THERMAL SPRINGS

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Contents

Summary

This article presents the fundamental concepts concerning groundwater circulations when liquid water experiences high temperatures traveling in the earth crust. Simplified models of hydrothermal circulation are presented to explain the basic processes. In convection-dominated systems, upward circulation of water transports heat to shallow reservoirs or to surface (springs). These systems commonly occur in areas of active volcanism and above normal heat flow. In conduction-dominated systems, deep aquifers are heated by near-normal heat flow, conditions that occur beneath many deep sedimentary basins throughout the world. Detailed descriptions are given of the geochemical techniques used in defining the origin of thermal waters and the mixing processes occurring between natural waters of different origins. Environmental isotopes, such as those of H_2O molecules, are extensively utilized to discriminate between different sources and to provide age dating of thermal waters. The chemical composition of the thermal solutions changes greatly with changing reservoir temperature, the nature of reservoir rocks, and the circulation time of water. The different relative concentrations of major solutes in thermal waters are used for evaluating the temperatures of the deep reservoir they are coming from. The more frequently used chemical and isotopic geothermometers are listed.

Humans and terrestrial heat began coexisting in the Paleolithic, when an ancestor first found an area with active thermal phenomena. A short account of myths, legends, cults, and popular beliefs in ancient times is reported, together with a brief discussion of the utilization of thermal water for recreation and luxury, medical treatments, cooking, bathing, and agriculture. The influence of the ancient peoples of the Eastern Mediterranean in mining, processing, and commercializing hydrothermal minerals is also illustrated.

1. Introduction

"Thermal spring" is a general name for any discharge of deep-seated, pure, or mineralized water whose temperature is higher than the local mean annual temperature of the atmosphere.

The activity of or pertaining to heated water, its action, and the products of such action is called "hydrothermal" activity. The "hydrothermal" term encompasses all types of hot water phenomena in the earth's crust although most commonly the term is used in reference to those associated with impressive geysers activity, aesthetically attractive hot pools, and so on. These features are most common in those geothermal systems that are extraordinarily abundant in the tectonically active volcanic zones of the earth's crust (see *Active Volcanism in the Earth, and Geothermal Systems*). In these regions, the anomalous high temperatures and the extensive tectonic fracturing, offer the possibility of deep vertical water exchange, and create very favorable conditions for the wide occurrence of underground thermal waters in deep-seated strata and their emergence to the surface. But other terrains also host hydrothermal activity even though subsurface temperatures may be relatively low and surface features less impressive. Warm springs also occur in the tectonically stable crust where the deep crustal penetration of groundwater occurs in favorable sedimentary formations such as limestones and the heat supply is the ambient continental heat flow (see *Terrestrial Heat Flow*).

2. Conceptual Models of Water Circulation

To date (2002) practically all geothermal energy that has been trapped for commercial power production is of the hydrothermal variety. The major hydrothermal systems are associated with seismically active regions with extensive faulting. Although some hydrothermal systems are associated with porous and permeable sedimentary/volcanic rocks, a larger number are in fractured rocks, which are otherwise more or less impervious (see *Geothermal System*). The fractures act as conduits for thermal fluids.

A large body of circumstantial evidence exists to suggest that faulted regions are frequently associated with geothermal systems. The exact role that the faults play in determining the structure of a hydrothermal system is, however, a matter of speculation since insufficient information is available on the detailed structure of fault regions at depth. The connection between faults and geothermal anomalies may be only indirect inasmuch as faulting may lead to fracturing and hence enhanced permeability.

In view of the fact that the water in hydrothermal systems appears to be mainly of meteoric origin (see *Groundwater Origin and Distribution*), it has been suggested that

surface water gradually seeps down in permeable sediments and/or volcanic rocks where it comes close to a deep hot source (Figure 1).
Temperature below the earth's surface is controlled principally by conductive flow of heat through the solid rocks, by convective flow in circulating fluids, or by mass transfer in magma.

In hydrothermal-convection systems, most heat is transferred in circulating fluids rather than by convection. Convection occurs because of the heating and consequent thermal expansion of fluids in a gravity field; heat that is supplied at the base of the circulation system is the energy that drives the system.

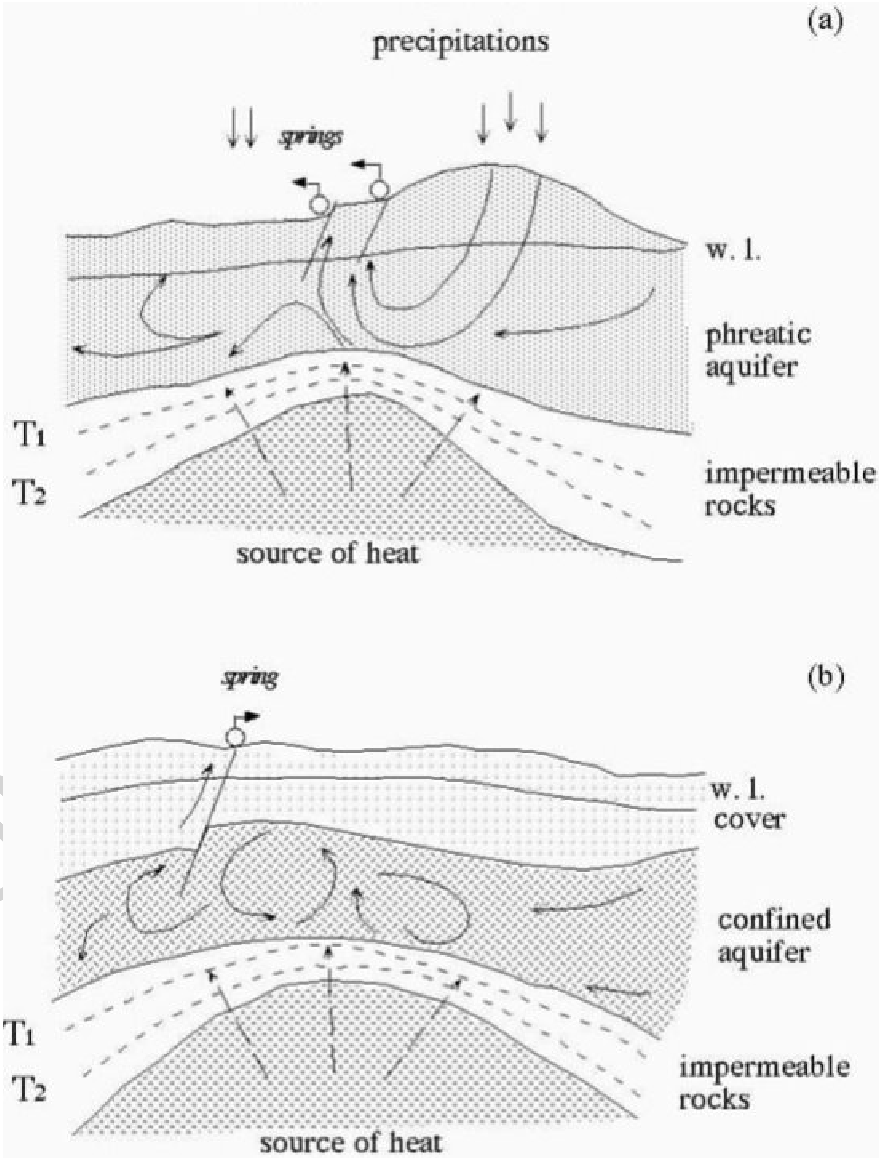

Figure 1. General sketch map of a water-dominated geothermal system. (a) phreatic aquifer; (b) confined aquifer; T1, T2:isotherm contour lines. Unbroken arrows show general ground water flow with convection circuits (open in case a, and closed in case b). Dotted arrows represent the conductive heat flow in the impermeable rocks; w.l.: phreatic level in (a) and piezometric level in (b).Water in a major water-convection

system (Figure 1) serves as the medium by which heat is transferred from deep sources to a geothermal reservoir at shallower depths—shallow enough, perhaps, to be tapped by drill holes.

Cool rainwater percolates underground from surface areas ranging across tens to possibly thousands of square kilometers, and then circulates downward. At a depth of 2 to 6 km, the water is heated by conduction from hot rock that, in turn, is probably heated by molten rock. The water expands upon heating and then moves buoyantly upward in a column of relatively restricted cross-sectional area (1 to 50 km^2). Heated water will rise through the faulted region, which is characterized by a relatively high permeability, and if the fault intersects a horizontal aquifer of high permeability, then the hot water rising through the fault will charge the aquifer. If the rocks have many interconnected pores or fractures of high permeability, the heated water rises rapidly to the surface and is dissipated rather than stored (Figure 1a). However, if the upward movement of heated water is impeded by rocks with few interconnected pores or fractures (that is, impermeable rock), geothermal energy may be stored in reservoir rocks below the impeding layers (Figure 1b).

The most common water circulation models for any kind of thermal springs assume the presence of one or more faults allowing both deep penetration of the infiltrated water and the upflow of hot water from great depth to the spring. Thus, convection cells are created in which leakage to the surface or out of the formation is replenished by inflow of meteoric groundwater.

The association of geothermal systems with active seismic regions assures that continuous mechanical fracturing (for example, that resulting from earthquake activity) will counteract any tendency of the fault zone to be blocked by solids precipitated from the rising and cooling column of saline water (see *Transport Processes in Groundwater*).

Convection, by its nature, tends to increase temperatures in the upper part of the system as temperatures in the lower part decrease. However, the water reaches the surface (the hot spring) at a temperature higher than the neighboring surface value but lower than the original reservoir value. This is because of the cooling of a rising column of hot water, which originates at the top of a deep reservoir. The cooling occurs because heat is conducted out of the conduit, through an impermeable barrier, into an adjacent near-surface aquifer.

In carbonate-evaporitic formations, thermal spring waters are found at the margins of the aquifer formation outcrops, in places showing no evidence of faults or major fractures. In this case dense and diffuse fracturation of the rock complex is observed, and the spring waters always emerge at the lowest points of the boundaries of the aquifer outcrops (Figure 2). In this case, topography seems to control spring location. The carbonate-evaporitic formations, on a large scale (distance of the order of 1 km), probably behave as a continuous porous medium. Heterogeneity may be important on a small scale (order of tens of meters) in the spring emergency area.

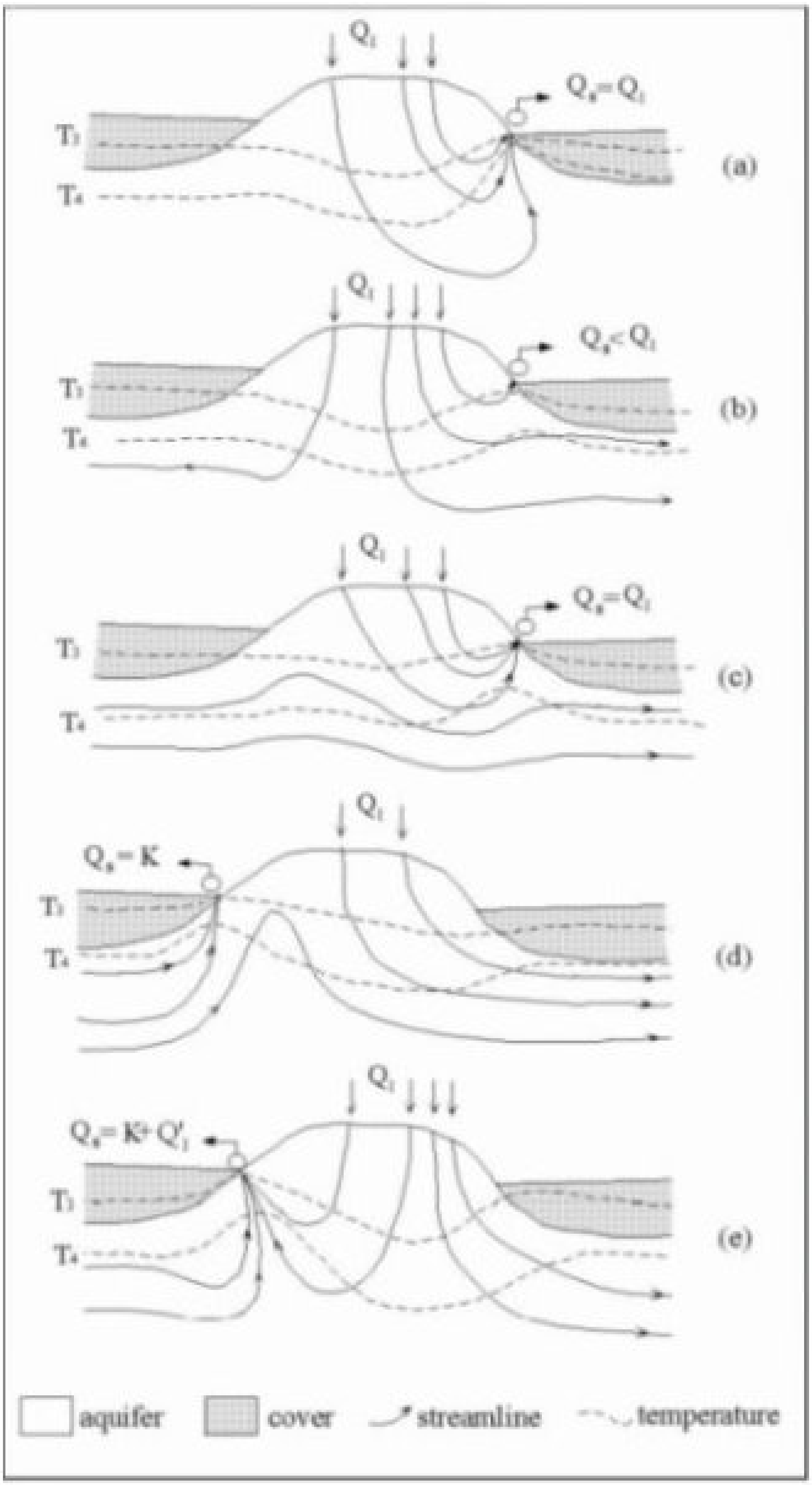

Figure 2. Flow patterns and temperature fields of large-scale underground circulations. (a) Thermal spring in a main recharge area with spring discharge equal to infiltration. (b) Thermal system in a main recharge area allowing deep circulation and supply of a thermal spring. c) Interaction between regional and local circulation occurring in the same direction. Infiltration and discharge are relatively small and nearly balanced. The two circulations are almost separated from one another and the spring discharges water

coming almost entirely from local infiltration. The temperature field is not greatly perturbed. d) Interaction between local and regional circulation. No local circulation is established, and the infiltrated water flows entirely towards the right boundary while the spring is fed by the regional circuit only. e) Interaction between local and regional circulation.

Two extreme cases of large-scale groundwater circulation, between which there is a wide range of possible intermediate situations, may be considered.

- The permeable outcrop represents a “main recharge area” for the aquifer. In this case the springs deliver only water that infiltrated in the permeable outcrop they belong to. This water must have circulated long and deep enough to reach its “anomalous” temperature and salinity.
- The permeable outcrop represents a discharge area. Small outcrops discharging much larger amounts of water than the possible local infiltration certainly belong to this class. Practically all of the delivered water comes from the regional circuit whereas the local infiltration makes only a small contribution.

In intermediate situations a significant amount of water of local infiltration mixes with the water from the regional circulation, so that the two are found in varying proportions in the delivered water.

In general, cases of mixed spring supply are obtained when the water level surface shows a deep minimum at the spring location, so that water flows towards the spring from the left to the right. The natural conditions favoring the mixed spring supply are deep depressions of the topographic surface or discharges that are higher than infiltration.

Spring exist in a few points only, because elsewhere the water level either does not reach the ground surface or the water outflow is impeded by the presence of impermeable layers. Whenever the water level reaches the ground in a permeable outcrop connected to the aquifer, water outflows. Usually the surface discharge from the point of minimal elevation of the outcrop border keeps the water level surface low enough to prevent discharge from other places of higher elevation. However, in cases of very widespread permeability outcrops there may be more than one spring in points that represent local minima of ground elevation.

In the case of a main recharge area, the springs will discharge all the infiltrated water that cannot be transmitted through the aquifer. In the case of a discharge area, the springs usually discharge water at such a rate that level surface is forced to pass through the spring points (see *Groundwater Flow In Porous Media and Through Fractured Rocks*).

3. A Special Spring: The Geyser

A geyser is a hot spring that periodically erupts, throwing water into the air. This seems simple and common enough, but in fact, geysers are extremely rare. In the entire world, there are only 700 geysers. Conditions must be just right for geysers to be present.

Three components must be present for geysers to exist: an abundant supply of water, an intense source of heat, and special plumbing. Water seems easy enough to find in nature, heat can come from volcanic activity, but the plumbing is critical.

It is conceivable that a cold spring could erupt intermittently as a geyser as a result of the slow and steady accumulation of gas in an underground cavity.

Water levels are controlled by permeability and flow rates in the upflow channels, regulated through the competing effects of seismic fracturing and self sealing, and by subsurface outflow (leakage) near ground level. In general, the rate of discharge of water from deep in the system would be faster than the actual rate of the system were it not restricted by a series of throttles. Pressure discontinuities that occur across these throttles result in "overpressures," relative to calculated ideal hot water hydrostatic pressure (see *Multiphase Groundwater Flow*), in the shallow parts of the hydrothermal systems. The net result is boiling point temperatures above those expected for local hydrostatic load, and very unstable conditions in which massive boiling and rapid discharge of water can be triggered as a result of a slight pressure decline. Such a pressure decline may result from the opening of a new fracture or widening of an old fracture during an earthquake, or by the upward surge of a slug of steam that displaces water from a geyser tube.

The following scenario is typical of many geyser eruptions. At the start of a cycle, shortly after a geyser eruption has occurred, water from deep in the system flows upward and refills a shallow water-holding reservoir immediately below the geyser. Continued convective flow heats the surrounding rock until the entire water–rock system is at the boiling point curve for the prevailing pressure. There is a progressive change from mainly conductive cooling to mainly adiabatic boiling of the upflowing fluid. With the increase in boiling there is an increase in the amount of steam that is formed.

Early in the cycle, bubbles composed by steam and non-condensable gases, such as CO_2, that forms the upward convecting fluid, rise through the overlying water column. However, with less conductive cooling the mass fraction of steam steadily increases, and eventually that steam starts to move upward through the geyser tube as a slug, lifting and ejecting the overlying water. As a slug of gas bubbles reaches the surface there is a momentary decline in pressure within the geyser tube, and this reduction in hydrostatic head may be sufficient to cause flashing in the shallow reservoir, resulting in the expulsion of large quantities of water. This results in further reductions in pressure deeper in the system and a chain reaction of rapid boiling at ever-greater depths is initiated.

During an eruption, water and heat are discharged much faster from the shallow holding reservoir than they are recharged, requiring a time of repose between eruptions to "reload" the system. A variety of behavior of the major geysers have been observed, including eruptions that average 60 m in height or more, with variable eruptive intervals and duration. Sometimes, the eruptive intervals are a function of the length of play of the preceding eruption.

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Biographical Sketches

Dr. Costanzo Panichi received his degree in chemistry in 1965 from the University of Pisa. He has been engaged in several national and international geothermal projects from that time until the present. He is currently Research Director at the International Institute for Geothermal Researches of the National Research Council (CNR) Pisa, Italy.

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His academic career includes the following: Teaching at Pisa, Siena, and Rome Universities, the UN International School of Geothermics of Pisa from 1969 to 1985, and at IAEA international courses; Expert rapporteur of the EC Geothermal Program for the period 1980–1983; Director of the International Institute for Geothermal Researches in Pisa, from 1984 to 1987; Project leader of the Italian National Program for Geothermal Researches from 1968 to 1990; Expert of the International Atomic Energy Agency of Vienna for geochemical investigations in Ecuador, Columbia, Costa Rica, Greece, and Ethiopia; and Co-coordinator of the geochemical activities of the National Volcanic Group of Italy.

Dr. Panichi was President of the National Volcanic Group of Italy of the National Research Council from 1994 to 1997, and has been a Member of the Scientific Consultant Committee for the National Resource Council since 1998.

Dr. Panichi is the author of 90 scientific publications on thermal fluid geochemistry.

Dr. Giorgia La Ruffa received her degree in geology in 1995 from the University of Cagliari. She took a Ph.D. in 1999 in isotope geochemistry at the International Institute of Geothermal Research of the National Research Council of Italy in Pisa, delivering a dissertation on “The use of the stable isotopes geochemistry to hydrological, environmental and energetic problems.”

Currently she is engaged in research on the relations between surface and underground waters, in a framework of the National Group for Prevention from Hydro-Geological Disasters of the National Research Council of Italy. She is also involved in a geothermal research project in Greece, sponsored by IAEA, and some hydrological research dealing with the environmental aspects of selected mineralized areas in Latin America, under the auspices of UNESCO.
Dr. La Ruffa is the author of 12 scientific publications.