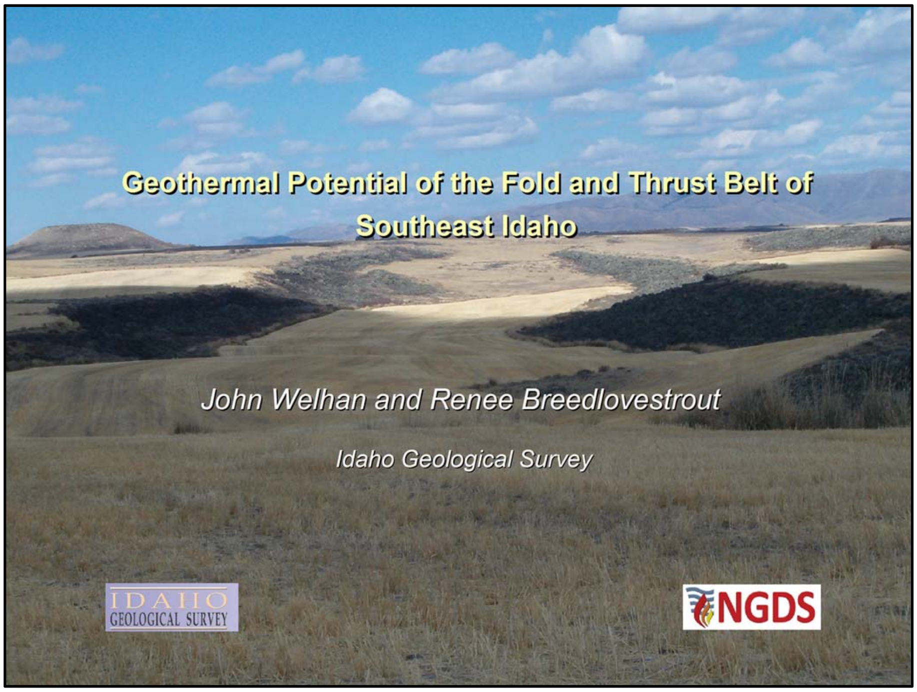
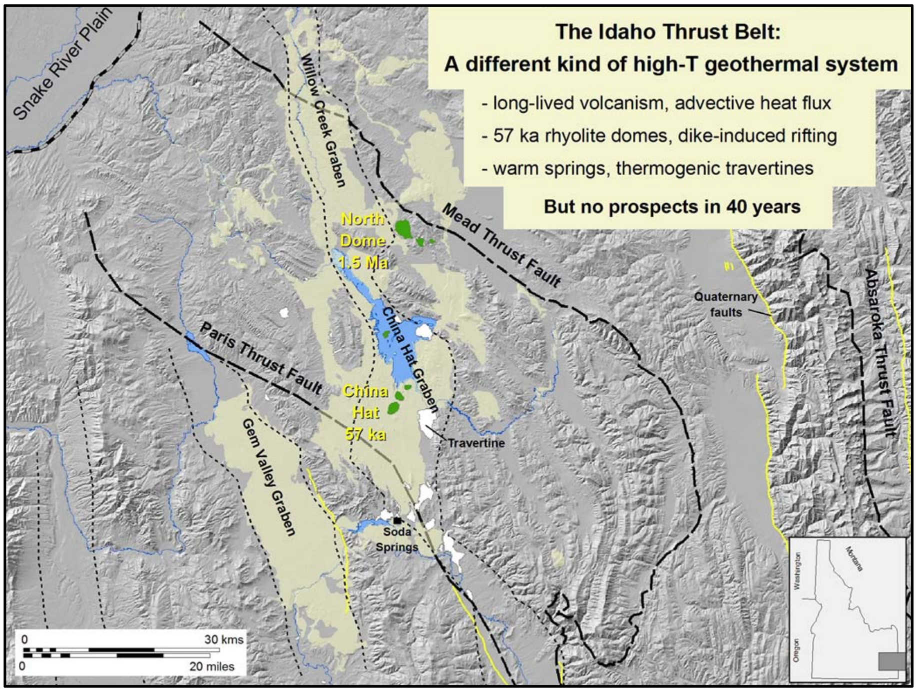


This paper summarizes what we know about a fascinating, previously unknown hi-T geothermal system in SE Idaho

that came to light during the compilation of geothermally relevant data for the DOE's National Geothermal Data System (NGDS) program that was
created to help promote geothermal exploration and development.

This is a view, looking north, of part of the Blackfoot volcanic field (BVF) ca. 20 km north of Soda Springs, ID, showing a volcanic rift valley that
developed in response to dike injection and the eruption of three rhyolite lava domes <1 km east of this location within the last 100,000 years or so.

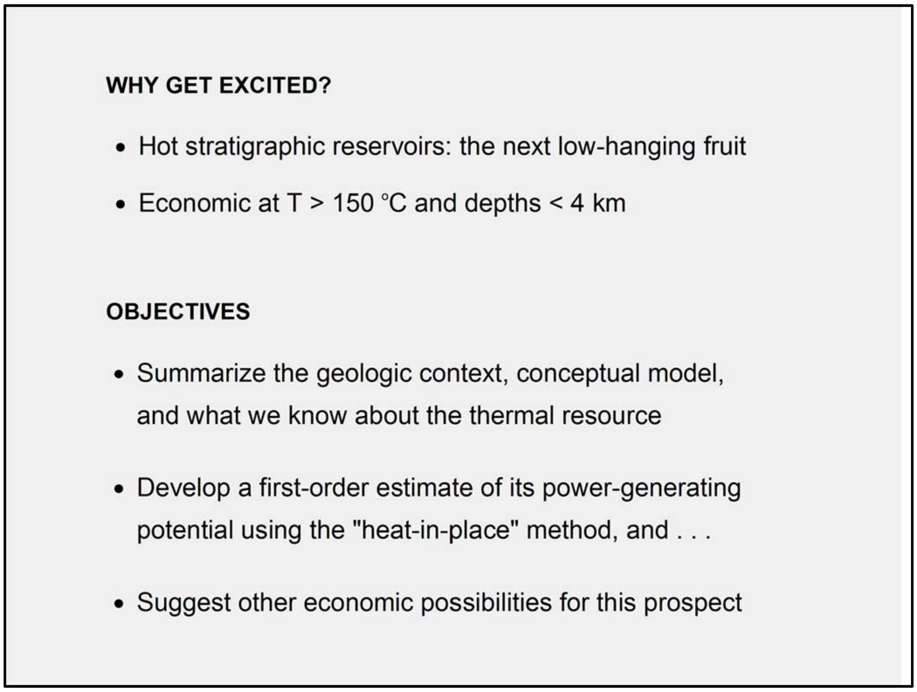


This is the BVF, a long-lived bimodal volcanic field with two rhyolite lava dome fields.

The oldest erupted 1.5 Ma, which indicates that this is a long-lived magmatic system.

It is a textbook example of a hidden geothermal system that has defied conventional exploration attempts to make sense of its thermal clues

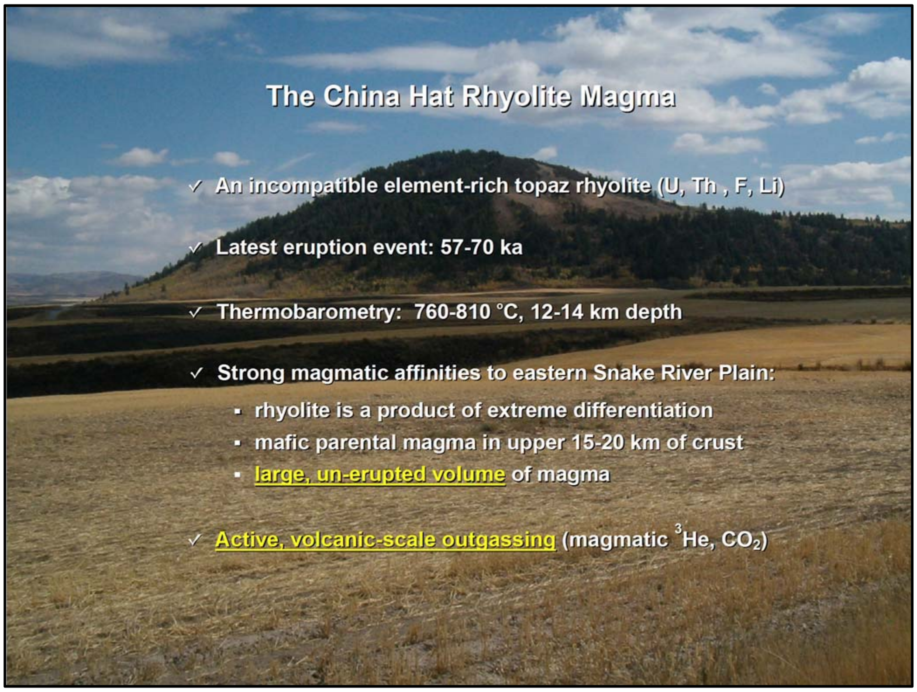
because the accessible resource is not located in the area of young volcanism, but east of it, in the Idaho thrust belt (ITB).



Rick Allis and others have championed the idea that hot stratigraphic reservoirs in thick sedimentary sequences represent the next level of low-hanging fruit that can compete economically with conventional geothermal power-generating resources when T > 150 ^{o}C at depths <4 km.

I'll review the evidence for such a resource in the ITB, estimate its power-generating potential using the Monte Carlo stored-heat method.

and suggest that this GT system may have other, non-thermal economic possibilities, as well.

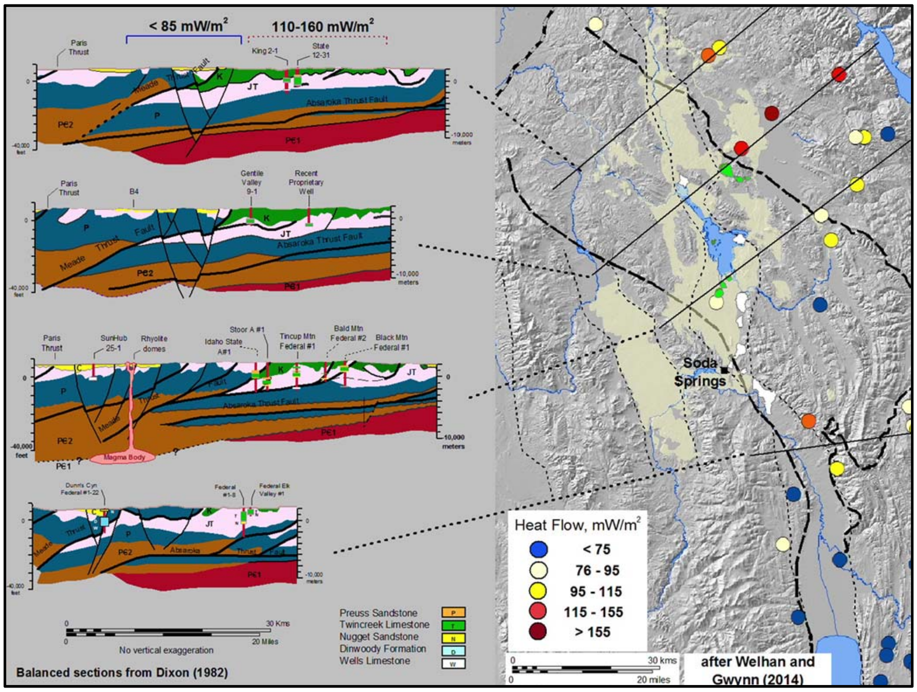


This is the China Hat rhyolite dome, largest of three,
which is the youngest expression of the magmatic heat source that sustains this thermal system.

It is an incompatible element-rich - so-called topaz or rare-metal – rhyolite
that represents the youngest phase of volcanism in the BVF, having erupted from a depth of 12-14 km.

Based on work by Mike McCurry, Bill Leeman and others,
it is a product of extreme fractionation from a much larger mafic parent magma

and measurements made 20 km to the south (Lewicki et al, 2012) indicate that this magma is still actively outgassing CO_2 and ^{3}He
at rates comparable to quiescent active volcanic centers worldwide.

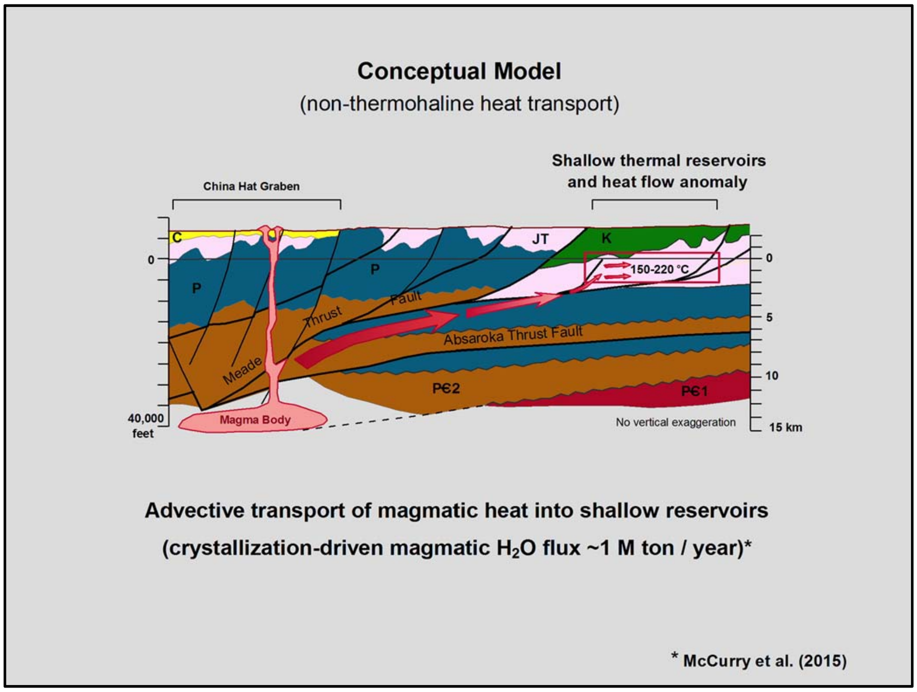


This map shows the deep oil exploration wells that have been drilled in the ITB, which provided the evidence for this hidden geothermal prospect.

The borehole thermal data were corrected for drilling disturbance by Mark Gwynn of the Utah Geological Survey, using several different correction procedures, so these HF estimates are the most accurate and comprehensive compilation for this area of SE Idaho.

Also shown are balanced structural cross sections based on well and seismic data collected through the early 1980s.

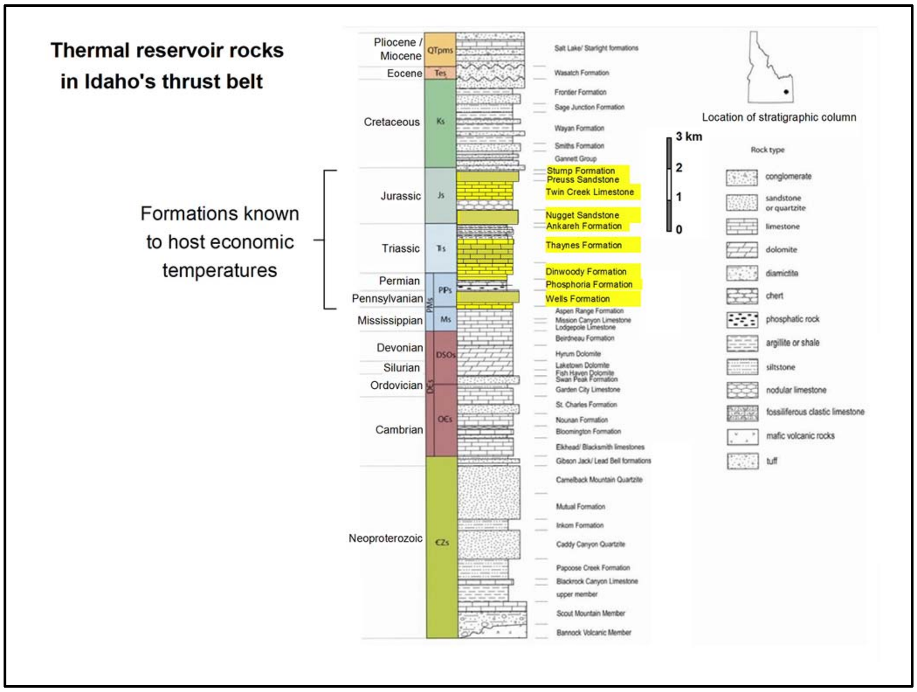
The rhyolite magma is depicted beneath China Hat in this cross section, but its actual geographic location is unknown and could even be located beneath the primary heat flow northeast of the northern rhyolite dome field.



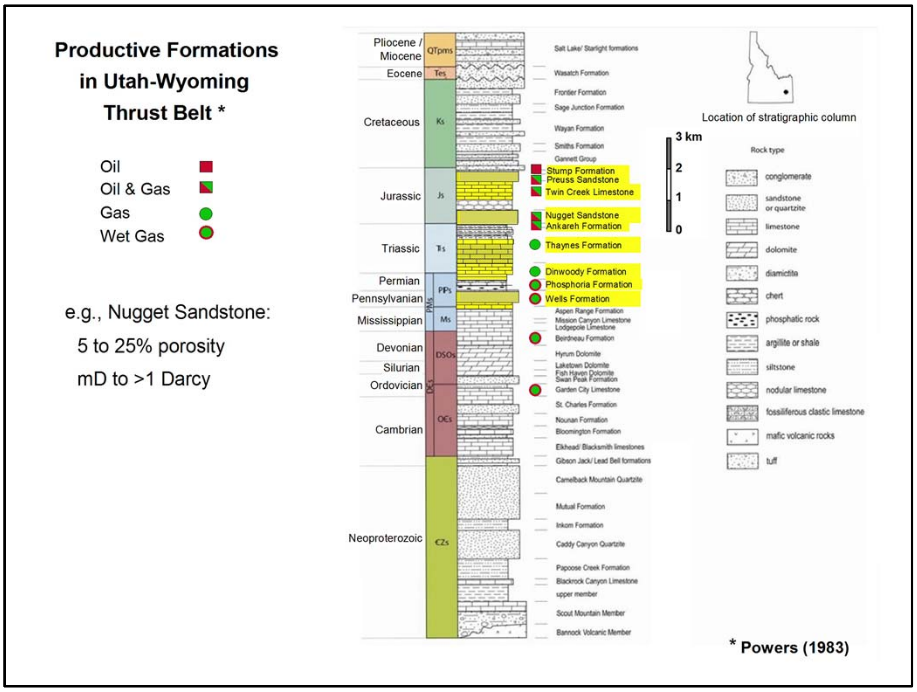
The most likely heat transport mechanism involves advective flow of hot fluids along structurally controlled pathways into shallow crustal reservoirs.

Over its 1.5 Ma time-averaged crystallization life, McCurry et al. proposed that this topaz-rhyolite magma could inject juvenile water at a rate of a Mton or more annually, into the crust.

Therefore, whether or not meteoric ground water flow systems extend to these depths, it is possible that at least some advective heat transport is driven directly by magmatic outgassing.



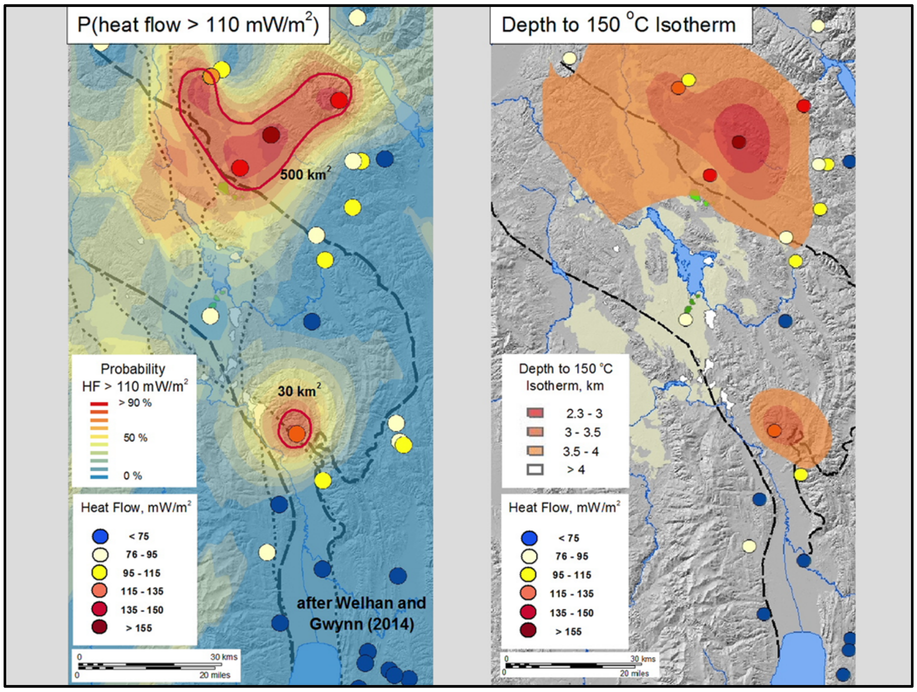
This summarizes the formations that are known to host geothermal fluids in the ITB . . .



. . . and the same formations in the Wyoming - Utah thrust belt that host productive oil and gas reservoirs.

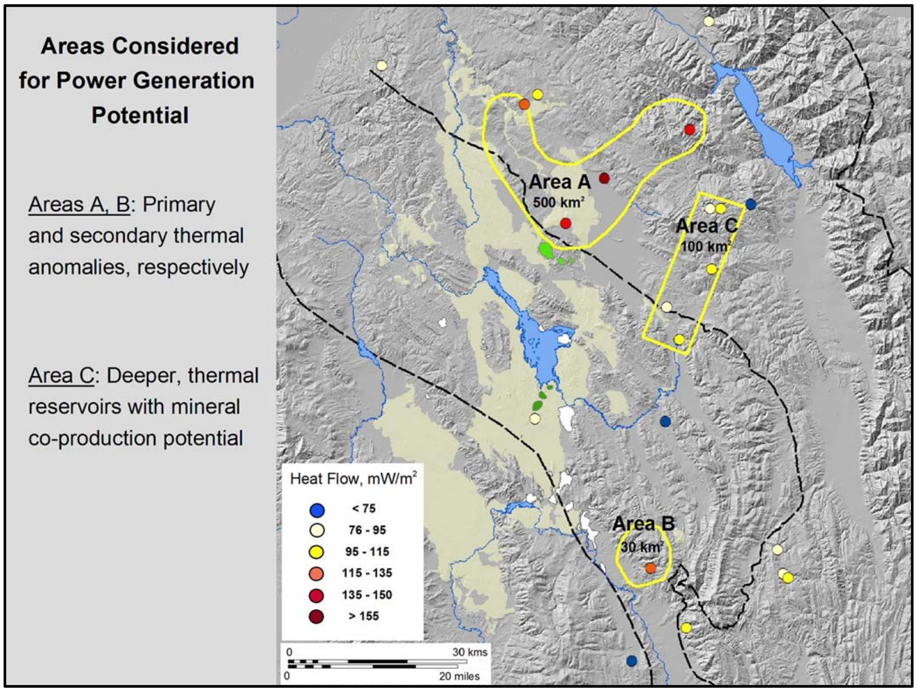
Some, like the Nugget Sandstone and the fractured Twin Creek limestone, are obvious candidates as productive hot-water reservoirs,

but there is good reason to expect that many of these formations are capable of producing hot water at economic flow rates.



The geographic extent of the thermal resource was inferred using probability kriging around a 110 mW/m^2 threshold,
where the size of the thermal anomalies is defined by an 80% probability of exceedance.

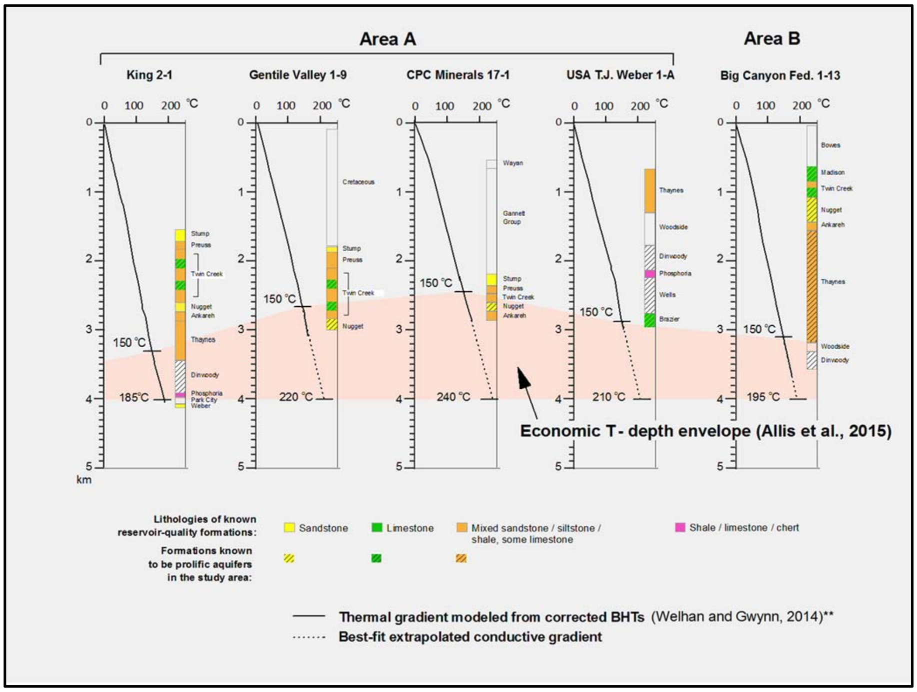
Note that the southern anomaly is defined on the basis of a single well, so its actual areal extent is unknown.



These are the areas that were evaluated for their power-generating potential.

Areas A & B are defined on the basis of heat flow data in the previous slide . . .

and Area C, having elevated HF but deeper reservoir-quality rocks, was evaluated for comparative purposes.

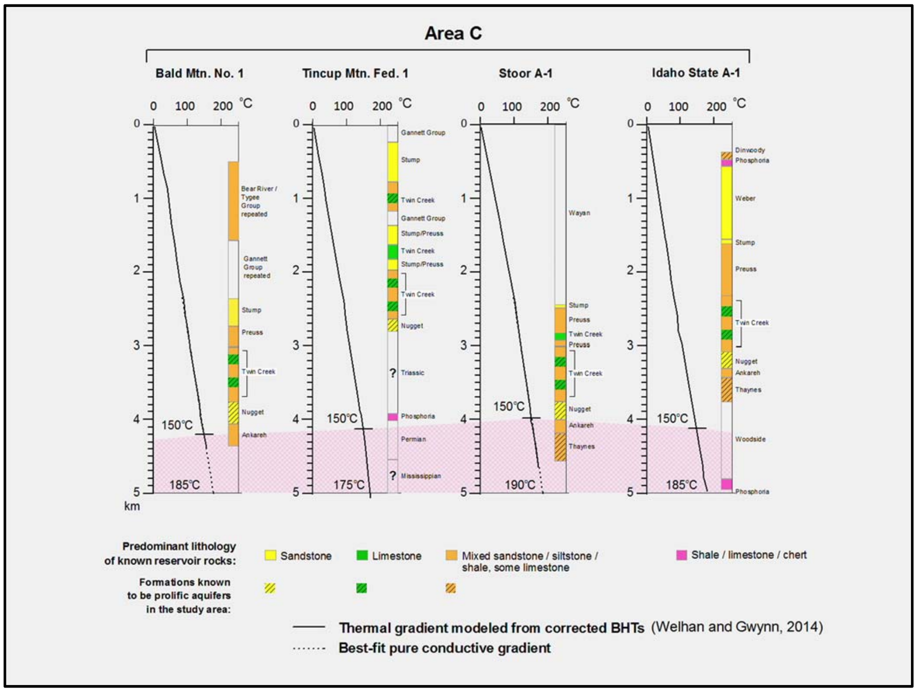


The thickness of potentially productive formations was estimated according to

where they occur relative to the economic T-Z window, defined as >150 °C at depths less than < 4 km.

The aggregate thicknesses of reservoir-quality formations within this T-Z window range from 100-700 meters.

This is a minimum estimate, however, because most wells do not penetrate far beyond the 150 °C isotherm.



In the third area, the 150 °C isotherm is deeper than 4 km,

so strictly speaking, these reservoirs lie outside the economic T-depth window for hot sedimentary rocks.

Summary of Inferred Reservoir Conditions

	Area A	Area B	Area C
Depth, km to 150 ^{o}C isotherm	2.8 ± 0.5	3.1 ± 0.5	4.1 ± 0.1
$T_{Maximum}$, ^{o}C	215 ± 15 at 4 km	195 ± 15 at 4 km	185 ± 15 at 5 km
$T_{Average}$, ^{o}C	185 ± 15 at 2.5 - 4 km	170 ± 15 at 2.5 - 4 km	170 ± 10 at 4 - 5 km
Resource thickness, m	400 ± 300 at 2.5 - 4 km	>400 at 2.5 - 4 km	400 ± 300 at 4 - 5 km

For the heat-in-place method of energy analysis, the fundamental variables are summarized here:

Depths to the 150 ^{o}C isotherm for Areas A & B are well within the economic depth envelope for hot stratigraphic reservoirs,

reservoir temperatures are in excess of 170 ^{o}C and range upward of 200 ^{o}C,

and potential reservoir thicknesses range from 100 to 700 meters.

Heat-in-Place Energy Assessment

Stored Reservoir Thermal Energy:

$$E_R = C_R * V_R * (T_R - T_O)$$

Electric Power Generation Capacity (30 year life):

$$P_E = n * R * E_R / (F * t)$$

Thermal Recovery and Energy-Conversion Factors:

$R = E_X / E_R$ = 0.02 - 0.1 * (0.08 - 0.2) +

$n = E_E / E_X$ = 0.05 - 0.12 ** (average of 52 flashed-steam plants)

= 0.05 - 0.08 ** (range of 31 binary plants, T_R = 150 - 220 °C)

(0.3 - 0.4) +

+ Williams et al. (2008); GeoFRAT *** Sanyal et al. (2002)** **** Moon and Zarouk (2012)**

The stored reservoir energy is based on the volumetric heat capacity, volume and temperature of reservoir rocks
relative to a reference temperature, at which energy conversion takes place,

and the power generation capacity depends on the thermal recovery factor, the fraction of stored thermal energy that can be delivered to the plant,

and the power plant's energy-conversion efficiency, or the fraction of thermal energy delivered to the wellhead that is converted to electric energy.

Monte Carlo calculations were constrained by values of these parameters taken from dozens of flashed-steam and binary GT power plants world wide,

that are much more conservative than a popular risk-assessment tool (GeoFRAT) commonly used for such evaluations.

Constraints on Monte Carlo Power Estimates

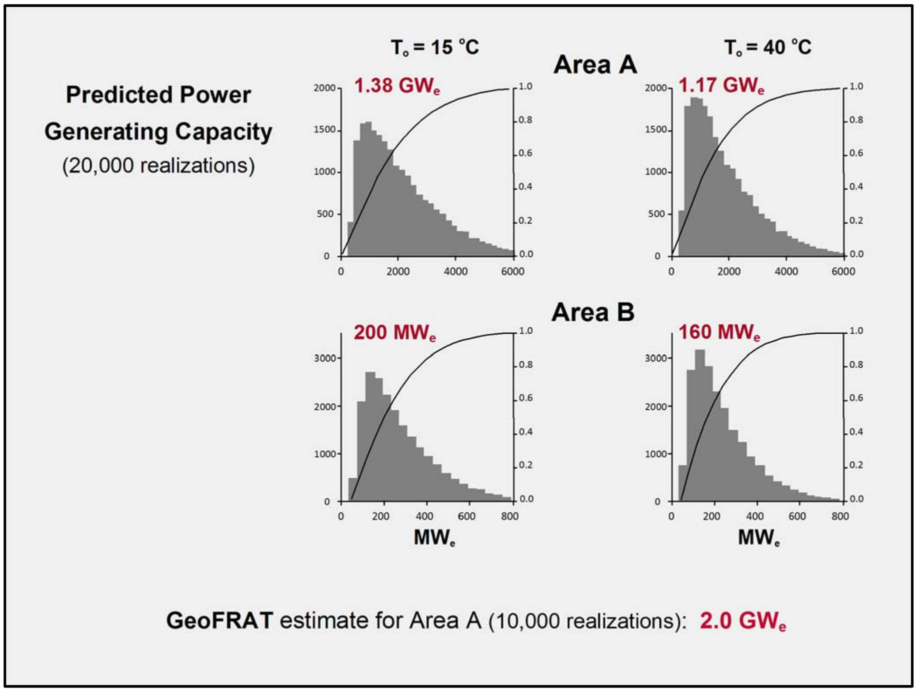
		T_R, °C *	V_R, km^3	Power conversion	Recovery factor
Area A	Min	170	20	0.05	0.02
	Max	200	350	0.12	0.10
Area B	Min	150	8	0.05	0.02
	Max	195	21	0.12	0.10
Area C	Min	150	10	0.05	0.02
	Max	170	70	0.08**	0.10

* Average T between the 150 °C isotherm and 4 km (Areas A, B) or 5 km (Area C) depth

** For binary-cycle power conversion of lower temperature and possibly high-salinity fluid

These are the ranges of relevant variables and parameter values used in the Monte Carlo estimates,

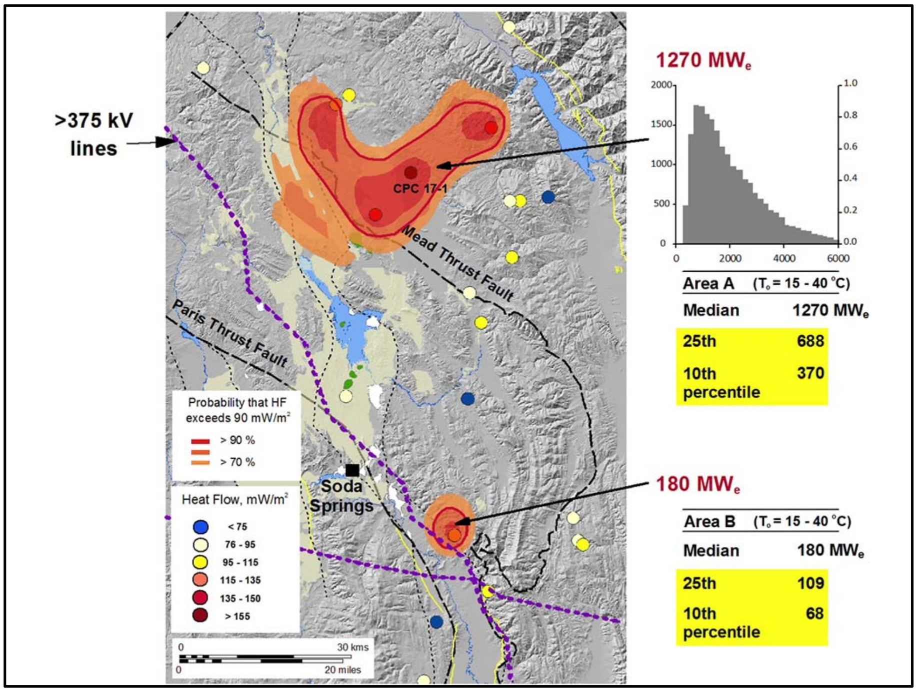
and considering a generous range of estimated reservoir volumes.



The predicted power-generating capacity for Area A comes in at over 1 GWe,

compared to GeoFRAT's even more optimistic estimate, which is based on a more optimistic reservoir recovery and energy conversion factors.

The predicted power-generating capacity for Area B comes in at between ca. 150 and 200 Mwe.

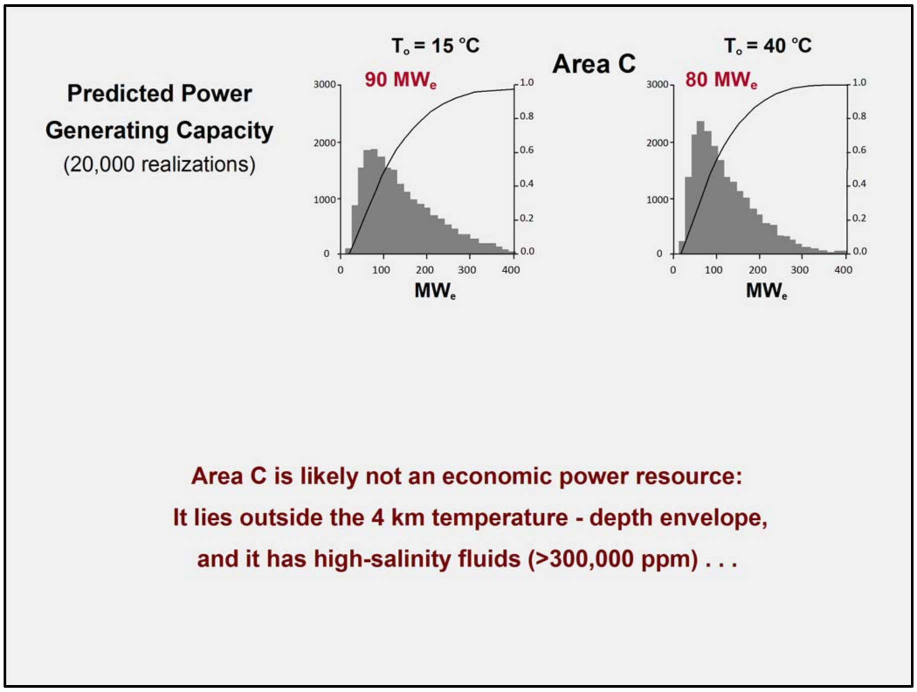


To place these results in perspective, the median of estimates for Area A correspond to power densities of the order of 2.3 to 5.5 MW_e/km^2,

which are well in the range required to keep the levelized cost of electricity (LCOE) competitive with conventional shallow geothermal reservoirs.

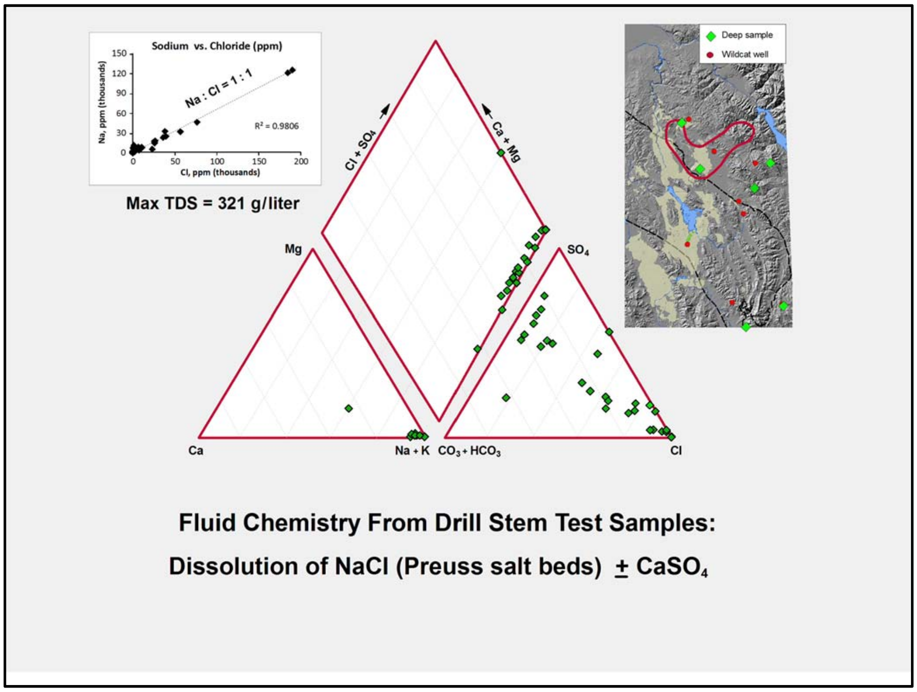
However, even the lowest 10th or 25th percentile estimates for Area A or B represent significant thermoelectric capacity, in the hundreds of MWe.

Furthermore, the location of these areas relative to existing high-voltage transmission lines AND near the high power-demand market of Monsanto's phosphate-smelting center in Soda Springs suggests that this resource is ripe for targeted exploration and development.

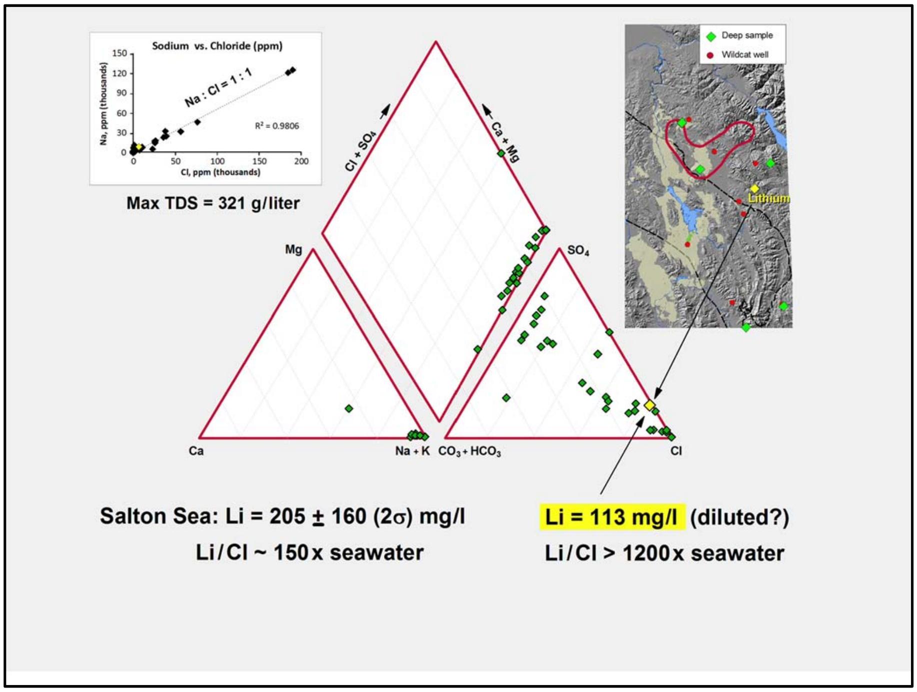


Taking into account Area C's greater reservoir depths and high-salinity fluids,

it is likely uneconomic if power-production, alone, is considered.



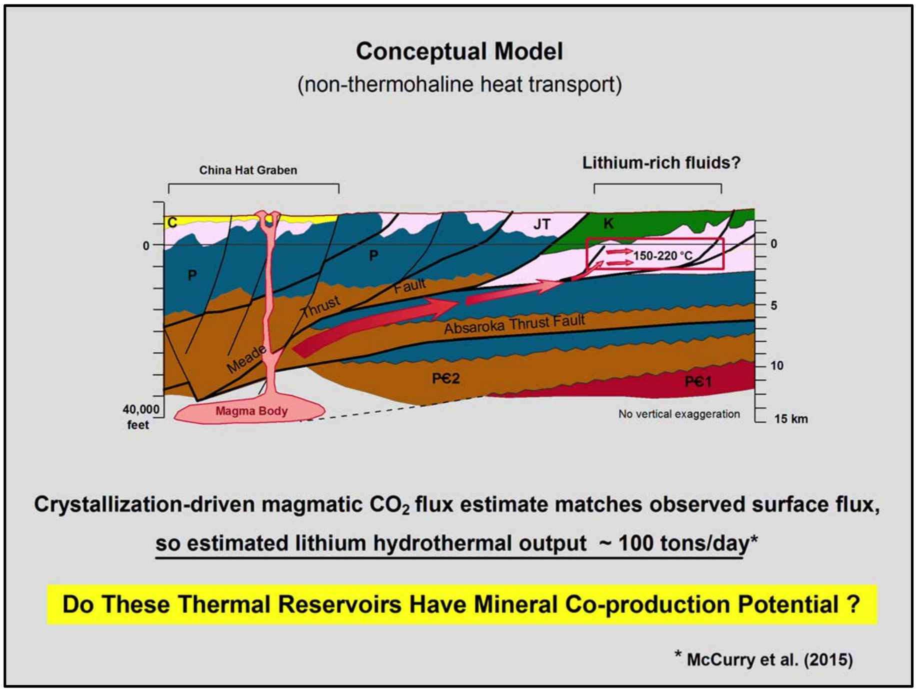
These high salinities derive from the dissolution of Jurassic salt beds, primarily NaCl, in the lower Preuss Formation.



However, the only reported drill stem test (DST) fluid sample with analytical data on other than major ions, had a Li concentration of over 100 mg/l,

and if the Li/Cl ratio is any indication, the actual Li concentration in this brine may be 10x higher than the Salton Sea's.

On its face value, this Li concentration is comparable to those reported in Salton Sea geothermal brines, where a pilot plant has successfully co-produced Li from geothermal fluids extracted for power.



A final piece of the puzzle may lie in the analysis by McCurry et al. who pointed out the crystallization-driven flux of magmatic CO_2 that has been documented in the Soda Springs area,

which implies an associated Li flux of the order of 100 tons per day from this topaz-rhyolite magma.

Therefore, the possibility that advective heat transport has sequestered considerable lithium in these formation fluids needs to be considered as a working hypothesis.

Conclusions and Recommendations

Favorable Factors

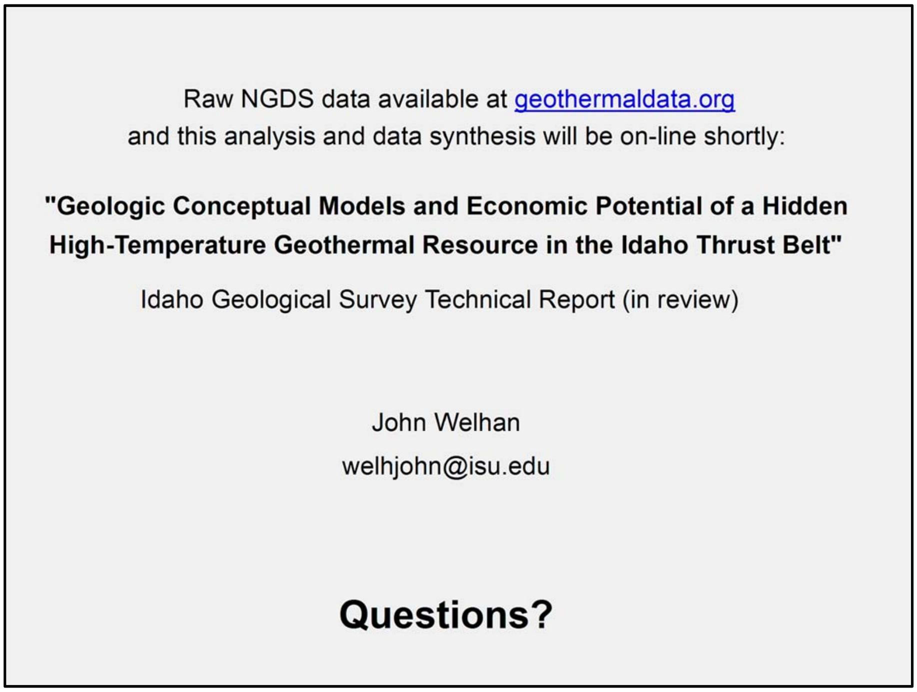
- potentially very large thermal resource at 150 - 240 °C
- thermal replenishment via advective transport of magmatic heat?
- Area A is within 30 km of existing HVT lines; Area B, within 5 km
- lithium co-production potential (?)

Significant Unknowns

- reservoir thickness, poropermeabilities, compartmentalization ?
- how sensitive are economics to drilling depth & rock properties ? *
- how sensitive are levelized costs to T_R, reservoir productivity ? *

*** Sanyal and Butler (2009)**

To summarize . . .



The raw data on which this analysis is based are available on-line at the NGDS website

and IGS will be publishing the results of the technical analysis and recommendations, shortly,

including an on-line compendium of raw and derivative data on which the analysis is based.

Previously Published Reports:

Welhan (2014)
Proc. 41st Workshop on Geothermal Reservoir Engineering, Stanford
https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2016/Welhan.pdf

Welhan et al. (2014)
Proc. 39th Workshop on Geothermal Reservoir Engineering, Stanford
https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2014/Welhan.pdf

Welhan and Gwynn (2014)
Geothermal Resources Council Transactions, v. 38, p. 1055-1066

Welhan et al. (2013)
Geothermal Resources Council Trans., v.37, p. 365-374

Welhan et al. (2013)
AAPG Search and Discovery #80329, AAPG Rocky Mountain Section Meeting
http://www.searchanddiscovery.com/pdfz/documents/2013/80329welhan/ndx_welhan.pdf.html