Geothermometry of selected Montana hot spring waters

by Michael Bernard Kaczmarek

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE with concentration in Geology
Montana State University

Abstract:
The base temperature of hot-water dominated hydro-thermal systems can be quantitatively estimated using two different methods. One method uses the concentration of dissolved silica in the discharge wasters in equilibrium with respect to quarts. The other method is based on the ha, K, and Ca concentrations in the discharge waters in equilibrium with solid mineral phases in the wall rocks. Experimental studies and practical applications of these two hydrogeothermometers have been largely limited to the temperature range of 200 to 360°C. This paper presents some results of application of both methods in the temperature range 15 to 150°C.

Dissolved silica calculated base temperatures are reliable for undiluced thermal waters in the temperature range studied. Sources of error are cold water dilution of thermal waters and assimilation of silica from amorphous silica in wall rocks.

Base temperatures calculated from Na, K, and Ca concentrations in discharge waters are generally inaccurate. Errors in the calculated temperatures result from the fact that net water/rock reactions in the temperature range 15 to 150°C may be significantly different from those in the range 200 to 360°C, Net water/ rock reactions for the temperature range 15 to 150°C are presented here and the importance of E-mica versus kaolinite mineral phase stability is discussed.

The hydrogeology of six Montana and one Idaho hot springs is presented herein. Base temperatures are calculated for each hydrothermal system and are evaluated as to their reliability. Suggestions are made for further research on application of the Na-K-Ca hydrogeothermometer in the temperature range 15 to 150°C.

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Signature Michael B Kaczmarek

Date June 17, 1974

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VITA

Michael Bernard Kaczmarek was born on May 7, 1945 in Missoula Montana. His parents are Bernard Kaczmarek (deceased) and Wilma Osmond Kaczmarek. He is married to the former Helen Phyllis Gruel of Portage, Montana and they have two children, Jennifer and John.

Michael graduated from Shelby High School in Shelby, Montana, in May of 1963. He entered Montana State University in Bozeman, Montana, in the fall of that year. After receiving his Bachelor of Science degree in Earth Sciences (Geology option) from that institution in August of 1968, he began four years of active duty as an officer in the Army Corps of Engineers.

Following their marriage on April 12, 1969; Michael and Helen lived 15 months in Sattahip, Thailand, and two years in Fort Lewis, Washington. Michael returned to Montana State University in August of 1972 where he has since held a Graduate Teaching Assistantship while working towards the degree of Master of Science.

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ABSTRACT

The base temperature of hot-water dominated hydrothermal systems can be quantitatively estimated using two different methods. One method uses the concentration of dissolved silica in the discharge wasters in equilibrium with respect to quartz. The other method is based on the Na, K, and Ca concentrations in the discharge waters in equilibrium with solid mineral phases in the wall rocks. Experimental studies and practical applications of these two hydrogeothermometers have been largely limited to the temperature range of 200 to 360°C. This paper presents some results of application of both methods in the temperature range 15 to 150°C.

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The hydrogeology of six Montana and one Idaho hot springs is presented herein. Base temperatures are calculated for each hydrothermal system and are evaluated as to their reliability. Suggestions are made for further research on application of the Na-K-Ca hydrogeothermometer in the temperature range 15 to 150°C.

INTRODUCTION

Purpose and Scope

Subsurface temperature of geothermal hot-water systems is a critical factor in determining the potential for power production in geothermal areas. Geochemistry of surface hot spring discharge waters is often a useful tool in estimating subsurface water temperatures. The two best chemical indicators (hydrogeothermometers) of subsurface temperatures in hot-water systems to date are dissolved silica content (Fournier and Rowe, 1966) and Na-K-Ca atomic ratios (Fournier and Truesdell, 1973). This paper discusses the application of the dissolved silica and Na-K-Ca hydrogeothermometers for estimating subsurface temperature of Montana hot-water systems. Salmon Hot Spring in Idaho is also discussed to provide an additional example of a specific geochemical relationship.

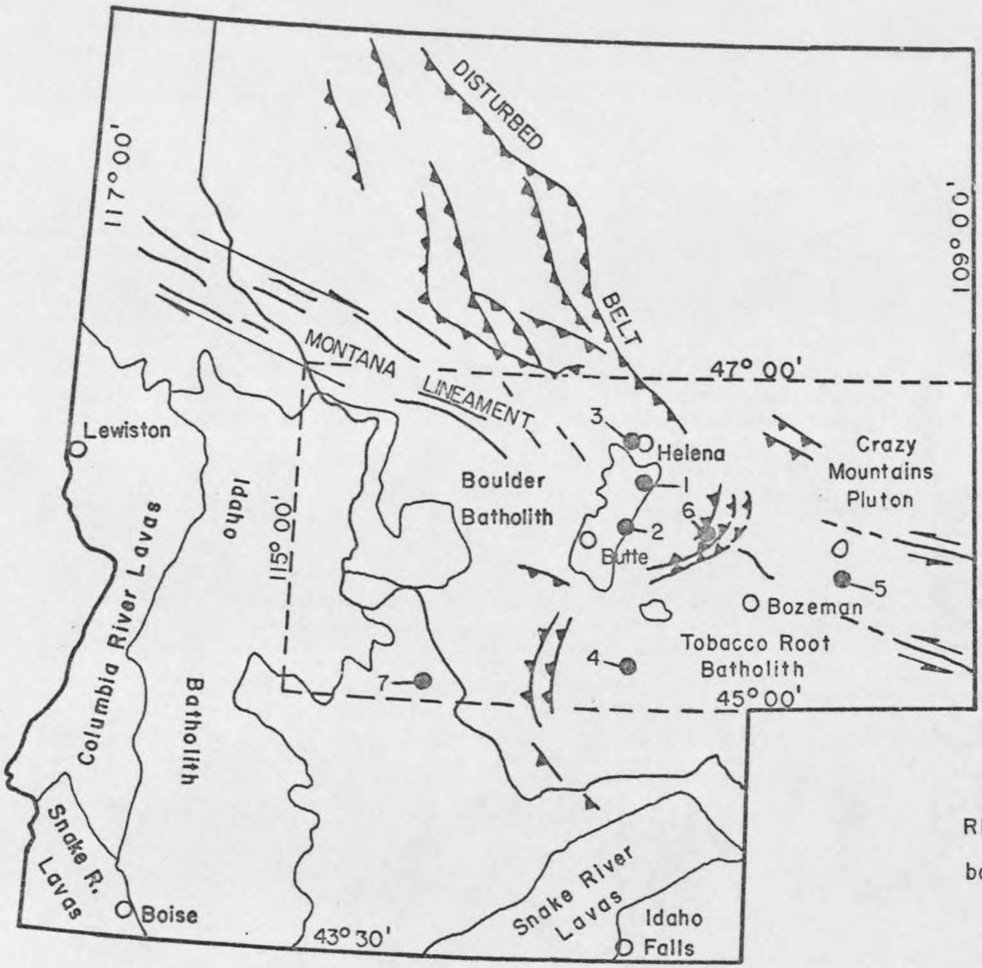
This paper presents a general overview of geology and geochemistry of hot spring areas in Montana. The six Montana hot spring areas examined in detail herein are representative of all of the types of hot-water geothermal systems (hydrothermal systems) currently known to exist in Montana. Montana hot springs are classified in this paper on the basis of the hydrologic nature of their subsurface flow systems as determined by local geology, and this classification scheme is presented in conjunction with the silica and Na-K-Ca hydrogeothermometers as a general method to further evaluate the economic potential of hydrothermal systems. Possible relations between hot springs in the western United States and regional tectonic features are explored in an attempt to establish guides to the occurence at depth of a commercially exploitable geothermal system.

Location and Physiography

Figure 1 depicts the general area investigated and shows the locations of the individual hot springs. The six representative Montana hot springs and the one Idaho hot spring lie within the Northern Rocky Mountains physiographic province except for Hunters Hot Springs, which is in the Great Plains physiographic province. Specifically, Alhambra, Boulder, and Helena Hot Springs discharge from Late Cretaceous quartz monzonite rocks of the Boulder batholith; Pullers Hot Springs discharges from Quaternary and Tertiary sediments in the intermontane Ruby River Valley, Hunters Hot Springs issues from Late Cretaceous sediments on the extreme southwestern flank of the Crazy Mountains Basin, and Big Spring near Toston discharges from deformed and faulted Amsden carbonates along the margin of an intermontane basin comprising the Townsend Valley. Salmon Hot Spring in Idaho issues from Tertiary age Challis Volcanics extruded through Tertiary sediments at the southern end of the intermontane Salmon Basin.

Methods of Investigation

Methods of investigation for this study were twofold and consisted of: (1) field mapping of surface geology of hot spring areas, and (2) field analysis of hot spring water for dissolved silica and laboratory analysis of hot spring waters for sodium, potassium, calcium, magnesium, and chloride concentrations. Appendix I describes analytical methods. Field studies were conducted from June 1973 through September 1973. Mapping was accomplished on



REGIONAL GEOLOGY AND HOT SPRING LOCATION

based on Geologic Map of North America by the USGS 1965

FIGURE 1

U.S. Geological Survey topographic quadrangles where coverage was available and on U.S. Department of Agriculture aerial photos, U.S. Forest Service base maps, and county land maps in other areas. Existing geologic maps from various sources were used to the extent available.

Previous Work

Excellent summaries of hot spring chemistry and geothermometry are provided by Ellis (1970), Mahon (1970), Tonani (1970), and White (1970). Known Montana hot spring locations and temperatures are summarized by Balster and Groff (1972). Thermal gradient measurements from oil and gas drill holes in the plains of eastern Montana are contoured on AAPG geothermal gradient maps of portions of the United States (AAPG 1973). Waring (1965) summarizes all literature referring to Montana and Idaho hot springs to that date including references to descriptions of Montana hot springs by Lewis and Clark (1814) and Mullan (1855). Significant early contributions are a tabulation of hot springs in the Montana Territory including six chemical analyses of waters by Peale (1886) and an excellent study of hot spring vein mineralization at Boulder Hot Springs by Weed (1900). Other early references provide brief descriptions of Montana hot springs and a few chemical analyses: Clark (1886), Weed and Pirsson (1896), Weed (1904, 1905), and Perry (1934). More recent contributions have been made in the field of heat flow studies by Blackwell (1969), Blackwell and Baag (1973), and Blackwell and Robertson (1973). Various workers too numerous to cite here have contributed to the knowledge of basic geology in Montana hot spring areas and will be referred to individually.

PHYSICAL CHARACTERISTICS OF HOT SPRINGS

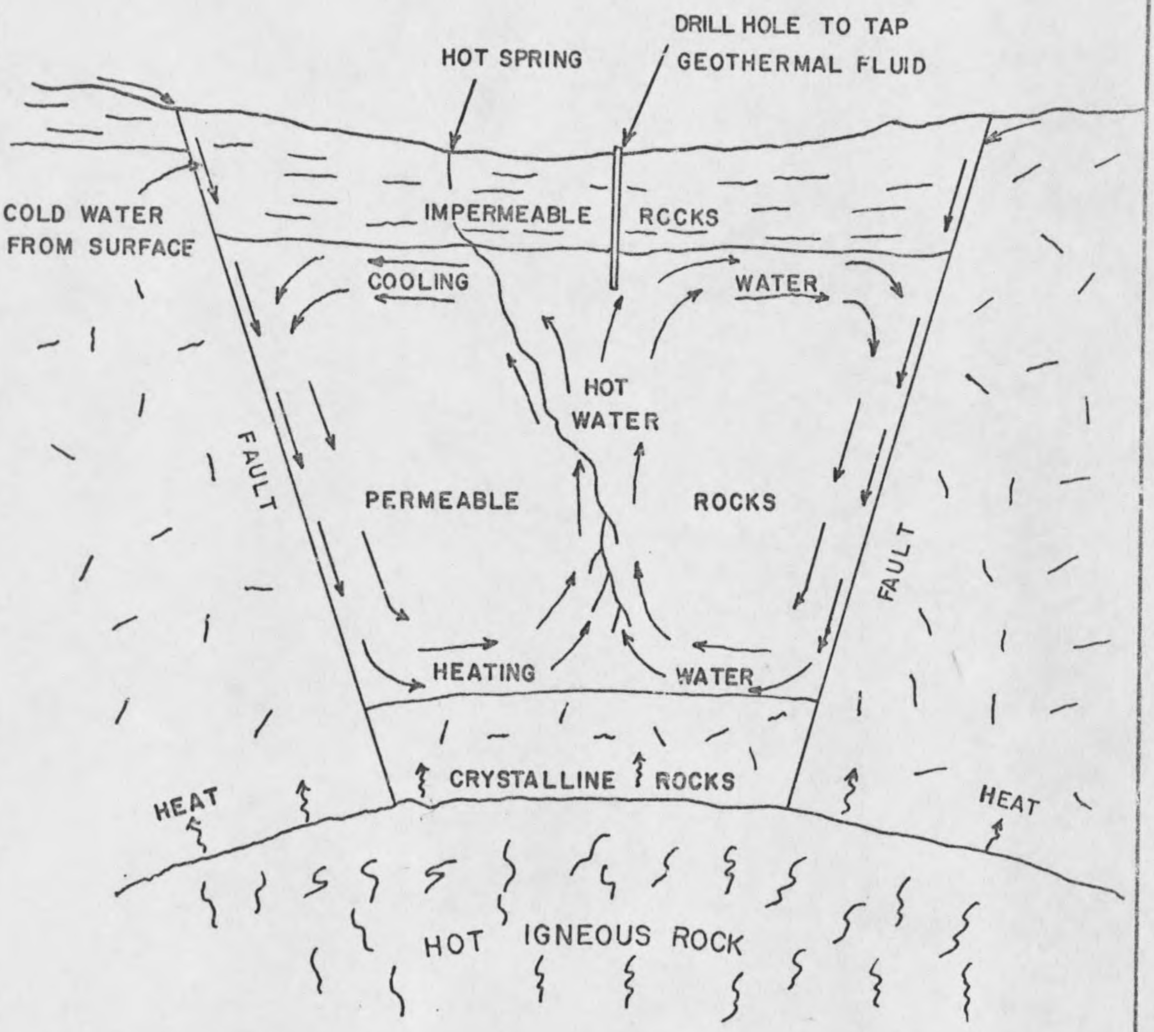
Hydrothermal Systems

Hot spring areas as well as geysers and fumaroles are the surface expression of geothermal systems which involve circulating waters; i.e., hydrothermal systems. A hydrothermal system (Figure 2) includes zones of convective up-flow of hot water as well as marginal zones of convective down-flow of cold recharge waters or recirculated thermal waters. Thus, the essential elements of a hydrothermal system discharging through a hot spring consist of a heat source, a circulation system, a source of recharge water, and the discharge system feeding the hot spring (Elder, 1965).

Heat Sources

Proposed sources of heat for hydrothermal systems include decay of radioactive elements, heat of friction along active faults, deep circulation of ground water and heating in equilibrium with the geothermal gradient, and heating of deep ground water by a cooling intrusive rock body. Proposed mechanisms to transfer heat from the source to the thermal water include derivation of geothermal water primarily from condensation of juvenile volcanic steam, heating of deep meteoric ground waters by heat transfer from juvenile volcanic steam (steam heating), and heating of deep circulating meteoric ground water due to conductive heat transfer from a cooling intrusive body.

Studies by Blackwell (1969) show that heat generation due to decay of radioactive elements in the earth's crust is not sufficient to support a hydrothermal system. A study of the San Andreas Fault by Henyey (1968) indicates



SKETCH OF MODEL HYDROTHEMAL SYSTEM

CROSS-SECTIONAL VIEW

AFTER

J. Eric Schuster (1973)

FIGURE 2

that heat generated by friction along active faults also is not adequate to produce hydrothermal systems.

Many hot springs probably result from deep circulation of meteoric waters in confined aquifers where the waters adjust to subsurface temperatures along the geothermal gradient, especially in areas of higher than normal regional heat flow. Hot springs of this type are discharging from low temperature hydrothermal systems in which the water temperature is a product of the geothermal gradient times the depth of circulation. Discharge of the heated water from depth must be fairly rapid to prevent heat loss back to the country rocks as the water ascends. Deep circulation of meteoric ground water in this type of system typically occurs in permeable fault zones or vertically deformed sedimentary aquifers.

It is necessary to explain the high temperatures and high dissolved solids concentration of some thermal waters in terms of a localized high-temperature heat source. The most acceptable model for a localized high-temperature heat source which satisfies geophysical and geochemical data for known geothermal areas and which is compatible with current geologic concepts is a cooling(?) rock body in the upper crust. Three mechanisms for heat transfer from a cooling magma or hot intrusive rock body to circulating thermal waters have been proposed.

Derivation of thermal waters primarily from condensation of juvenile volcanic steam has been considered possible by most early investigators of thermal waters. However, comparisons of the chemistry of surface ground water with deep thermal water by White (1957b) and comparisons of the O^{18}/O^{16} ratios of surface ground water with deep thermal waters by Craig (1963) and White (1968), as summarized by White (1970), indicate that at least 90 to 95 percent by mass of the water recharging most hydrothermal systems consists of local meteoric water. Similarly, it can be reasoned that if only about 5 percent of thermal water by mass is from juvenile sources, heating of deep meteoric ground water by juvenile volcanic steam or supercritical juvenile water would not be significant enough to explain the total heat flow of most hydrothermal systems (White, 1970). Though the isotopic evidence indicates a predominately meteoric origin for thermal waters, one might postulate that deep circulating meteoric ground water coming in contact or near contact with a cooling intrusive rock body may change temporarily to steam which in turn could transfer heat to the circulating ground water. However, thermodynamic considerations (James, 1968) render this concept invalid.

White (1968, 1970) and White, Muffler, and Truesdell (1971) suggest that heat from an intrusive body may be conducted through the surrounding country rocks where it is transferred to deep meteoric ground waters circulating through the heated country rocks without formation of a vapor phase. Circulation in the hydrothermal system may then result from thermal convection and flow along piezometric gradients intrinsic to the hydrologic system. Mathematical treatments by White, Muffler, and Truesdell (1971) and theoretical considerations presented by Tonani (1970) make this concept appear to be the most likely of the three presented here for a heat transfer mechanism transferring heat from a cooling intrusive body to deep ground water.

Temperature

Perhaps the most important characteristic of a hydrothermal system in terms of potential geothermal energy production is temperature. Temperature in a hydrothermal system increases with depth until a "base" temperature is reached (White, 1961 and Bovarrson, 1964) beyond which no significant increase of temperature with depth occurs. Under current geothermal technology, most turbines are designed for an absolute operating pressure of 5 kg/cm^2. Utilization of steam pressures lower than 5 kg/cm^2 requires construction of disproportionately larger turbines resulting in increased installation costs per unit of plant capacity and higher operational cost due to the less efficient utilization of the energy. The saturation pressure of steam is 5 kg/cm^2 at 150°C and thus geothermal reservoirs with a base temperature of less than 150°C are not currently of economic interest for power production. Reservoirs with base temperatures of 150 to 200°C may be economically developable where permeability is high and sufficient volume exists. Reservoirs with base temperatures above 200°C are especially attractive.

Hansen (1964) describes a process whereby low-temperature thermal waters might be used for geothermal power generation. Low-temperature thermal water is circulated through a closed heat exchange unit where heat is transferred at a constant temperature from the thermal water to a low boiling temperature working fluid. The vaporized working fluid is used to drive a turbine, condensed, and recycled to the heat exchanger in a closed circuit. This process could utilize water as a working fluid, however, the high heat of vaporization of water would make the process inefficient. Use of a volatile liquid such as freon may increase efficiency 2:1 over water (Hansen, 1964).

Theoretically, low-temperature thermal water over any range of temperature could be used in this process by building larger heat exchange units for lower temperature water. In practice, the available volume of thermal water and the construction costs of heat exchange units versus amortization will limit the temperature of utilization of thermal water to a practical minimum yet to be determined. Thus, even in utilization of low-temperature thermal water reservoir base temperature will continue to be a critical consideration in geothermal resources development.

Geohydrology

Hydrothermal systems may exist in an almost infinite variety of geologic settings. Regardless of the details of the local geology of a hydrothermal system, the physical geology of any individual hydrothermal system determines critical factors including boundary conditions and reservoir porosity and permeability. Boundary conditions dictated by geologic structure determine the extent and volume of a hydrothermal system. Volume and potential production can be estimated if stratigraphic units of known hydrologic properties can be identified and correlated with structure. Identification of fault zones and permeable aquifers may also facilitate recognition and location of potential zones of maximum production.

The existence of an impermeable cap formation may confine a hydrothermal system under static pressure thereby allowing a liquid water phase to exist at reservoir base temperatures sufficient to generate steam when the static pressure is released by means of a drill hole penetrating the cap formation. Confinement of a hydrothermal system under static pressure greatly reduces boiling and heat loss accompanying boiling and is probably a necessary condition for an economically exploitable reservoir. Consequently, a permeable aquifer overlain by an impervious formation constitutes the most favorable geologic setting for geothermal steam production, and structural or stratigraphic traps of this nature accompanied by high heat flow are the objectives of geothermal exploration.

An impervious cap may consist of any type of normally low-permeability rock strata such as siltstone or shale. Normally permeable sandstones and carbonates may act as impermeable cap formations if they are well cemented. In addition, the existence of self-sealing hydrothermal systems should not be overlooked.

Facca and Tonani (1967) suggest that silica deposition may be an important mechanism of self-sealing at depth, and calcium carbonate deposition and argillization may act as shallow sealing mechanisms. Silica deposition is the most likely sealing mechanism at depth where steam loss from boiling waters with temperatures above 150 to 180°C results in supersaturation of water with silica and subsequent silica precipitation. At lower temperatures near the surface, heating of descending recharge water causes loss of CO_2 and subsequent precipitation of calcite. Vapor from ascending boiling waters may include H_2S and CO_2.

which react with atmospheric oxygen and water, respectively, to form acids which in turn cause argillization of wall rocks. The Geysers field in California and Wairakei and Waiotapu in New Zealand are cited as examples. White, Muffler, and Truesdell (1971) point out that silica self-sealing is probably not significant in hydrothermal systems with base temperatures below 150°C due to lack of silica concentrations sufficient to result in supersaturation even with steam loss, and that self-sealing is most extensive where water temperatures decrease most rapidly during discharge of water from the hydrothermal reservoir.

Facca (1969) describes the detection of self-sealed areas by geophysical means in volcanic reservoir rocks in South America and the United States. Self-sealed areas appear as magnetic low anomalies due to oxidation of magnetite to hematite during the hydrothermal alteration producing the sealed zone. The alteration and the increased temperature result in low resistivity. Thus magnetic lows correlating with low resistivity indicate self-sealed areas whereas magnetic highs correlating with low resistivity indicate unsealed areas of thermal water circulating in unaltered rocks with unoxidized magnetite content.

The magnitude of trapped heat available for geothermal power exploitation is determined by the reservoir dimensions and temperature; however, the productivity is determined by the reservoir permeability and recharge volume (Facca and Tonani, 1961). Thus hot-water systems in permeable sedimentary or volcanic rocks may have more potential for steam production than systems in open channels in fractured or faulted massive rocks such as granite where the reservoir volume or water supply is limited. Similarly, hydrothermal systems in sedimentary or volcanic strata with permeabilities that are too low will not provide satisfactory steam production despite adequate reservoir base temperatures (Brown, 1970).

Reservoir Fluid Phases

Wells penetrating hydrothermal systems may yield dry or superheated steam with little or no associated liquid water. Examples are The Geysers steam field, California and the Larderello steam field, Italy. Most hydrothermal systems yield hot water when penetrated by drill holes as at Wairakei, New Zealand and Steamboat Springs, Nevada. Part of the water flashes to steam due to decreasing pressure as the hot water rises up the drill hole. The result is a mixture of hot water and steam at the surface. Steam may comprise 10 to 20 percent of the total mass flow (White, Muffler, and Truesdell, 1971). Other hydrothermal systems may yield only hot water and negligible steam due to base temperatures which are inadequate for steam generation or barely above the boiling point at the hydrostatic pressure of the system. In systems of this type, increasing hydrostatic pressure with depth in the reservoir limits boiling to the upper 20 to 30 feet below the water surface; however, conduction of heat from the ascending thermal water into the wall rocks probably cools the water to the point where no boiling occurs in the system at all. As an alternative, such a system could be pictured as a column of water under normal hydrostatic pressure and everywhere at its boiling point. Either gentle boiling with minimal steam separation or conductive heat loss to the wall rocks would maintain water temperature in the