International Symposium on Regional Groundwater Flow:
Theory, Applications and Future Development

Yellowstone National Park: Regional Groundwater Dynamics in High-Temperature Geothermal Areas

K. Udo Weyer and James C. Ellis
WDA Consultants Inc., 4827 Vienna Drive NW, Calgary, Canada, T3A 0W7
Email: weyer@wda-consultants.com

1. Introduction

The volcanic caldera at Yellowstone National Park (YNP, Figure 1) has been selected for documenting the physical processes which concentrate the flow of geothermal water to discharge areas of gravitationally-driven regional groundwater flow systems. At Yellowstone, the location of the hotspot has been static with reference to the earth mantle but has, over the last 12.5 million years, migrated about 400 km along the Snake River Plain due to the westward movement of the North American plate. The depth of the rhyolite magma chamber is thought to be about 5 km within the crust while in the deeper part of the crust a basaltic magma chamber resides at about 25 km depth (Figure 2).

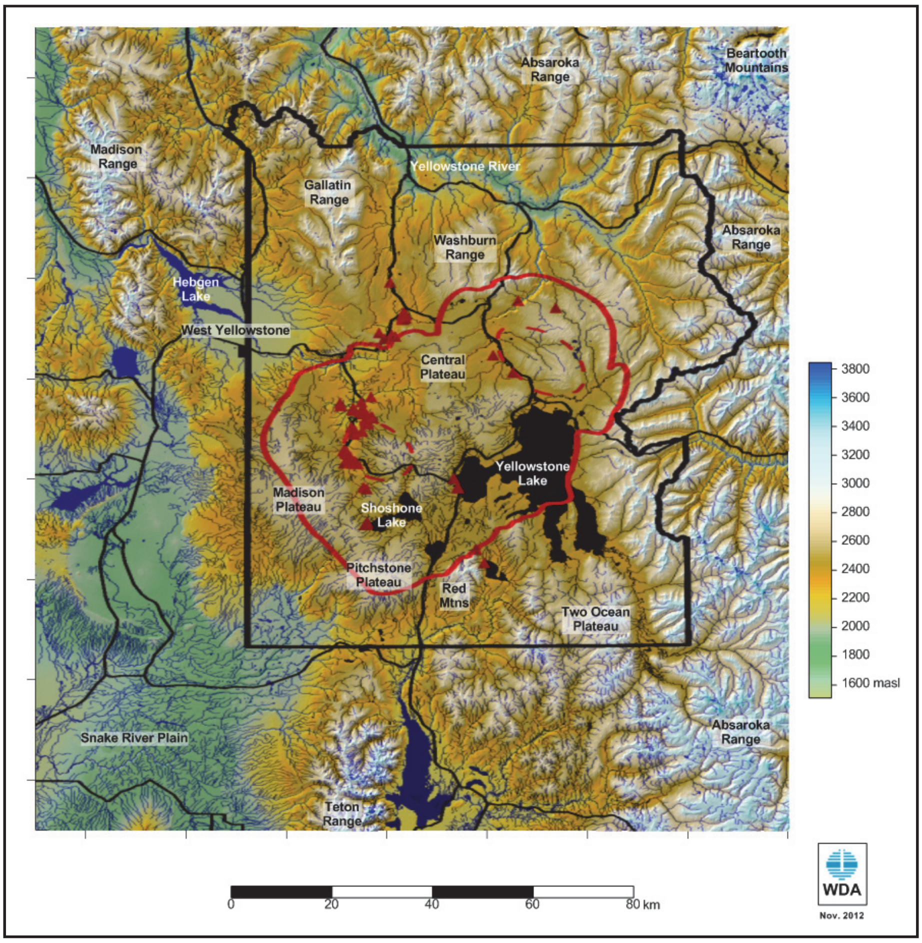
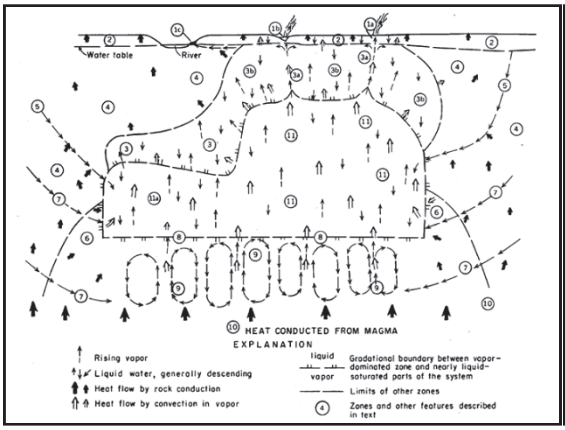


Figure 1. Bird's-eye view of Yellowstone DEM showing location of geysers (red triangles). Geyser locations extracted from http://www.geyserstudy.org and YNP Thermal Features database: http://www.rcn.montana.edu/resources/features/features.aspx. (Thick black line shows outline of Yellowstone Park; solid red line shows outline of caldera; dashed red lines show resurgent domes.)



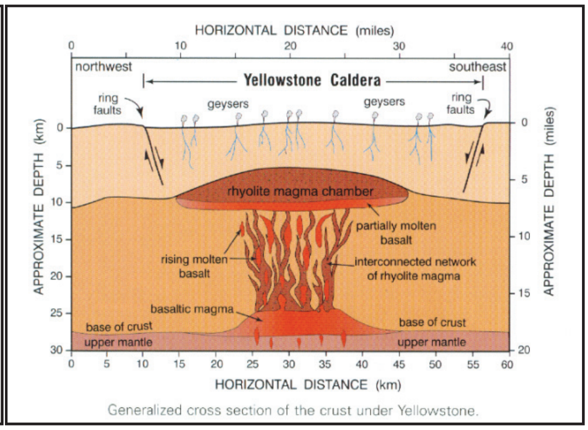


Figure 2. Geologic cross-section at YNP. By permission Hendrix (2011, p146).

Figure 3. Assumed convection cells in YNP (White et from al., 1971, Figure 7).

2. Geothermal groundwater physics

Buoyancy driven groundwater flow is often thought to be the motor for flow of geothermal groundwater within convection cells (Figure 3). This is, however, not the case under hydrodynamic conditions prevailing onshore [*Weyer*, 2010]. Convection cells may, however, develop offshore under hydrostatic conditions. On land, gravitationally-driven groundwater flow systems occur as described by *Tóth* [1962] and *Freeze and Witherspoon* [1967]. They are caused by topographical elevation differences between recharge and discharge areas. These flow systems may penetrate to depths exceeding 5 km [*Tóth*, 2009]. The underlying physics of Force Potential Theory has been summarized by *Hubbert* [1940] and extended for 'Buoyancy Reversal' by *Weyer* [1978]. Fluid flow in the surface is driven by force potentials not by velocity potentials as assumed in Continuum Mechanics [*Bear*, 1972]. Continuum Mechanics takes the pressure gradient (grad p) as the driving force for subsurface fluid flow. That is, however, physically incorrect. Hence all geothermal modelling based on continuum mechanical principles and assumptions leads to unreliable results.

3. Groundwater Recharge at Yellowstone National Park

Before the 1970s, groundwater recharge for the geysers in Yellowstone National Park was thought to be on the nearby rhyolite plateaus, such as the Madison Plateau, the Central Plateau, and others. The application of deuterium isotope studies then resulted in the birth of a new concept caused by measured and back-calculated isotope values [*Truesdell et al.*, 1977; *Fourier*, 1989]. The new concept argued that the recharge of the deep groundwater was to have taken place at colder temperatures either in the high areas of the Gallatin Range or dating back to the Pleistocene. During the Pleistocene age Yellowstone National Park was covered by ice caps/glaciers on two occasions: (1) about 150,000 years ago at the height of the Bull Lake glaciation (covering much of the West Yellowstone Basin), and (2) about 17,000 to 20,000 years ago at the peak of the Pinedale glaciation (covering much of YNP).

By applying various chemical and isotopic methods [*Fourier*, 1989] it has been argued that only 0.2 to 3% of the discharged groundwater originated from the magma chambers. The other 97+% would have recharged at the surface, penetrated to depth, and subsequently ascended to the surface by buoyant forces to discharge as hot springs and geysers. Hydrograph base flow evaluations of the Firehole and Gibbon Rivers indicate that the groundwater discharge in their catchment basins would be approximately 7.5 m3/s and 2.5 m3/s respectively [*Gardner et al.*, 2010]. Transmission of these amounts through major fault zones only (as is often assumed) does not appear to be feasible for two reasons: (1) the large amount of flow, and (2) the role of groundwater dynamics. Recharge from the ice sheet and delayed discharge is improbable due to time delays, relatively high permeabilities and hydraulic gradients involved. Additional stable isotope investigations by *Gardner* [2009] on deuterium, oxygen and noble gases and their interpretation [*ibid*, p.73] indicate that the previous and new data do not need recharge by cold waters in Gallatin Mountains or during the Pleistocene. In fact, proponents of the previous concept used geologic reasoning to assume simple groundwater systems which can neither be supported by Continuum Mechanics [*Bear*, 1972] nor by *Hubbert's* [1940] Potential Theory.

4. Groundwater temperatures

White et al. (1971) report water temperature gradients for the geyser areas of YNP, whereby the temperature at 1 km depth would be <310°C. Nevertheless, at greater crustal depth and closer to the rhyolite magma chamber, temperature and pressure would exceed the critical point of water (373°C at 25 MPa). At the critical point water exists as liquid, supercritical fluid and as vapour simultaneously. Any upward deviation of temperature or pressure would directly cause the water to turn supercritical. Under supercritical conditions water loses its surface tension enabling it to penetrate low permeable geologic layers with much higher efficiency than liquid water possessing surface tension. The water content of magma is sufficient to sustain significant flow of supercritical water upwards into the domain of liquid water. Supercritical water is subject to the same hydraulic force fields as liquid water. Due to very significant density reduction for supercritical water as compared to liquid water, the resultant flow directions within the same force field will be very different than the flow directions for liquid water. As under discharge areas the supercritical water may occur at a depth of only 2 km, the low percentage (above: 0.2 - 3 %) of water released by the magmatic chambers probably needs to be revised upwards significantly.

5. Conclusions

The application of Hubbert's Potential Theory and Groundwater Flow Systems Theory leads to an improved understanding of the role of groundwater recharge on the various Yellowstone Plateaus, supporting the occurrence of thermal areas and geysers. In the area of silica dominated dissolution processes (Upper, Midway and Lower Geyser Basins) and other dissolution processes (Norris Geyser Basin) permeabilities are continuously enhanced by heated water flow thereby improving the effectiveness of both shallower and deep regional groundwater flow systems. The groundwater recharge calculated from base flow and surface catchment areas to the groundwater flow systems exceeds 350 mm precipitation per annum for the Firehole River basin and 270 mm precipitation per annum for the Gibbon River basin and may locally be considerably higher.

We argue that the concept of recharge on the adjacent plateau mountains into shallow and deep groundwater flow systems and the application of modern gravitational groundwater dynamics is a simple, straightforward, and physically consistent explanation for the occurrence of discharge in thermal areas of the Yellowstone National Park, within and outside of the reach of the present Yellowstone caldera. The systems are not driven by convection or buoyancy forces. The application of gravitational groundwater dynamics withstands the necessary and unforgiving test of physical causality in applying groundwater flow to geological processes.

References

Bear, J. (1972), Dynamics of Fluids in Porous Media. American Elsevier Publishing Company Inc., New York, New York, United States.

Fournier, R. O. (1989), Geochemistry and dynamics of the Yellowstone National Park hydrothermal system, Annual Review of Earth and Planetary Sciences, 17, 13-53.

Freeze, R. A., and P. A. Witherspoon (1967), Theoretical analysis of regional groundwater flow: 2. Effect of water table configuration and subsurface permeability variation, Water Resources Research, 4 (3), 581-590.

Gardner, W. P. (2009), Groundwater dynamics of the Norris Geyser basin area, Ph.D. thesis, University of Utah, Salt Lake City, Utah, United States.

Gardner, W. P., D. D. Susong, D. K. Solomon, and H. Heasler (2010), Snowmelt hydrograph interpretation: Revealing watershed scale hydrologic characteristics of the Yellowstone volcanic plateau, Journal of Hydrology, 385, 209-222.

Hendrix, M. S. (2011), Geology underfoot in Yellowstone Country, Mountain Press Publishing Company, Missoula, Montana, United States.

Hubbert, M. K. (1940), The theory of groundwater motion, Journal of Geology, 48 (8), 785-944.

Lowenstern, J. B. and S. Hurwitz (2008), Monitoring a supervolcano in repose: Heat and volatile flux at the Yellowstone caldera, Elements, 4, 35-40

Tóth, J. (1962), A theory of groundwater motion in small drainage basins in Central Alberta, Canada, Journal of Geophysical Research, 67(1), 4375-4387.

Tóth, J. (2009), Gravitational systems of groundwater flow; Theory, Evaluation, Utilization, Cambridge University Press

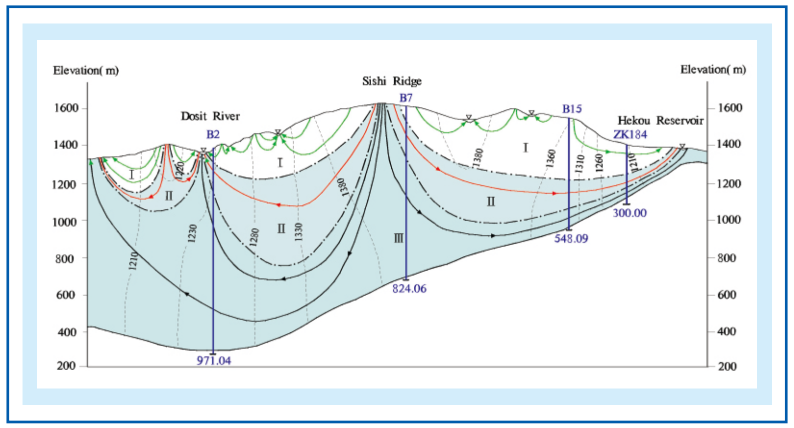
Truesdell, A. H. M., M. Nathenson, and R. O. Rye (1977), The effects of subsurface boiling on the isotopic compositions of Yellowstone thermal waters, Journal of Geophysical Research, 82(26), 3694-3704.

Weyer, K.U. (1978), Hydraulic forces in permeable media, Mémoires du B.R.G.M., (91), 285-297 [available from http://www.wda-consultants.com].

Weyer, K.U. (2010), Differing physical processes in off-shore and on-shore CO2 sequestration, paper presented at GHGT-10, Amsterdam, The Netherlands [word version of poster available from http://www.wda-consultants.com].

Proceedings of the International Symposium on Regional Groundwater Flow: Theory, Applications and Future Development

21-23 June 2013, Xi'an, China

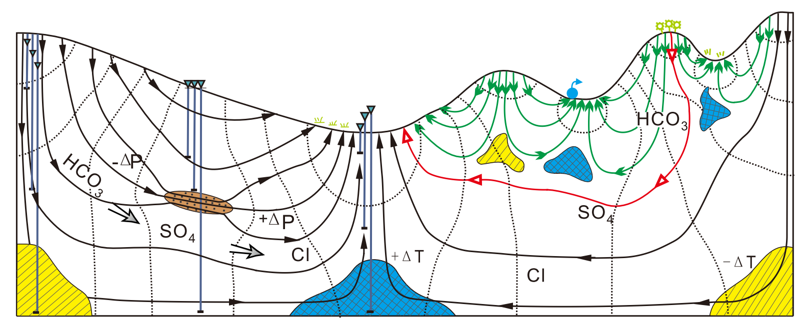


Printed by China Geological Survey

Proceedings of the International Symposium on Regional Groundwater Flow
21-23 June 2013, Xi'an, China

Proceedings of the International Symposium on Regional Groundwater Flow: Theory, Applications and Future Development

21-23 June 2013, Xi'an, China



China Geological Survey
Commission on Regional Groundwater Flow, IAH