Geothermal Potential of Deep Sedimentary Basins in the United States

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Keywords

Resource, sedimentary, basins, United States, porosity, permeability, stratigraphy

Introduction

Geothermal energy development has a promising future as part of a broad energy supply mix to meet growing demand in the United States and globally. Currently developed hydrothermal systems are a significant energy source, but these systems have limited geographic extent. Research is underway, including ongoing pilot projects, to evaluate the potential for EGS, or Engineered Geothermal Systems, to drill into hot crystalline rock and create fractured reservoirs suitable for water injection and production cycles. However, a challenge to the economics of these systems is the drilling and fracturing cost.

"Co-production" of geothermal energy associated with oil operations has been demonstrated successfully at Teapot Dome (Anderson et al, 2009), where produced water is of sufficient quantity and adequate temperature to generate electricity with binary/hybrid systems. However, this approach has yet to be embraced by the oil industry.

A potential new path toward expanded geothermal energy production is to use known porous and permeable reservoir rocks in appropriate sedimentary basins, where those packages of rocks have sufficient temperature, thickness, porosity, and permeability, existing at depths that are not so great that drilling costs make the potential system uneconomic. This presentation describes a DOE-funded project to identify, screen, and model these potential systems, incorporating geology, engineering, and economic modeling disciplines.

Although sediment-hosted geothermal systems have not previously been an exploration target in the U.S., some producing reservoirs are hosted in sedimentary units. Many of the Imperial Valley geothermal systems (for example Salton Sea, Heber, and Cerro Prieto) are hosted in Quaternary-Tertiary sediments that have accumulated in the rift-basins associated with plate boundaries. A few Basin and Range geothermal systems are also hosted in Paleozoic and older sedimentary units (for example Cove Fort and Thermo, Utah). But a much larger potential target exists in "deep" sedimentary basins with known reservoir rocks, especially many that have produced oil and gas and that have extensive datasets available.

Basins Studied

Two published maps identify prospective basins and sedimentary thickness. The first (Figure 1) is from the landmark 2006 MIT Report (Tester, et al 2006). The second (Figure 2) is from a map published by the Idaho National Laboratory (2005), and it also shows estimated temperatures at 4 km depth. From these sources, as well as the National Renewable Energy Laboratory (NREL) study of Porro et al (2012), described in the next section, 17 basins in the western U.S. were selected for further evaluation (see also Figure 14 for location map with names):

- Anadarko
- Bighorn
- Delaware/Permian
- Denver (Denver-Julesburg)
- Fort Worth
- Great Basin
- Green River
- Gulf Coast
- Hanna (incl. Laramie and Shirley)
- Imperial Valley (or Salton Trough)
- Powder River
- Raton
- Sacramento
- San Joaquin
- Uinta/Piceance
- Williston
- Wind River

Sedimentary Basin Volumes and Temperatures

A recent project completed by National Renewable Energy Laboratory (NREL) staff was presented at the AAPG Annual

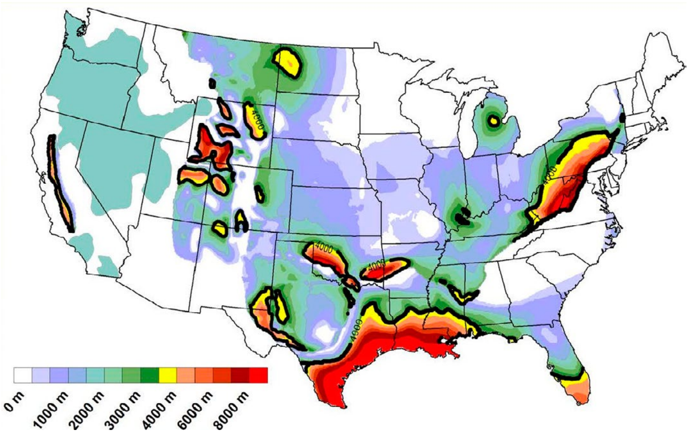

Figure 1. Sediment thickness in the continental U.S. (Tester et al 2006).

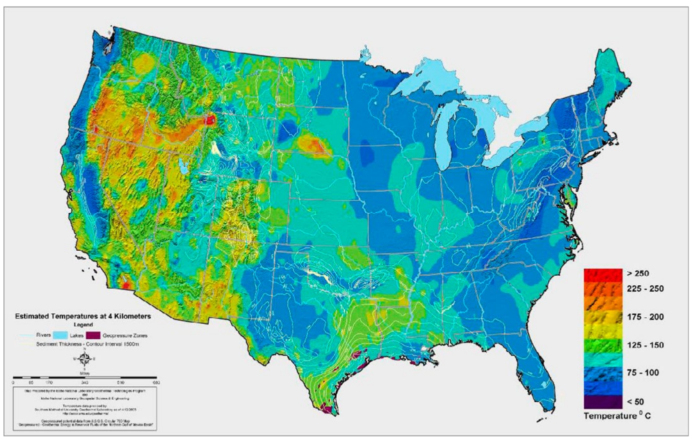

Figure 2. Map of U.S. showing sediment thickness contours and temperature at 4 km depth (INL, 2005).

Conference in April, 2012 by Colleen Porro (formerly from NREL) and was also presented by Ariel Esposito at the GRC Annual Meeting in Reno in September-October, 2012. This work has contributed significantly to the effort to evaluate and screen deep sedimentary basins for geothermal potential. The extended

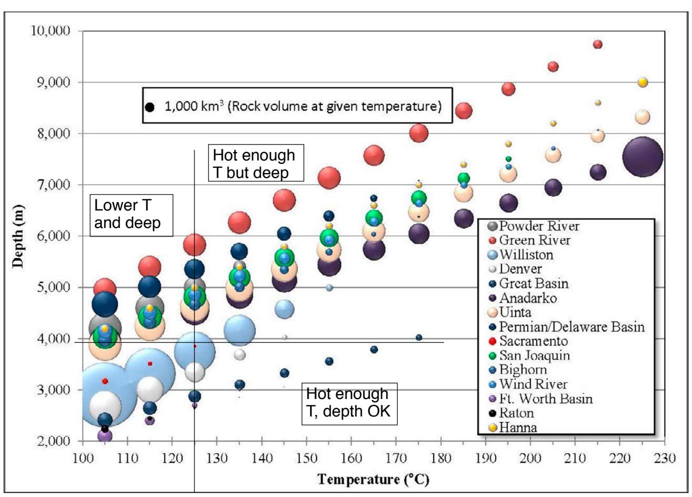

Figure 3. Sedimentary basin volume vs. temperature and depth for basins studied (Porro et al, 2012). Threshold lines and annotation overlaid on graphic by present author.

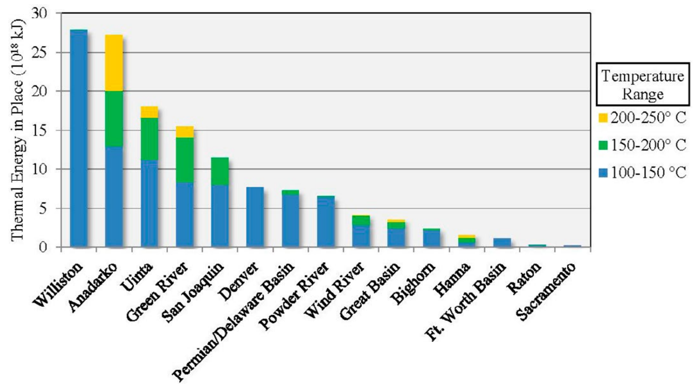

Figure 4. Total heat in place for basins studied (Porro et al, 2012).

abstract (Porro et al, 2012) from the GRC presentation shows an innovative method (Figure 3) for illustrating sedimentary volume, depth, and temperatures for all basins they studied, consisting of 15 of the 17 basins listed above.

Note that Porro et al (2012) did not include the Gulf Coast region and the Imperial Valley (Salton Trough) included in the present study. Also, their areal extent for the Great Basin covered Nevada only, and so their Great Basin didn't include the Utah portion, and apparently focused on basin fill sediments rather than Paleozoic reservoirs. Finally, in contrast to the present expanded study, they didn't consider quantitative porosity and permeability or specific potential target reservoirs. Figure 3 shows their cross-plot of depth vs temperature for each basin (Porro et al, 2012). For current study screening purposes, thresholds of < 4 km depth and > 125 °C temperatures were applied to meet economic targets, and these lines and annotation are overlaid on Figure 3. Figure 4 (Porro 2012) shows total heat in place for each of the basins they studied.

Results from the Porro et al study indicate that many of those basins should be excluded, for example, the Bighorn Basin (Figure 5) has good temperatures for geothermal energy production, but these occur at over 5 km, assumed too deep for economic drilling costs. The temperature at the 4 km threshold is only 100-110 °C, in the barely marginal range for binary power systems.

Based on the work of Porro et al, basins meeting the temperature/depth criteria imposed by the present study are the Williston,

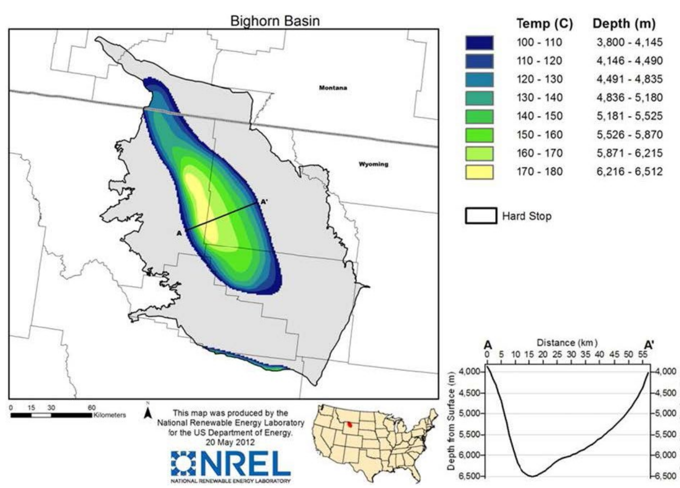

Figure 5. Bighorn Basin structure and temperatures (Porro et al, 2012).

Period	Formation (Group)	Lithology	Thickness (ft)	Depth (ft)	Porosity %	Perm. md	Temp. °C	HC Zones
Tertiary	**Castle Rock**	**Conglomerate**	**400**	**-**				
Cretaceous	Dawson	SS, Sh	1,200	-				
	Denver	SS, Sh	1,000	1,200				CBM
	Arapahoe	SS	600	2,200				
	Laramie	SS	150	2,800				CBM
	Fox Hills	SS	200	2,950				
	Pierre	Sh, SS	6,000	3,150			100-110	Oil/Gas
	Niobrara	Sh, LS	350	9,150			110-120	Oil
	Codell	SS	20	9,500			120-130	Oil/Gas
	Carlile	Sh	100	9,520			120-130	
	Greenhorn	LS	300	9,620			120-130	
	Graneros/ "D" SS	Sh	200	9,920			120-130	Oil/Gas
	Mowry	Sh	200	10,120			120-130	
	Muddy "J" SS	SS	500	10,320			120-130	Oil/Gas
	Skull Creek	Sh	200	10,820			130-140	
	Plainview/Dakota	SS	200	11,020			130-140	Oil/Gas
	Lytle/Lakota	SS	100	11,220			130-140	Oil/Gas
Jurassic	Morrison	Sh, SS, LS	250	11,320			130-140	
	Ralston Creek	Sh, LS, SS	100	11,570			130-140	
	Entrada	Sh, SS	150	11,670			130-140	
Triassic	Jelm	SS	150	11,820			140-150	
Permian	Lykins	SS	650	11,970			140-150	
	Lyons	**SS**	130	12,620	15	45	140-150	Oil/Gas
	Ingleside	**Dol**	330	12,750	19	100	140-150	
Pennsylvanian	Fountain	SS	1,200	13,080			140-150	
Mississippian	Guernsey			14,280				
Cambrian	Flathead	SS		14,280				

Figure 6. Denver Basin stratigraphic column.

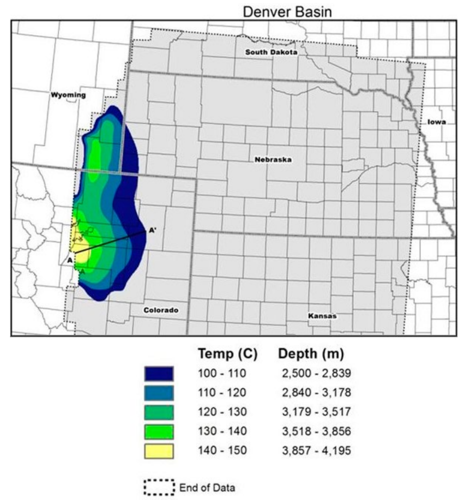

Figure 7. Denver Basin structure map with temperatures (Porro et al, 2012).

Sedimentary Basin Stratigraphic Columns

Published geologic columns (over 70) were identified and compiled for all of the basins studied (the number for each basin is shown in Table 2). An example for the Denver Basin is shown in Figure 6 (porosity/permeability for target reservoirs also shown; discussed later). The aggregate unit thicknesses and corresponding depths were then compared to the basin structure maps presented by Porro, et al (2012) to ensure consistency and "calibrate" the geologic columns to the maximum basin depth (see Figure 7 for the Denver Basin example from Porro et al 2012).

To understand the stratigraphy, depth, and structural relationships of each basin, geologic cross sections were also found and examined, as in the examples from the Anadarko Basin shown in Figure 8 and the Green River Basin shown in Figure 9.

Regional Porosity and Permeability Data

A search for available porosity and permeability data identified a U.S. Geological Survey Open-File Report (Nelson and Kibler, 2003) that compiles data from 70 data sets covering 49 basins

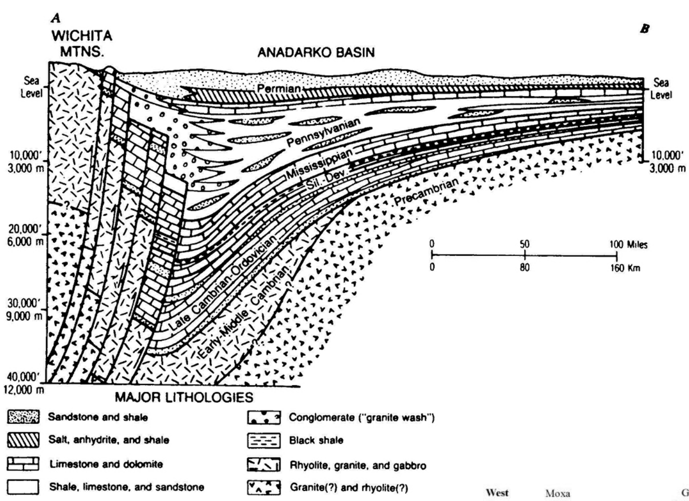

Figure 8. Geologic cross section through the Anadarko basin (Johnson, 1989).

Denver, Great Basin, Fort Worth, Raton, and Sacramento. But total heat-in-place (Figure 4) would probably exclude the last three. Added to these, as will be seen, the present study adds the Gulf Coast and Imperial Valley as favorable. The next step needed, building upon Porro et al, is to evaluate specific reservoir rock stratigraphy and quality.

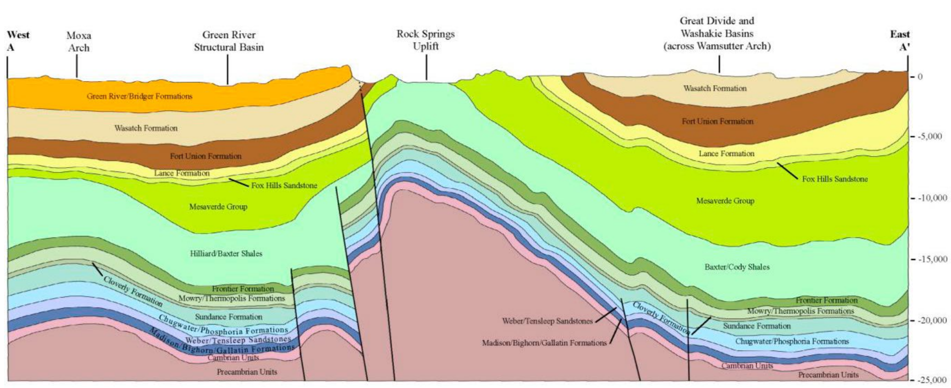

Figure 9. East-west cross section through the Greater Green River Basin (by Fred McLaughlin and Yuriy Ganshin, Wyoming State Geological Survey, *in* Clarey et al, 2010).

Table 1. Sources, ages, and locations of porosity-permeability data sets.*

Ref. No.	Authors and Date	Geologic Age	Formation Name	Location	Basin	Field	Max. Porosity %	Max. Permeability md
59	Sneider and others, 1977	Pennsylvanian	L & M zones	Oklahoma	Anadarko Basin	Elk City Field	24.2	524.8
47	Morgan and others, 1977	Pennsylvanian	Tensleep	Wyoming	Big Horn Basin	Oregon Basin Field	22.5	758.8
22	Dutton and others, 2003	Permian	Bell Canyon	Texas	Delaware Basin	East Ford Unit	30.6	249.0
44	Montgomery, 1997	Permian	Bone Spring	New Mexico	Delaware Basin	Red Tank Field	20.6	19.1
61	Spain, 1992	Permian	Cherry Canyon	Texas	Delaware Basin	Rhoda Walker Field	29.5	169.8
20	Dolly and Mullarkey, 1996	Late Cretaceous	Frontier Sand	Wyoming	Green River Basin	Lincoln Roads Field	23.7	25.0
33	Keighin and others, 1989	Late Cretaceous	Almond	Wyoming	Green River Basin	various fields	22.1	44.0
49	Muller and Coalson, 1989	Early Cretaceous	Dakota	Wyoming	Green River Basin	Henry Field	22.2	630.9
14	Corcoran and others, 1994	Eocene	Wilcox Group	Louisiana	Gulf Coast	Wildsville Field	34.7	1990.0
25	Ganer, 1985	Jurassic	Cotton Valley	Louisiana	Gulf Coast	Terryville Field	16.9	416.9
28	Grigsby and others, 1992	Paleocene	Wilcox Group	Texas	Gulf Coast	Lake Creek Field	16.0	7.8
32	Hosseini and Hayatdavoudi, 1986	Cretaceous	Tuscaloosa	Louisiana	Gulf Coast	wildcat	31.2	193.0
36	Langford and others, 1990	Oligocene	Vicksburg	Texas	Gulf Coast	McAllen Ranch Field	20.5	2.9
38	Luffel and others, 1991	Early Cretaceous	Travis Peak	Texas	Gulf Coast	four counties in E. Texas	17.2	75.9
41	Miller and Groth, 1990	Cretaceous	Tuscaloosa	Louisiana	Gulf Coast	Baywood Field	18.0	316.0
56	Smith, 1985	mid-Cretaceous	Tuscaloosa	Louisiana	Gulf Coast	Rigolets & Ft. Pike Fields	22.5	851.1
57	Smith, 1985	mid-Cretaceous	Tuscaloosa	Louisiana	Gulf Coast	False River Field	28.8	1258.9
58	Smith, 1985	mid-Cretaceous	Tuscaloosa	Louisiana	Gulf Coast	Judge Digby & False River	28.5	1621.8
63	Stricklin, 1999	Late Cretaceous	Woodbine	Texas	Gulf Coast	Double A Wells Field	22.4	1215.0
8	Bowker and Jackson, 1989	Permian-Pennsylvanian	Weber Sand	Colorado	Piceance Basin	Rangely Field	18.2	173.8
19	Dolly and Mullarkey, 1996	Early Cretaceous	Muddy Sand	Wyoming	Powder River Basin	Collums Field	29.6	56.0
21	Dutton and Willis, 1998	Early Cretaceous	Fall River	Wyoming	Powder River Basin	Buck Draw Field	13.3	89.1
67	Tillman and Martinsen, 1987	Late Cretaceous	Shannon Sand	Wyoming	Powder River Basin	Hartzog Draw Field	17.7	94.0
29	Hall and Link, 1990	Late Miocene	Monterey	California	San Joaquin Basin	Midway-Sunset Field	37.0	1445.0
42	Miller and others, 1990	Pleistocene	Tulare	California	San Joaquin Basin	South Belridge Field	40.6	10000.0
64	Taylor and Soule, 1993	Oligocene	64-zone Sand	California	San Joaquin Basin	North Belridge Field	19.1	281.8
54	Shade and Hansen, 1992	Tertiary-Cretaceous	Wasatch	Utah	Uinta Basin	Natural Buttes Field	14.5	7.8
69	Wendlandt and Bhuyan,1990	Cretaceous	Mesaverde	Utah	Uinta/Book Cliffs	none	23.3	1393.6
60	Soeder and Randolph, 1987	Late Cretaceous	Mesaverde	Colorado	Uinta/Piceance Basin	Rulison Field	11.5	1.0
24	Estes-Jackson and others, 2001	Cretaceous	Muddy Sand	Wyoming	Wind River Basin	Riverton Dome Field	22.4	4.3

*excerpted from Nelson and Kibler (2003)

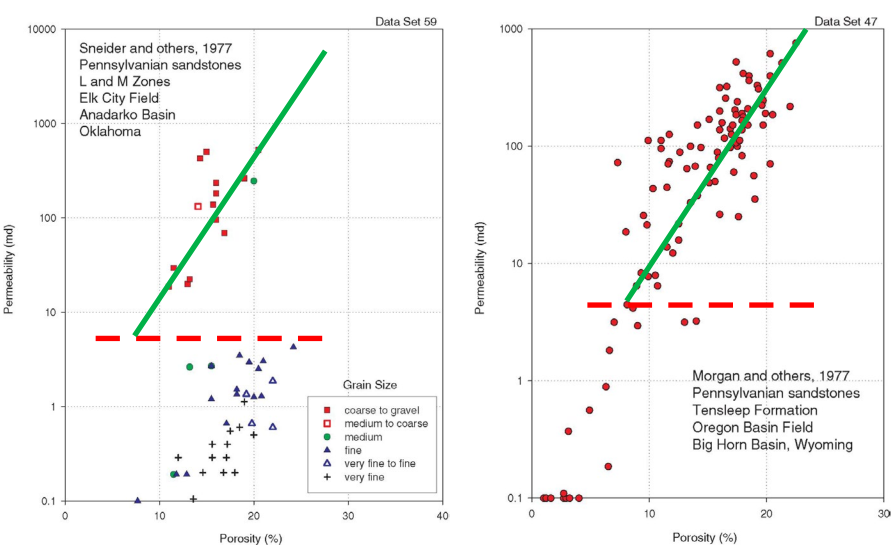

Figure 10. Plots of permeability (in md) versus porosity (in %) for units in the Anadarko and Bighorn Basins (Nelson and Kibler, 2003).

Lithologic Unit	n[1]	Depth (m)				Permeability (mD)			
		Median	Geo-mean[2]	Mini-mum	Maxi-mum	Median	Geo-mean	Mini-mum	Maxi-mum
Great Basin basin fill	97	110	96	4.2	686	4467	2776	0.08	177038
Great Basin igneous rocks	253	749	683	48.8	2243	100	83	0.00	241387
All carbonate rocks	250	1750	1534	13.9	7214	41	68	0.13	1111438
All siliciclastic rocks	588	1999	1793	58.2	5530.9	25	25	0.26	6054
Utah and Great Basin carbonate rocks	55	1106	686	13.9	3792.9	292	610	0.13	1111438
Utah and Great Basin siliciclastic rocks	59	1535	1283	100	4774.1	32	19	0.26	6054

[1]Number of occurrences
[2]Geometric mean taken as the exponent of the mean of logs of either depth or permeability

Figure 11. Summary of permeability data by lithologic unit for the Great Basin (Kirby, 2012).

worldwide, including 9 of the basins on our list. Table 1 is extracted from this report showing a summary of this compilation for a subset of the basins relevant to the present study.

Beyond the summary shown in Table 1, which only shows "Maximum Porosity" and "Maximum Permeability", detailed data plots from Nelson and Kibler (2003) for selected units, extracted from the source references cited, were used to calculate trendlines, generally above a permeability cutoff of 6 md, to define average values for permeability and porosity (Figure 10).

This data was augmented by searching the U.S. Geological Survey Core Research Center online catalog (http://my.usgs.gov/crcwc/), adding data from eight basins. This site has analysis data available online including some porosity and permeability data. Wells with cores having this additional poro-perm data were selected for deeper

Table 2. Compilation of porosity and permeability data representing basins studied.

Basins	Geo-Col	Formation	Ref*	Ave Poro	Ave Perm	Max Poro	Max Perm
Anadarko	8	Pennsylvanian L&M	59	15.0	100.0	24.2	524.8
Bighorn	4	Tensleep	47	16.6	100.0	22.5	758.8
Delaware-Permian	5	Bone Spring	44	14.4	2.0	20.6	19.1
		Bell Canyon	22	24.0	40.0	30.6	249.0
		Cherry Canyon	61	12.5	10.0	29.5	169.8
Denver-Julesberg	2	Lyons Sandstone	CRC	13.0	100.0	18.8	1400.0
		Lyons Sandstone	CRC	15.0	45.0	18.8	159.0
		Ingleside	CRC	19.0	100.0	31.0	1905.0
Fort Worth	3	Ellenburger	RRC	15.0	50.0	18.0	100.0
Great Basin	6	Paleozoic carbonates	UGS	10.0	75.0	18.0	200.0
Green River	10	Frontier Sandstone	20	15.0	0.7	23.7	25.0
		Almond	33	18.0	10.0	22.1	44.0
		Dakota	49	14.0	40.0	22.2	630.9
Gulf Coast	6	Travis Peak	69E	9.0	1.0	22.0	300.0
		Wilcox Group	14	28.5	100.0	34.7	1990.0
		Cotton Valley	25	12.5	25.0	16.9	416.9
		Tuscaloosa	32	28.0	100.0	31.2	193.0
		Tuscaloosa	57	22.0	85.0	28.8	1258.9
		Vicksburg	36	19.5	2.5	20.5	2.9
		Travis Peak	38	12.0	9.0	17.2	75.9
		Woodbine	63	18.0	100.0	22.4	1215.0
		Edwards carbonate	70	25.0	179.0	n/a	n/a
		Wilcox sandstone	70	24.0	488.0	n/a	n/a
		Jackson-Yegua sands	70	31.0	604.0	n/a	n/a
		Frio fluvial sandstone	70	25.0	432.0	n/a	n/a
Hanna-Shirley-Laramie	2	Tensleep (from PRB)	DOE	11.0	20.0	21.1	296.0
Imperial Valley	3	Palm Springs	DOE	25.0	250.0	33.0	2100.0
Powder River	6	Muddy Sandstone	19	24.0	10.0	29.6	56.0
		Fall River (Dakota)	21	11.0	25.0	13.3	89.1
		Shannon Sandstone	67	14.0	20.0	17.7	94.0
		Tensleep	DOE	11.0	20.0	21.1	296.0
		Madison	PP	17.5	30.0	31.4	390.0
Raton	2	Trinidad Sandstone	CRC	7.0	1.0	13.5	1.0
		Entrada	CRC	16.0	2.0	n/a	n/a
Sacramento-San Joaquin	5	Monterey	29	32.0	800.0	37.0	1445.0
		Tulare	42	35.0	700.0	40.6	10000.0
		64-zone Sandstone	64	14.5	30.0	19.1	281.8
Uinta-Piceance	4	Weber Sandstone	8	12.5	10.0	18.2	173.8
		Mesaverde Group	60	7.5	0.3	11.5	1.0
		Wasatch	54	10.0	1.0	14.5	7.8
		Mesaverde Group	69	18.0	75.0	23.3	1393.6
Williston	2	Lodgepole	CRC	7.3	0.1	20.0	165.0
		Interlake	CRC	11.5	30.0	16.1	320.0
		Interlake	CRC	10.0	20.0	16.6	220.0
		Red River	CRC	15.0	10.0	24.7	158.0
		Red River	CRC	13.0	12.0	21.7	108.0
Wind River	5	Muddy	24	17.5	0.5	22.4	4.3
		Tensleep	CRC	15.0	70.0	22.0	1000.0
			poor		<= 10		
			moderate		11 to 99		
			good		>= 100		

*Primary references: Nelson and Kibler, 2003, A Catalog of Porosity and Permeability from Core Plugs in Siliciclastic Rocks: USGS Open-file Report 03-420; USGS Core catalog (CRC) http://my.usgs.gov/crcwc/; Texas Railroad Comm. (RRC)

*U.S. Dept. of Energy (DOE) reports, incl. Los Alamos NL, Sandia NL, and RMOTC

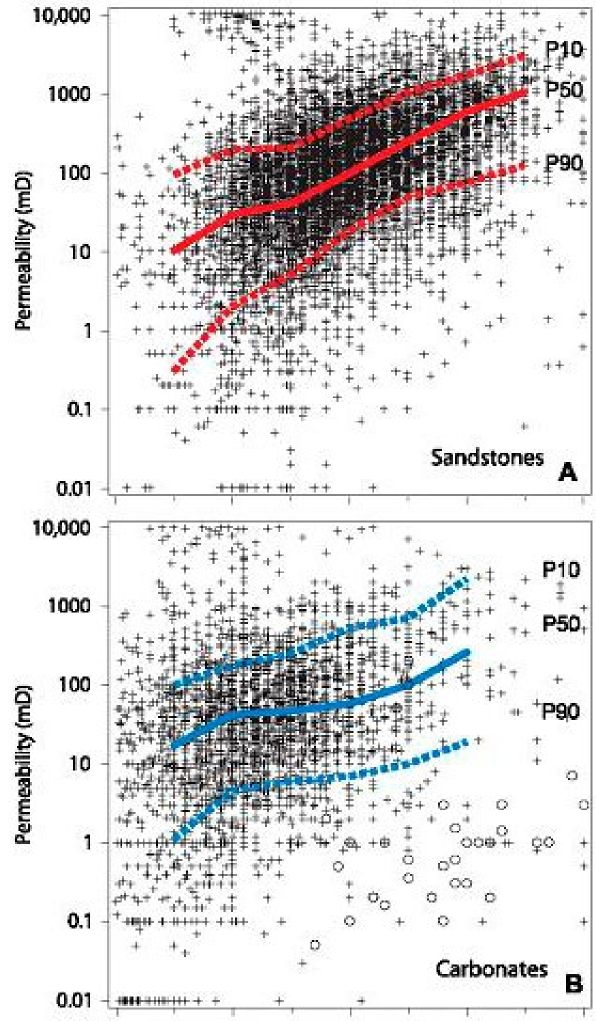

Figure 12. Average permeability vs. average porosity for global petroleum reservoirs composed of sandstone (A) & carbonate (B). Chalk reservoirs (open circles in B) were not included in trends. Porosity scales on X-axes is 0% - 40%, same as shown in Figure 13 (Ehrenberg and Nadeau, 2005).

units likely to be targets for geothermal resource development. Finally, some additional data was obtained from the Utah Geological Survey, the Texas Railroad Commission, the Texas Bureau of Economic Geology, and the South Texas Geological Society.

All of these were plotted in the same manner as the Nelson and Kibler data to define average values for permeability and porosity. Figure 10 shows two examples of permeability (log scale in md) versus porosity (linear scale in %) plots for units in the Anadarko and Bighorn Basins, to illustrate the methodology used for defining average values. In some cases, for example the Great Basin (Figure 11), other existing compilations were reviewed. Table 2 shows the results of this search and compilation for all basins studied.

For comparison, Figure 12 illustrates points plotted from a global dataset for sandstones and carbonates (Ehrenberg and Nadeau, 2005), and Figure 13 shows their P10-P50-P90 range lines with present study compiled data from Table 2 overlaid and annotated.

Application of screening thresholds of < 4 km depth and > 125 °C temperatures on Figure 3 (lines and annotation overlaid by present author on original source graphic) show the only basins meeting the threshold maximum depth and minimum

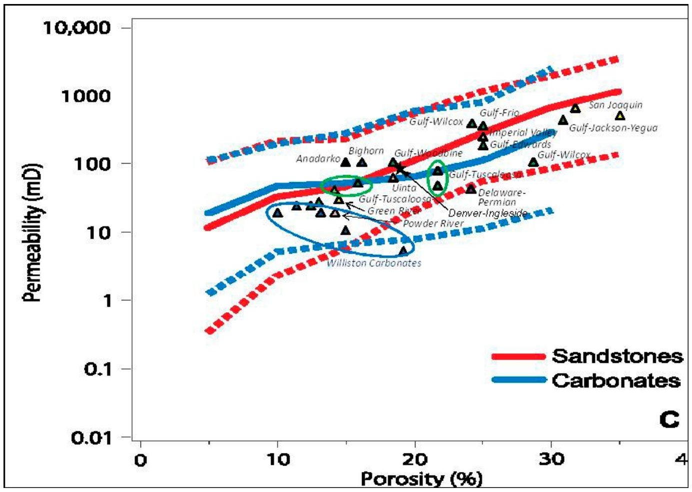

Figure 13. Data points from Table 2 overlaid and annotated on trends from Ehrenberg and Nadeau, (2005).

temperature are the Williston, Denver, Great Basin, Fort Worth, Sacramento, and Raton Basins. Of the two we added to the Porro et al (2012) list, both the Gulf Coast and Imperial Valley also meet these criteria. As a way to show the combined results, the three parameters of Average Porosity, Average Permeability, and Target Depth/Temperature criteria are illustrated with different display attributes on Figure 14.

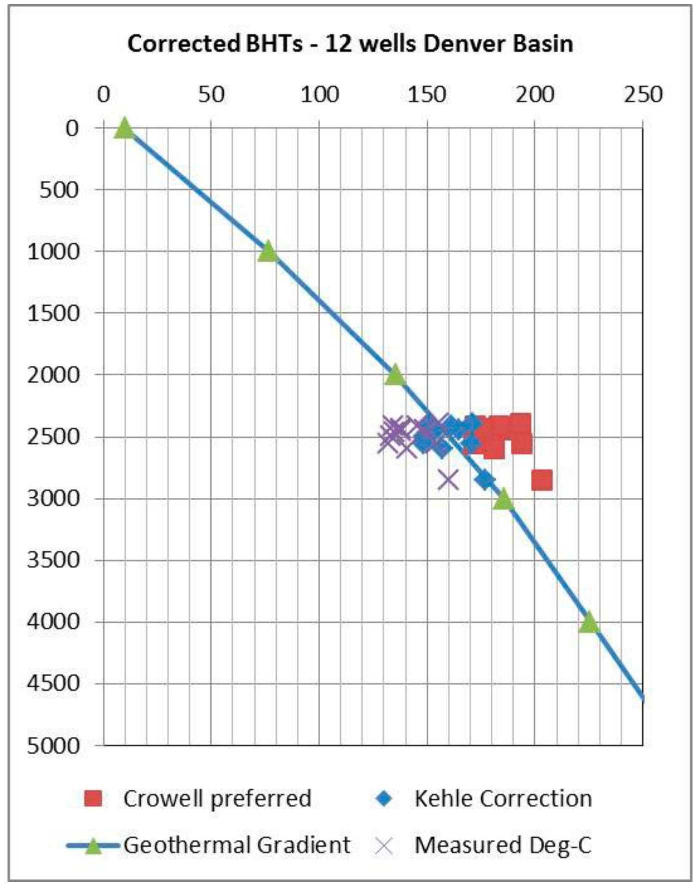

Figure 15. Bottom-hole temperatures (°C) for wells in the Denver Basin, including measured and corrected; Cretaceous Dakota Group (Crowell et al, 2012, 2013).

Conclusions

The following basins have adequate temperatures (>125 °C) within maximum depths (<4km) and porous (>10%) reservoir rocks to be considered for additional evaluation and modeling:

- Denver
- Fort Worth
- **Great Basin**
- **Gulf Coast**
- **Imperial Valley**
- *Raton*
- Sacramento
- *Williston*

However, when considering permeability, based on reservoir data evaluated so far, two basins don't make the cut of minimum acceptable permeability (approx. 50-100 md): the Raton and the Williston, thus they are italicized in the above list. Additional work may move these into solid consideration. The target area of the Raton is also quite small. The areal extent of the targets for the Fort Worth and the Sacramento Basins probably also limit them.

The best basins identified are highlighted in bold text in the list above (Great Basin and Gulf Coast). The Imperial Valley is a special case, since there is existing geothermal development and electrical production that can be expanded upon.

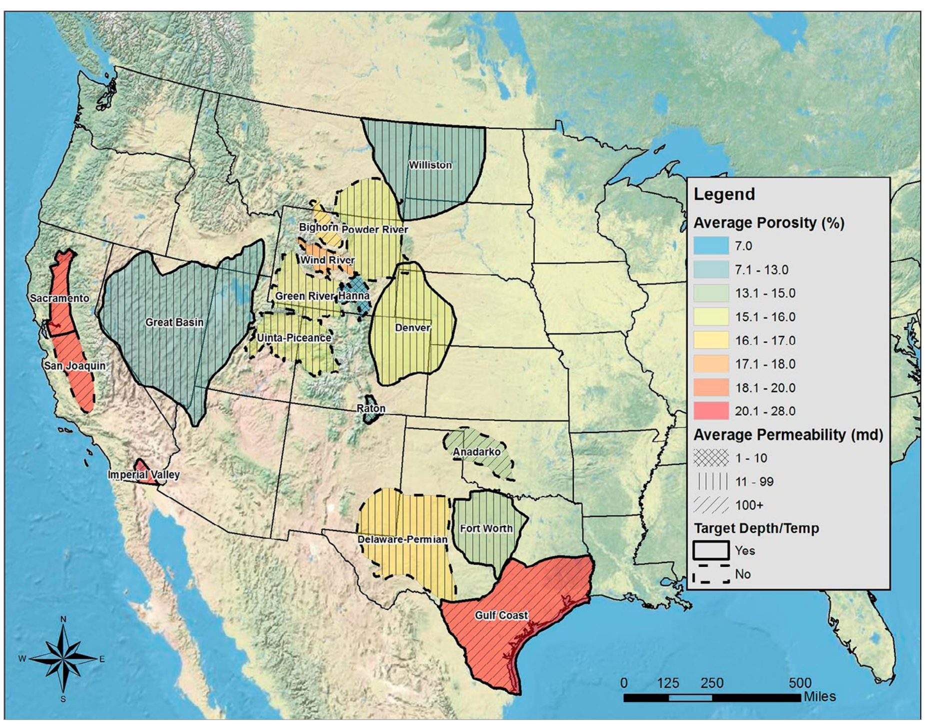

Figure 14. Symbolic representation of porosity, permeability, depth, and temperature relationships for candidate sedimentary basins in the western U.S.

Finally, the Denver Basin has mid-range potential and should be further evaluated. However, recent bottom-hole temperature (BHT) corrected data analysis by Crowell et al (2012, *2013 in preparation,* see Figure 15) indicates the Denver Basin Dakota Group has better temperatures than previously thought (Figure 7). This is expected to be even better in the Paleozoic (Permian) Ingleside Dolomite, which has excellent porosity (19%) and permeability (100 md), is not a known producing hydrocarbon zone, and at a depth of 4 km, temperatures could be at > 180 °C.

Acknowledgments

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