GPFA-AB Reservoirs Data Appendix

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This memo is intended to augment the Natural Reservoirs Methodology memo, by providing additional details about the original databases and modified inputs for the Appalachian Basin Geothermal Play Fairway Analysis project. All research and literature that affected decisions for the reservoir data inputs are recorded here, including data for geologic formations in the Appalachian Basin.

DATABASE INTEGRATION

Two disparate databases were integrated for this project: 1) the Empire State Organized Geologic Information System (ESOGIS; data for reservoirs in New York), and 2) the Midwest Regional Carbon Sequestration Partnership (MRCSP; data for reservoirs in Pennsylvania and West Virginia). When the two databases were merged, there were discrepancies between the available data and the terminology used in each database.

1. Geologic Formation Name: The following formation codes were listed in the MRCSP database. The decrypted formation name for each is listed next to the code. Very often, the name of a formation in Pennsylvania and West Virginia is different than the given name of the same formation in New York. For those formations, the New York formation name was used. If a reservoir is listed as having produced from a smaller unit within a larger formation, the formation name was used. Any formation name changes are listed in parentheses next to the original formation name, shown below.

a. BLDG: Bald Eagle
b. BILDF: Bass Islands Formation
c. BKMN: Beekmantown
d. BNSN: Benson
e. BERE: Berea
f. BRRL: Brallier (Elk Group)
g. CHZY: Chazy (Black River)
h. CLNN: Clinton (Medina)
i. DVSHL: Devonian Shale
j. DVNNU: Devonian Unconformity Play
k. ELKG: Elk Group
l. GBRG: Gatesburg (Rose Run)
m. GRDN: Gordon
n. HDBG: Helderberg
o. HRVL: Huntersville
p. HVOK: Huntersville/Oriskany
q. KEFR: Keefer
r. LCKP: Lockport
s. MDIN: Medina
t. MLTI: "Multi"
u. NWBG: Newburg
v. ONDG: Onondaga
w. ORSK: Oriskany
x. RSRN: Rose Run
y. SCHR: Scherr (Elk Group)
z. SDCI: Silurian Devonian Carbonate Interval (Lockport)
aa. TRNN: Trenton
bb. TLLY: Tully
cc. TCRR: Tuscarora
dd. WEIR: Weir

2. Average Reservoir Depth

The MRCSP database holds values for each reservoir's "Average Production Depth", which is interpreted as the top of the reservoir production zone. The ESOGIS database does not have production depth data reported; therefore, reservoir depth was extracted manually from well completion reports downloaded from the ESOGIS website. To calculate an average production depth for the NY reservoirs, the reported reservoir tops from each well in a given reservoir were averaged.

3. NY Reservoir Polygons

The MRCSP database includes shapefiles of the reservoir polygons, which is an estimate of the aerial extent of each reservoir. The ESOGIS database does not contain shapefiles, so they were created manually in a GIS. The buffer distance around producing wells in each reservoir in NY was chosen as 900 meters. This choice was made by comparing the only available polygons for NY reservoirs, which were the Trenton-Black River reservoirs (Patchen et al., 2006). Inputting those shapefiles into a GIS and comparing them to the locations of the wells showed that an average distance of 900 meters around all wells in a reservoir would create polygons compatible with Patchen et al.'s approach (Figure 1).

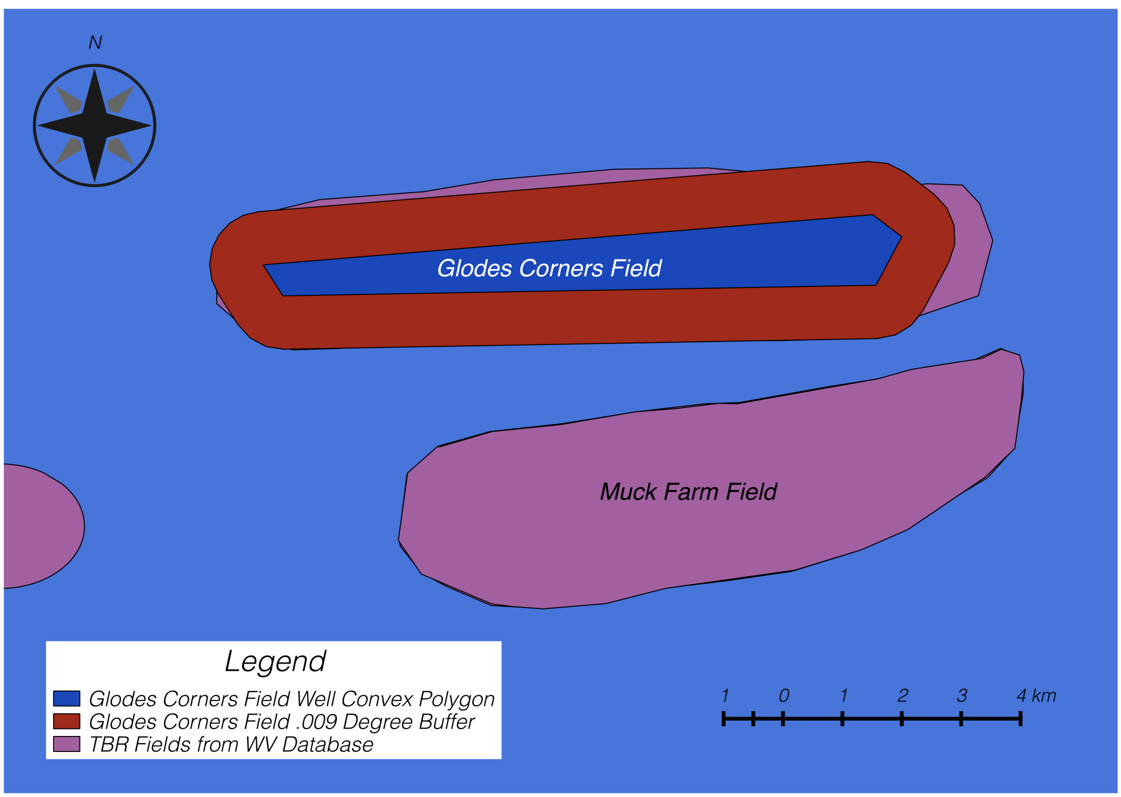

Figure 1. Example of Trenton-Black River polygons in GIS, which aided in creating a systematic buffer zone for NY reservoirs. 0.009 degrees is equivalent to 900 meters. The West Virginia Database comes from Patchen et al. (2006).

4. Porosity and Permeability

Porosity and permeability values were assigned based on the producing geologic formation in which the reservoir is located. New York reservoirs derivation required derivation of both porosity and permeability values from sources other than ESOGIS. The MRCSP database provided porosity data for reservoirs in Pennsylvania and West Virginia, so only permeability had to be input based on other sources. For all three states, empirical porosity-permeability relationships (if available) were applied to the porosity values for each formation. Otherwise, average permeability values were applied to all reservoirs of a given geologic formation.

If empirical relationships were used, the calculated permeability values are not reported below because the data vary from reservoir to reservoir. However, if an average permeability value was applied to all reservoirs of a given formation, that value is listed below. The first section describes formations that are host to reservoirs in New York, and therefore require porosity inputs; however, these formations may also be host to reservoirs in Pennsylvania and West Virginia. In such cases, any differences in average values across the three states are noted below. The last section describes formations that are host to reservoirs only in Pennsylvania and West Virginia, and therefore only require permeability inputs.

Formations located in New York:

a. Queenston: Data chosen for the Queenston were taken from Lugert et al. (2006). Eighty-three samples from the Delany Core were analyzed by H.J. Gruy and Associates, which gave the following results:
    i. Average porosity of core: 10.8%

ii. Porosity-permeability fit from core data, where *k* is permeability in units of mD and ϕ is porosity in porosity units (p.u.):

$$k = 0.0005\exp\,(0.5478\phi)$$

iii. Average core permeability for a porosity of 10.8% is 0.185 mD

iv. Lithology: Sandstone

b. Black River: Data chosen for the Black River Formation (also known as the Trenton-Black River in New York State) were taken from Lugert et al. (2006). Samples from the Whiteman #1 Core were analyzed by CoreLab, Inc.

i. Average porosity of core: 7%

ii. Porosity-permeability fit from core data, where *k* is permeability in units of mD and ϕ is porosity in porosity units (p.u.):

$$k = 1.8716\,\exp(0.4967\phi)$$

iii. Average Permeability for a porosity of 7% is 60.56 mD.

iv. Lithology: Limestone/Dolomite

c. Galway/Theresa/Rose Run:

i. New York: The Galway Formation has long been called the Theresa Sandstone play in the subsurface, but that name is inaccurate when compared to the outcrop stratigraphy. Smith et al. (2010) show that the Galway Formation is Upper Cambrian in age and occurs above the Potsdam Sandstone (earliest Upper Cambrian in age) and below the Little Falls Formation (uppermost Cambrian in age). The Theresa is Ordovician in age and is actually younger than even the Tribes Hill Formation. The Theresa can only be found in northernmost New York in the Ottawa Graben. The producing formation in Western New York is the Galway Formation. Smith et al. (2010) confirm that Bockhahn, Cascade Brook, and Northwoods fields all produced from the Rose Run, in the Galway Formation. Those are 3 of the 10 Galway fields in the New York database, and those 10 fields are all in the same region. It is believed that the Rose Run is the unit within the Galway which produced gas (B. Slater, pers. comm.). The following porosity and permeability core data are from the Hooker Chemical #1 Well, which include measurements from the Potsdam Sandstone. For this work, the Potsdam data were removed, as they are not stratigraphically part of the Galway Formation.

1. Average porosity: 6.5% for the Galway/Theresa/Rose Run reservoirs. (Smith et al., 2010)
2. Porosity perm relationship fit from core data, where k is permeability in units of mD and ϕ is porosity in porosity units (p.u.):

$$k = 0.6621\phi - 1.7261$$

3. Average permeability is 2.6 mD for a porosity of 6.5%, according to the above equation

ii. Galway in Pennsylvania and West Virginia: Data taken from reports of producing fields in Pennsylvania and West Virginia, in Roen and Walker (1996).

1. Porosity ranges from 2-25% and averages 10%.

2. Permeability ranges from 0.01 to 198 mD and averages 5 mD.
3. The MRCSP database reports porosities between 8-10 for the Galway/Rose Run fields, so an average of 5 mD was applied for all the PA and WV Rose Run reservoirs.

iii. Lithology: Sandstone

d. Medina: Data chosen for the Medina were taken from Lugert et al. (2006). No core data were available, so average values from a high-volume producing field–the Lakeshore Field–were applied. The following values were applied to Medina reservoirs in all three states.

i. Average porosity: The report states that porosity ranges between 6-8%, so an average porosity of 7% was chosen.

ii. Average permeability: 0.1 mD.

iii. Lithology: Sandstone

e. Onondaga: Data for Onondaga reservoirs come from Roen and Walker (1996). Average porosity and permeability values were derived from plugs taken from a productive Onondaga field in Steuben County, NY. The following values were used for reservoirs in all three states, due to a lack of permeability data available for Onondaga reservoirs in Pennsylvania and West Virginia. Because reported porosity values from Onondaga reservoirs in Pennsylvania and West Virginia were similar to the average porosity of Onondaga reservoirs in New York, the average permeability value from Onondaga reservoirs in New York was applied to those in Pennsylvania and West Virginia as well.

i. Average porosity: 5.2%.

ii. Average permeability: 22.4 mD.

iii. Lithology: Limestone

f. Oriskany: Data for the Oriskany reservoirs come from Appendix D of Riley et al. (2010). All the data presented there come from cores in Pennsylvania and Ohio, but were applied to reservoirs in New York and West Virginia as well.

i. Average porosity: 5%.

ii. Average permeability: 1 mD

iii. Lithology: Sandstone

g. Helderberg: There is one producing field from the Helderberg Formation in the database: the Stagecoach field. According to Lugert et al. (2006), geologists reclassified the producing formation of the Stagecoach to the Oriskany Formation (page 23).

h. Bass Islands: There is no available porosity or permeability data for the Bass Islands Formation in the Appalachian Basin; however, there are data from the Bass Islands Formation in the Michigan Basin (Harrison III et al., 2009). The following value were used for Bass Islands reservoirs in all three states.

i. Average porosity: 12.5%. This value from Harrison et al. (2009) agrees with the range of porosity values listed for Bass Islands reservoirs in the PA/WV database, which is 10–14% porosity.

ii. Average permeability: 22.4 mD

iii. Lithology: Dolomite

Formations found only in Pennsylvania and/or West Virginia regions of the Basin:

i. Lockport: Data for the Lockport reservoirs come from Appendix A of Riley et al. (2010).
   i. Porosity-permeability relationship fit from core data, where k is permeability in units of mD and ϕ is porosity in porosity units (p.u.):

$$k = 3.0\times10^{-5}\exp(1.1716\phi)$$

   ii. Lithology: Dolomite

j. Elk Group: For simplicity, the Brallier, Gordon, and Benson were combined into the Elk Group, based on formation grouping. Data for the Elk Group were taken from Roen and Walker (1996).
   i. Porosity of the Elk Group ranges from 5–10%
   ii. Permeability ranges from 0.1–2.0 mD.
   iii. Validation: The MRCSP database reports an average porosity of 11% for all the Elk Group reservoirs; therefore, the upper end of average permeability (2 mD) was used.
   iv. Lithology: Sandstone; clay-rich turbidite slope apron deposit (Roen and Walker, 1996).

k. Lockhaven: Lockhaven was given the same permeability values as Elk Group, but not renamed.
   i. Lithology: Mudstone

l. Bald Eagle: There is only one Bald Eagle reservoir in the MRCSP database: the Grugan field, located in Pennsylvania.

    i. Permeability: 0.07 mD was reported in Roen and Walker (1996). Most permeability is from fractures.
    ii. Lithology: Sandstone

m. Beekmantown: Lugert et al. (2006) state that there are no major distinctions between the reservoir properties of the Queenston and the Beekmantown, so they were not evaluated separately.
    i. Permeability: 0.185 mD
    ii. Lithology: Limestone/Dolomite
n. Berea:
    i. Porosity: 12% (Roen and Walker, 1996)
    ii. Permeability: 3.84 mD (Roen and Walker, 1996)
    iii. Validation: The Berea reservoirs in the MRCSP database report 10% porosity, which is consistent with the Roen and Walker (1996).
    iv. Lithology: Sandstone
o. Chazy: According to Walcott (1896), the Chazy is another term for the Black River limestone. These fields are listed as having porosity of 8% in the MRCSP database. Their formation name was therefore changed to Black River, and the empirical porosity-permeability relationship from the Black River reservoirs in New York was applied. This results in a permeability of 99.5 mD for all four reservoirs in Pennsylvania.
p. Helderberg: According to Lewis et al. (2009), the permeability of the Helderberg Formation is very low, approximately 0.001 mD.
    i. Lithology: Limestone

q. Huntersville and Huntersville/Oriskany play: Riley et al. (2010) provides a maximum permeability of 0.003 mD for the Huntersville/Oriskany play. This value was used for the Huntersville reservoirs as well, due to a lack of data unique to the Huntersville.

    i. Lithology: Chert and Sandstone

r. Loysburg: Applied values from Beekmantown Dolomite. No other data available.

s. Newburg: The accompanying database to Roen and Walker (1996) contains two sets of core porosity and permeability data points. Because the other fields without permeability data had very similar porosity values, those data were fit to get an exponential relationship where permeability is in mD and porosity is in porosity units:

$$k = 2.1591\exp\left(0.1699\phi\right)$$

    i. Lithology: Limestone

t. Weir: There are two Weir reservoirs with porosity data in the MRCSP database, and one of those reservoirs is listed in Roen and Walker (1996) and has average porosity and permeability values. Because the porosity values aligned with what was already reported in the MRCSP database, the following permeability value was applied to both reservoirs.

    i. Permeability: 8 mD
    ii. Lithology: Sandstone

u. Keefer:

i. Permeability: Roen and Walker (1996) report an average permeability for the Keefer Formation of 7.06 mD. That value was applied to the single Keefer reservoir in the MRCSP database.

ii. Lithology: Sandstone

v. Devonian Unconformity Play:

i. Permeability: Roen and Walker (1996) report an average permeability of 15.3 mD for this formation.

ii. Lithology: Limestone

Formations with Very Limited Data:

w. Tuscarora: Roen and Walker (1996) report one Tuscarora field with permeability ranging from 0 to 10.7 mD. Many reports note similarities between Tuscarora, Medina, and Clinton. Due to a lack of specific data, a value of 0.1 mD was used for the Tuscarora, consistent with the Medina Formation.

i. Lithology: Sandstone

x. "Multi": These are reservoirs that produced hydrocarbons from a wide variety of undetermined formations. With no data to use, a high uncertainty and low permeability value of 0.1 mD was used.

y. Trenton: This play is found only in West Virginia, where permeability is associated primarily with fractures. Just like similar play types, a permeability of 0.1 mD was applied because more precise data cannot be found.

i. Lithology: Limestone

z. Tully: There is only one Tully reservoir in the MRCSP database. There is no permeability data available, so it was assigned a low permeability value of 0.1 mD with a high uncertainty.
    i. Lithology: Limestone

aa. Mahantango: There is only one Mahantango reservoir in the MRCSP database. There are no permeability data available, so it was assigned a low permeability value of 0.1 mD with a high uncertainty.
    i. Lithology: Mudstone

UNCERTAINTY INDEX ASSIGNMENTS

Permeability

The following list describes how the uncertainty index was assigned to each reservoir's permeability value, and the respective assignment of standard deviation from the mean:

0: Data is site-specific (pertains to that *exact* reservoir). This assignment was very uncommon. 0% SD

1: Published porosity-perm equation available from local/nearby reservoirs of same formation. Standard deviation: 12.5% SD

2: Data come from use of a published equation from data that is region specific. Standard deviation: 25% SD

3: Computed equation from available data; Range or average value for the formation is available, or state/region specific data are available. Standard deviation: 50% SD

4: Porosity-permeability relationship (or average value) can be applied from a similar formation or same formation from another state/region. Standard deviation: 100% SD

5: Generic low value assigned due to lack of data or understanding. Standard deviation: 200% SD

Reservoir Thickness

The following list describes how the uncertainty index was assigned to each reservoir's thickness value:

0 Not used for reservoir thickness. 0% SD

1 Not used for reservoir thickness. 10% SD

2 Assigned to all reservoirs in the project, because all reservoir thickness data are derived from the producing thickness of the hydrocarbon reservoir. 20% SD

3 Not used for reservoir thickness. 30% SD

4 Not used for reservoir thickness. 40%

5 Not used for reservoir thickness. 50%

Fluid Viscosity

Because fluid viscosity is a function of the reservoir temperature, the uncertainty of the assigned viscosity values was dependent on the uncertainty underlying the calculation of the temperature of the reservoir. The following list describes how the uncertainty index was assigned to each reservoir's fluid viscosity value:

0 Not used for fluid viscosity. 0% SD

1 Assigned to all reservoirs in the project. One standard deviation of the reservoir temperatures is 10ºC, which equates to a viscosity standard deviation of approximately 10% from the mean value. 10% SD

2 Not used for fluid viscosity. 20% SD

3 Not used for fluid viscosity. 30% SD

4 Not used for fluid viscosity. 40% SD

5 Not used for fluid viscosity. 50% SD

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