractures, dehydration of naturally present sorbing clay minerals and carbonate mineral decomposition.

Condensation and mineral dissolution

Condensation and mineral dissolution can be detected in some geothermal systems. Condensation occurs when up flowing steam comes into contact with cooler meteoric waters (very diluted and with distinct chemical composition) in the shallow portions of geothermal systems.

Mineral alteration and precipitation

Mineral alteration and precipitation processes are ubiquitous in geothermal fields and they can significantly affect the porosity, permeability and sorption properties of both matrix and fractures, resulting in the sealing of former fluid flow paths. The rate of precipitation is often controlled by kinetic processes. Supersaturation can be caused by processes such as boiling, cooling, heating, degassing and the mixing of two distinct fluids. Such processes were documented for example from Imperial Valley (USA), Wairakei (New Zealand), Medicine Lake (California, USA) and Otako (Japan). The precipitation processes also occur as scale formation in pipelines and wells.

Alteration and precipitation processes are predicted for the Yucca Mountain system, potentially influencing permeability and sorption properties of various minerals.

Generally, a variety of alteration and precipitation processes have been described from geothermal systems, varying as a function of temperature, pressure, solution and rock chemistry, along with other factors such as:

- Silicification (origin of Si polymorphs and cryptocrystalline forms such as opal)
- Zeolitization
- Argillitization
- Precipitation of carbonates

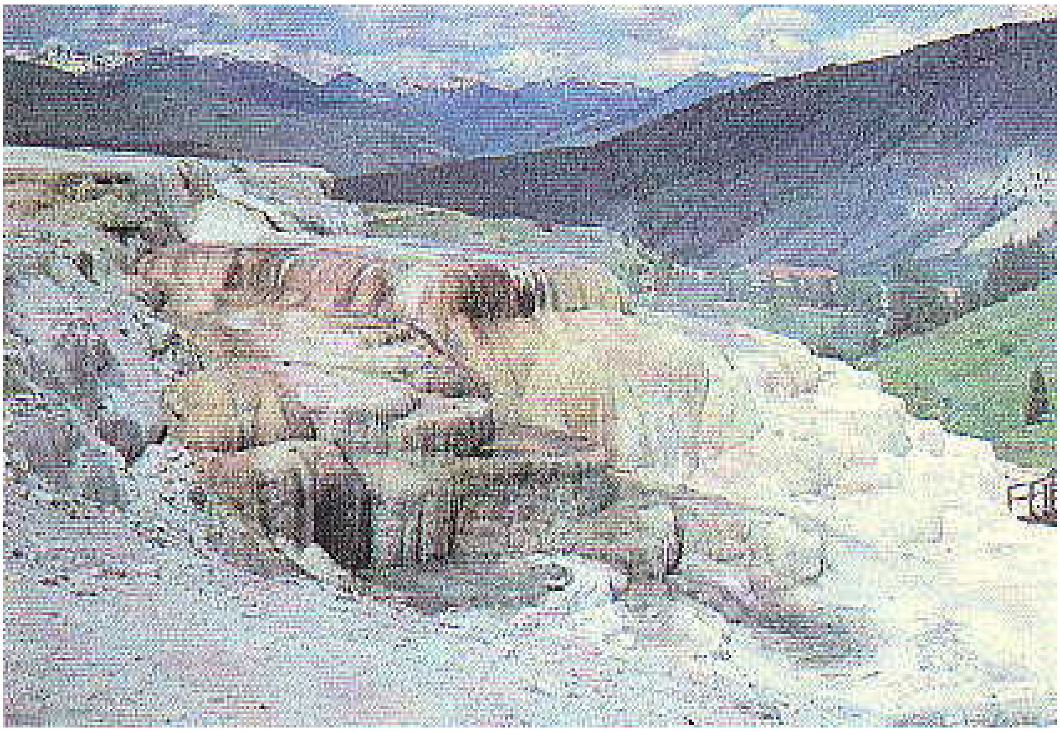

Fig. 1: Yellowstone Park, an example of a geothermal analogue

Relevance: Geothermal and hydrothermal studies are generally relevant for those deep repository concepts which are expected to result in high temperature impacts on the host rock (currently only Yucca Mountain). The applicable time period is mainly that immediately following waste emplacement (the period of maximum heat transfer).

Position(s) in the matrix tables: Both near-field (nuclide movement and retardation in barriers) and far-filed processes (disruptive processes, radionuclide migration at high temperatures in volcanic or sedimentary rocks).

Limitations: There are many limitations in the use of results from studies of various geothermal systems, due to dissimilarities between presumed repository conditions and natural geothermal/hydrothermal systems; between unsaturated and saturated environments; with regard to temperature evolution, the existence of oxidizing vs. reduced conditions, and gas content, etc.

Quantitative information: Probably the most important application of the (indirectly quantitative) results from studies of geothermal natural analogues lies in the area of validation of geochemical codes. These include speciation-solubility, evolution along flow path in high temperature environments, dynamical heat and non-isothermal flow). They are also relevant to some extent with regard to complex coupled processes.

Uncertainties: Uncertainties arise mainly from the limited similarities between many geothermal systems and the proposed Yucca Mountain repository (in terms of flow rates and thermal gradients).

Time-scale: Variable, but generally geological. Individual features frequently have rapid rates (various dissolution - precipitation processes in active geothermal systems) that can be directly observed.

PA/safety case applications: Geothermal studies have been carried out in conjunction with the Yucca Mountain Project (USA). Various examples are used in the safety documentation of the projected repository as illustrations of the character and consequences of high-temperature processes.

Communication applications: None known.

References:

Bechtel Saic Company (2002): Natural analogue synthesis report.- Report for U.S. DOE, Yucca Mountain Site Characterisation Office, Las Vegas Nevada

Bruton C. J., Glassley W. E. and Meike A. (1995): Geothermal areas as analogues to chemical processes in the near-field and altered zone of the potential Yucca Mountain, Nevada repository.- Lawrence Livermore National Laboratory, UCRL-ID-119842

Stockman H., Krumhansl J., Ho C. and McConnell V. (1994): The Valles natural analogue project.- SAND94-0650 and NUREG/CR-6221

Added value comments: No comments here.

Potential follow-up work: It is probable that currently available information from geothermal and hydrothermal systems will be further re-interpreted for use in the safety documentation prepared for subsequent licensing steps at Yucca Mountain. It is unlikely that new larger-scale projects will be initiated, although smaller process-focused projects could be carried out.

Keywords: High-temperature system, migration, speciation

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