Geothermal Power from Coproduced Fluids in the Williston Basin

Will Gosnold[1], Richard LeFever[1], Robert Klenner[1], Michael Mann[1], Hossein Salehfar[1], and Joel Johnson[2]

[1]University of North Dakota
[2]Berrendo Geothermal

Keywords

Coproduced fluids, oil field, geothermal, organic Rankine cycle

ABSTRACT

All sedimentary basins have potential for development of geothermal power due to the existence of deep aquifers having sufficient temperatures and high fluid production capacities. Advances in commercial development of organic Rankine cycle (ORC) and other heat-to-power conversion technologies make geothermal power generation economical with water temperatures as low as 90 ºC and flow rates of 30,000 bbls/day. The Williston Basin in particular possesses several advantageous characteristics for oil field geothermal power: 1) high geothermal gradients which lead to high temperatures at relatively shallow depths, 2) a large number of permeable formations that are producing oil and are capable of producing hot water, 3) a cool climate, which provides a large temperature drop for the ORC process, 4) a highly-developed petroleum industry infrastructure with a large demand for additional electrical power. This paper provides an overview of the potential to use coproduced fluids to generate electrical power.

The Williston Basin

The Williston Basin is a large cratonic basin extending over 933,000 km^2 including parts of the Dakotas, Montana, Manitoba, and Saskatchewan (Figure 1). The maximum thickness of sedimentary rock is about 4,900 meters, and all rock systems from Cambrian through Quaternary are present. The Paleozoic strata in the basin are largely carbonate rocks, while the Mesozoic and Cenozoic rocks are predominantly clastics. The basin includes more than 54 distinct formations, 20 of which produce oil and water having temperatures in the range of low-to-intermediate geothermal resources (65 °C to 150 °C). The basin has produced an estimated 3.8 billion bbls of oil through 2009, primarily from Paleozoic reservoirs. Recent activity in the basin has focused on the Bakken and Three Forks formations (Devonian-Mississippian), which have been estimated to contain more than 400 billion bbls of original oil in place (Polastro et al., 2008; Nordeng and Helms, 2010). More than 100 drill rigs were operating in the basin in the first quarter of 2010, and it is estimated that an additional 10,000 wells will be drilled by 2025 (Seifert, 2010).

Geothermal Gradients and Subsurface Temperatures in the Williston Basin

An important characteristic of the basin is that the 1 to 2 km thick Mesozoic and Cenozoic clastic rocks are predominately shale and have low thermal conductivities. Measured thermal conductivities of the Pierre Shale (Cretaceous), which is the thickest shale formation range, from 1.2 W m^{-1} K^{-1} (Sass and Galanis, 1983; Gosnold, Todhunter and Schmidt, 1997) to 0.9 W m^{-1} K^{-1} (Gosnold et al., 2010). Heat flow in the basin is about 40 to 60 mW m^{-2}, thus geothermal gradients in the shale sections are on the order of 40 to 60 K km^{-1} (Table 1).

The effect of variable thermal conductivity within the stratigraphic column is evident in temperature vs. depth measurements in three deep boreholes in western North Dakota (Figure 2). The low conductivity clastic formations extend to about 1600 m and

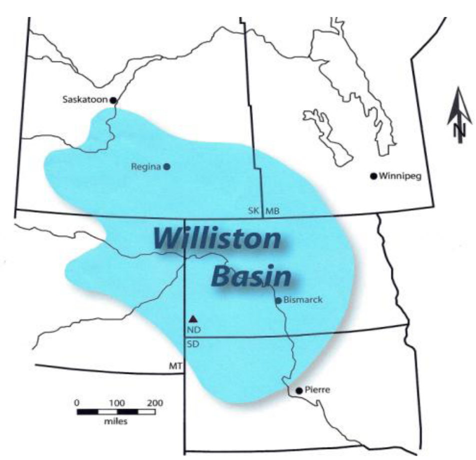

Figure 1. Location of the Williston Basin.

Table 1. Stratigraphic column of the Williston Basin with thermal conductivity and geothermal gradient values. * Indicates thermal conductivity inferred from the temperature gradient assuming constant heat flow. Ss=sandstone, Siltst=siltsone, Sh=shale, Ls=limestone, Do=dolomite, Anhyd=anhydrite

System	Group or Formation	Dominant Rock Type	Maximum Thickness (m)	Thermal Cond. (W/m/K)	Temperature Gradient (K/km)
Quaternary	Cole Harbor	Siltst/Clay/Sand	300	1.1*	55
Tertiary	White River	Siltst/Clay	75	1.1*	55
	Golden Valley	Siltst/Clay	95	1.1*	55
	Fort Union	Siltst/Clay	600	1.1*	55
Cretaceous	Hell Creek	Ss/Do/Sh	150	1.3*	46
	Fox Hills	Siltst/Sh	400	1.3*	46
	Pierre	Sh	700	1.1	55
	Colorado	Sh	345	1.1*	55
	Dakota	Sh/Ss	275	1.7*	35
Jurassic	Morrison	Sh/Siltst	80	2.3*	26
	Swift	Sh/Ls	150	2.3*	26
	Rierdon	Sh/Siltst	30	2.4*	25
	Piper	Sh/Ls/Do/Ss	190	2.4*	25
Triassic	Spearfish	Sh	225	1.2*	50
Permian	Minnekahta	Ls	12	2.7*	22
	Opeche	Sh	120	1.2*	50
Pennsylvanian	Minnelusa	Ss/Do/Sh	315	2.7*	22
Mississippian	Big Snowy	Sh/Ls/Ss	135	2.4*	25
	Madison	Ls	600	2.5	24
	Bakken	Sh	35	1.2	50
Devonian	Three Forks	Siltst/Sh	75	2.1	29
	Duperow	Do/Ls	140	3.0	20
	Souris River	Do/Ls	105	2.3	26
	Dawson Bay	Do/Ls	55	2.7	22
	Winnipegosis	Ls	55	2.7	22
	Elk Point	Do/ Ls/Anhyd	320	3.1	19
Silurian	Interlake	Do / Ls	335	4.2	14
	Stonewall	Do / Ls	35	3.9	15
Ordovician	Stony Mt.	Do / Ls	60	3.9	15
	Red River	LS / Do	215	3.3	18
	Winnipeg	Do / Ss	125	4.2	14
Cambrian	Deadwood	Do / Ss	300	3.3	18

have an average geothermal gradient of 45 K km^{-1}. The higher conductivity carbonates underlying the shales have an average temperature gradient of 26 K km^{-1}, which decreases as the higher conductivity dolomitic fraction increases (Table 1).

The increase in temperature gradient with depth in the shale sections is unexpected, and we offer two plausible explanations that require further study. The first is that the composition of fluids in the pore space of the shale changes with depth as methane generation occurs. Thermal conductivity would decrease as methane content increases causing an increase in the temperature gradient. However, compaction with depth would cause an increase in thermal conductivity that could offset the effect of increased methane content. We calculated the effect of compaction on porosity from: $\boldsymbol{\phi=\phi_0 e^{-cz}}$, where ϕ is porosity, **c** is a constant = 0.0005, and **z** is depth. The result was used to calculate thermal conductivity from $\boldsymbol{\lambda = (\lambda_w^{\phi})(\lambda_r^{1-\phi})}$, where $\boldsymbol{\lambda_w}$ is thermal conductivity of water and $\boldsymbol{\lambda_r}$ is thermal conductivity of rock. We have no data to quantitatively assess the effect of methane, thus the need for additional study.

The second explanation is that the curve is due to a strong post-glacial warming signal. This effect would mean that esti-

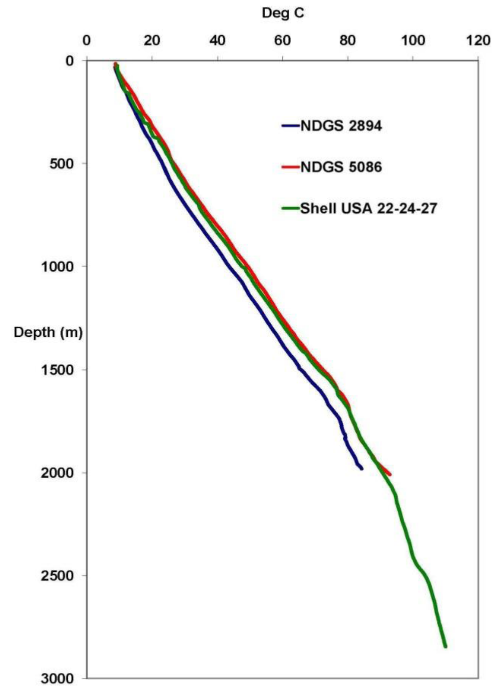

Figure 2. Temperature vs. depth plots for three wells in the Williston Basin measured under thermal equilibrium conditions. Temperature gradients in the clastic upper section average 45 K km-1 and show an increase with depth from 40 K km-1 to 61 K km-1. Temperature gradients in the carbonate-dominated lower section average 26 K km-1. NDGS 2894 and NDGS 5086 from Scattolini (1978), Shell USA 22-24-27 from (Blackwell, pers. comm.).

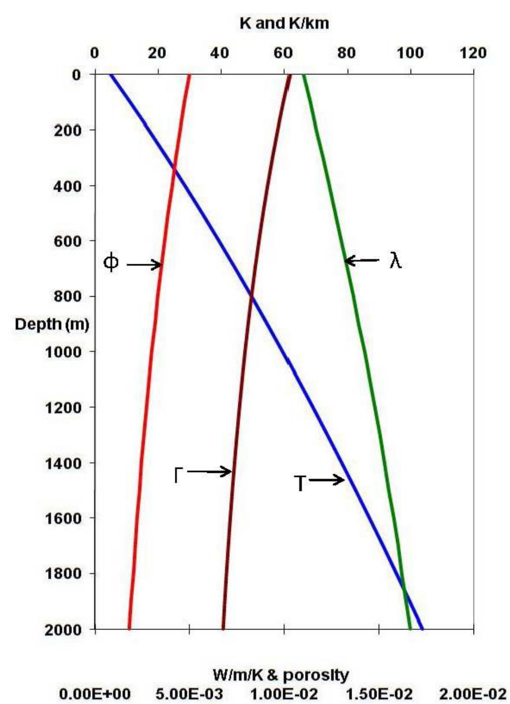

Figure 3. The effect of compaction on porosity (ϕ), thermal conductivity (λ), temperature gradient (Γ), and temperature (T) vs. depth. The effect of compaction on porosity is $\phi=\phi_0 e^{-cz}$, where ϕ is porosity, c is a constant = 0.0005, and z is depth. Thermal conductivity varies with porosity as: $\lambda = (\lambda_w^{\phi})(\lambda r^{1-\phi})$, where λ_w is thermal conductivity of water and λ_r is thermal conductivity of rock.

mates of heat flow for the region are low due to the effect on post-glacial warming on the geothermal gradient to depths of about 2 km. This possibility could be relevant for estimating Enhanced Geothermal Systems (EGS) resources to depths of 10 km. This explanation also requires additional study, specifically measurement of thermal conductivity and temperature vs. depth throughout the upper 2 km of shale.

Range of Low Temperature Geothermal Resource

We suggest a general range for low-temperature geothermal potential in the basin by presenting contour maps of the temperatures and depths of the uppermost and lowermost formations with potential for geothermal development. The shallowest formation having adequate temperatures and water production potential in the basin is the Lodgepole Formation, a member of the Madison Group (Mississippian), and the deepest formation is the Deadwood (Cambrian), which lies on the crystalline basement. We used heat flow, thermal conductivity and formation elevation data to generate temperature vs. depth profiles for the basin. From these we generated temperature contour maps (Figures 4 and 6) and structure contour maps (Figures 5 and 7). Approximately 2 km of Paleozoic carbonate formations lie between the Madison and Deadwood formations. Thus, the overall potential for geothermal fluids within the temperature range of 65 °C to 150 °C is significant.

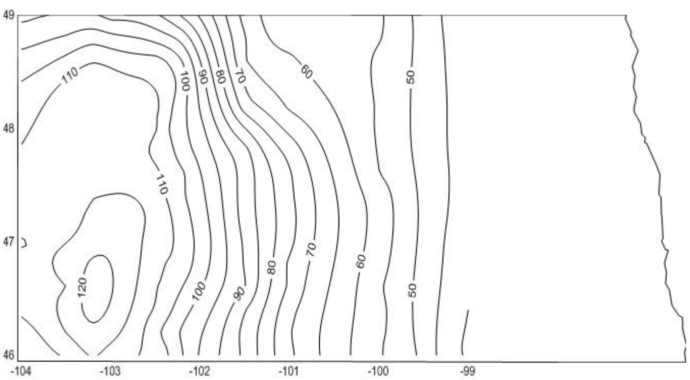

Figure 4. Temperature contour map in degrees Celsius on top of the Madison Group for the North Dakota portion of the Williston Basin. The Madison Group consists of limestones and includes the Lodgepole, Mission Canyon, and Charles formations. It has a maximum thickness of 753 m in the deeper parts of the basin.

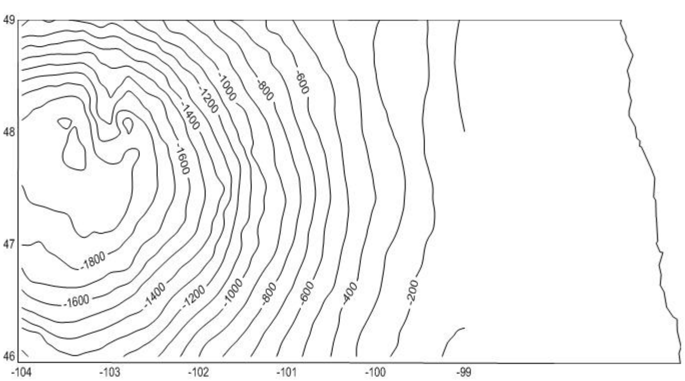

Figure 5. Structure contour map on top of the Madison Formation in meters. The top of the Lodgepole lies at variable depths up to 300 m below the top of the Madison.

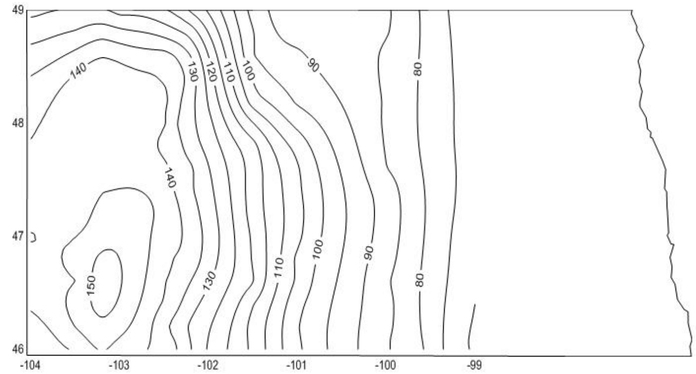

Figure 6. Temperature contour map in degrees Celsius on top of the Deadwood Formation (Cambrian) for the North Dakota portion of the Williston Basin. The Deadwood Formation consists of limestone, sandstone, and shale and has a maximum thickness of 300 meters in the deeper parts of the basin.

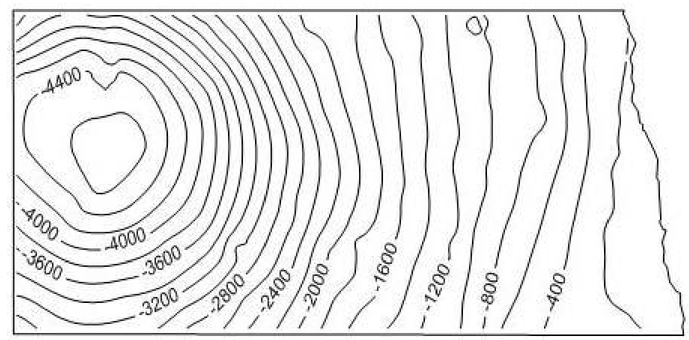

Figure 7. Structure contour map of the Deadwood formation in the North Dakota portion of the Williston Basin. The Deadwood formation rests on the preCambrian basement throughout the region and varies in thickness from a few tens of meters to a maximum of 300 m.

Power Generation and an Initial Project

The key to developing the low temperature geothermal resource is the development of small-scale power conversion systems. Binary power plants using ORC technology have operated for the past few decades at many geothermal sites where high temperatures and large water volumes allow generation of tens of MW. However, the economics of producing power from the lower fluid volumes and lower temperatures available in sedimentary basins have not been competitive with other power sources. This appears to be changing with new development of small-scale binary power systems using ORC, Kalina cycle, and other innovative concepts. An advantage for the Williston Basin is the region's cool climate has a mean annual temperature of 10 °C (50 °F) which allows for more efficient air-cooling for the condenser phase of the binary power cycle.

The University of North Dakota, Berrendo Geothermal, and two oil producers have initiated projects with funding from the US Department of Energy to evaluate the technologic and economic feasibility of generating electricity from low-temperature coproduced fluids in an active oil field in the Williston Basin. The projects will be conducted in three phases: 1) evaluation and design, 2) operation and analysis, 3) commercial operation. Phase 1 focuses on evaluating the power capacity, efficiency, and economics of commercially available power conversion systems. Phase 2 involves installation and O & M of the systems to further develop engineering and economic models for geothermal production. Phase 3 will begin a commercial operation with formation of an LLC that will begin selling power to the local utility.

References

Blackwell, D.D., Pers. comm.

Gosnold, W. D., Jr., Todhunter, P. E., and Schmidt, W., 1997, The borehole temperature record of climate warming in the mid-continent of North America: Global and Planetary Change, v. 15, no. 1-2, p. 33-45.

Gosnold, W., LeFever, R., Mann, M., Klenner, R., and Salehfar, H., 2010, EGS potential in the midcontinent of North America, GRC Tranactions, this volume.

Nordeng, S.H., and Helms, L.D., 2010, Bakken Source System, Three Forks Formation Assessment: North Dakota Department of Mineral Resources, 22 p.

Pollastro, R.M., Cook, T.A., Roberts, L.N.R., Schenk, C.J., Lewan, M.D., Anna, L.O., Gaswirth, S.B., Lillis, P.G., Klett, T.R., and Charpentier, R.R., 2008, Assessment of undiscovered oil resources in the Devonian-Mississippian Bakken Formation, Williston Basin Province, Montana and North Dakota, 2008: U.S. Geological Survey Fact Sheet 2008–3021, 2 p.

Sass, J. H., and Galanis, S. P., 1983, Temperatures, thermal conductivity and heat flow from a well in Pierre Shale near Hayes, South Dakota: U.S. Geol. Survey Open-file Rept. 83-25, 10 pp.

Scattolini, R., 1978. Heat flow and heat production studies in North Dakota, PhD dissertation, University of North Dakota.

Seifert, L., 2010, A Basic Analysis of the Bakken Oil Boom: Precautions and Planning, 2010 Williston Basin Petroleum Conference and Expo, Bismarck, ND.