Constraining Estimates of In-place Resources and Recovery Efficiency using Production Data

An Example from the Marcellus Play in Northern West Virginia

Ray Boswell
DOE/NETL

B.J. Carney
Northeast Natural Energy

Susan Pool
West Virginia Geological and Economic Survey

NATIONAL ENERGY TECHNOLOGY LABORATORY

northeast NATURAL ENERGY

WVGES GEOLOGY UNDERLIES IT ALL

Appalachian Geological Society, November 12, 2019

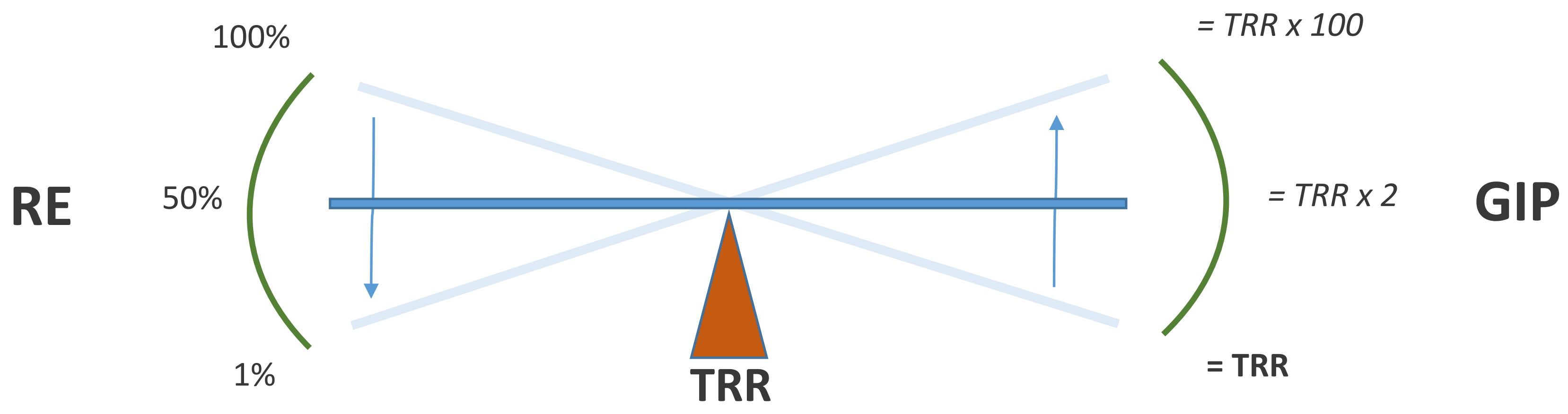
U.S. DEPARTMENT OF ENERGY

Introduction: Recovery Efficiency

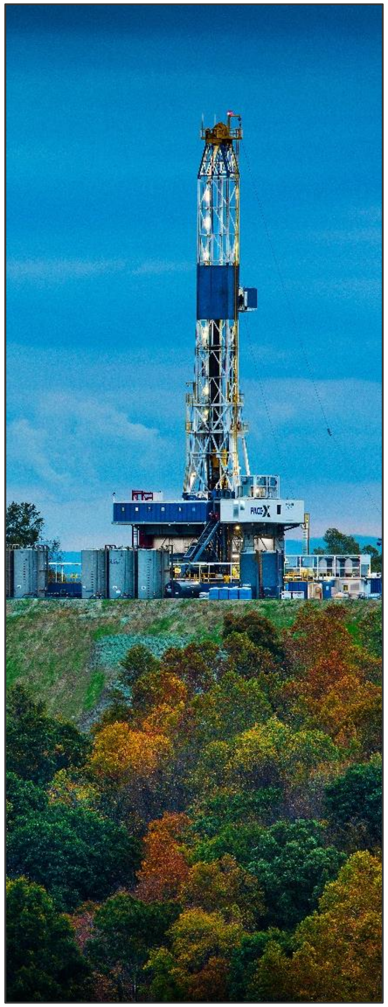
RE = TRR / In-Place Resources

- **Recovery Efficiency:** Many assume **RE** is low, but evidence is anecdotal.
- **Technically-Recoverable Resources:** Several public-domain assessments, but they do not agree. Relies on ability to estimate the Estimated Ultimate Recovery (and spacing) of current and future wells.
- **In-Place Resources:** A deceptively simple formula, but highly uncertain in unconventional applications. Must be greater than TRR!

The growing database of well histories provides greater confidence in EURs → a chance to constrain GIP & RE

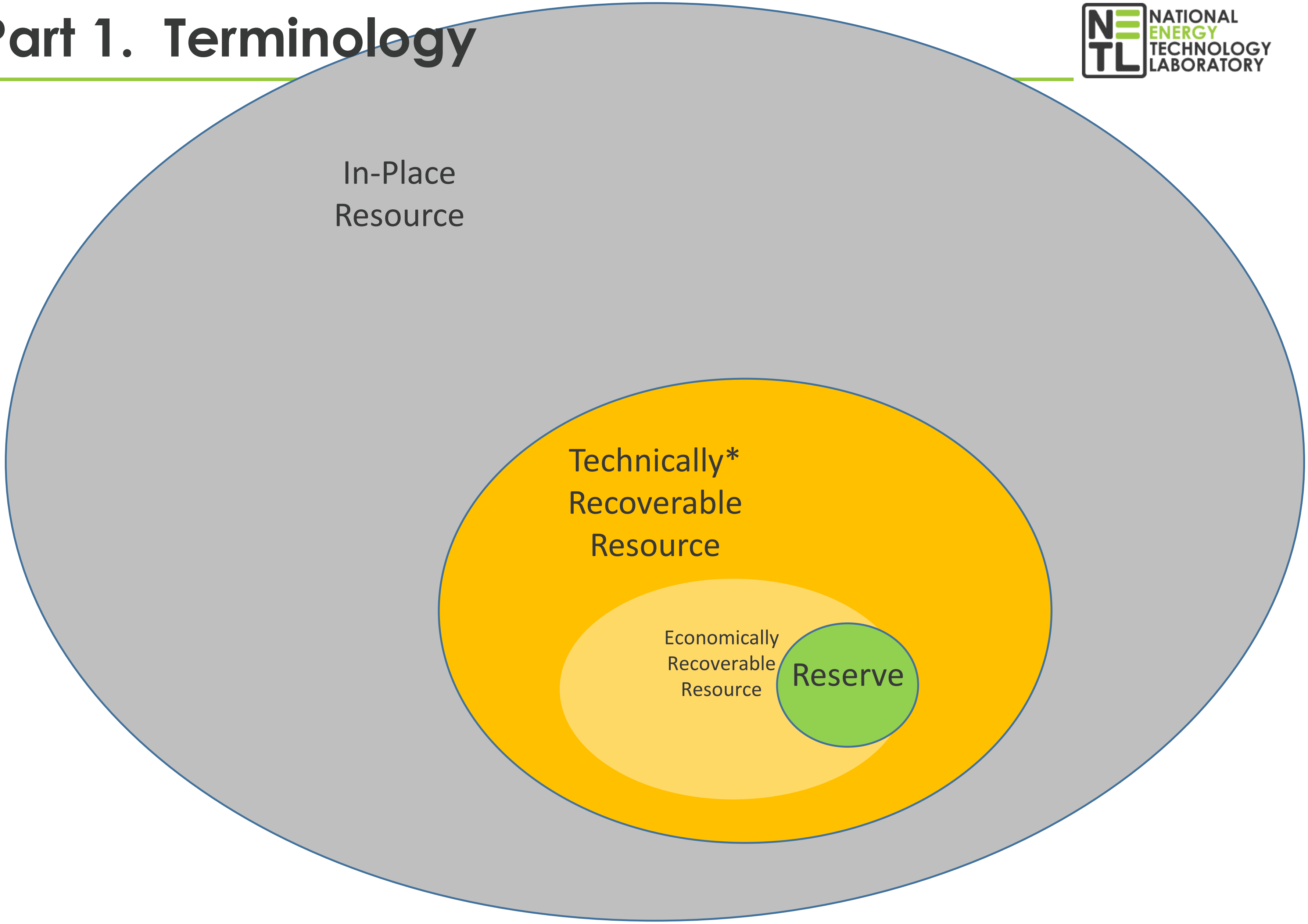


Outline



1. Define Terminology
2. Review existing assessments of resources and recovery for Marcellus development
3. Review our approach to estimating RE in northern West Virginia
4. Show that, using standard approaches, wells appear capable of producing more gas than was thought to be in the ground. ie TRR > GIP
5. Discuss potential explanations…
6. … and some very initial findings

Part 1. Terminology



**practically*

Resources Volumes are Not Static

Original Gas-in-Place (OGIP, OOIP…)

- *f (geology)*
- *fixed! …but not necessarily well known…*
- *all that exists*

Technically Recoverable (TRR)*

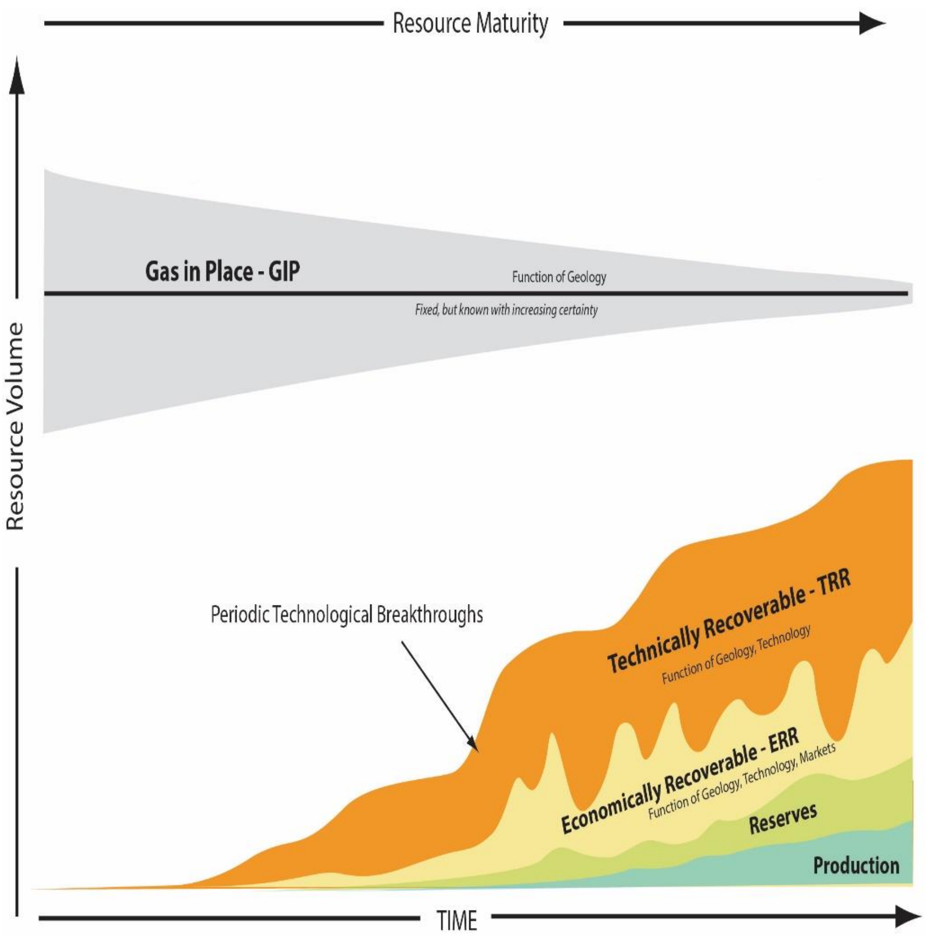
- *f (GIP + technology, policy/regulation, capacity?)*
- *always changing… always increasing…*
- *all that **is available to** be produced*

Economically Recoverable (ERR)

- *f (TRR + costs, prices, capacity)*
- *can contract…*
- *all that can be produced at a profit at a certain time*

Reserves (numerous categories)

- *f (drilling results/data certainty/economics)*
- *Confirmed by drilling and available for production*

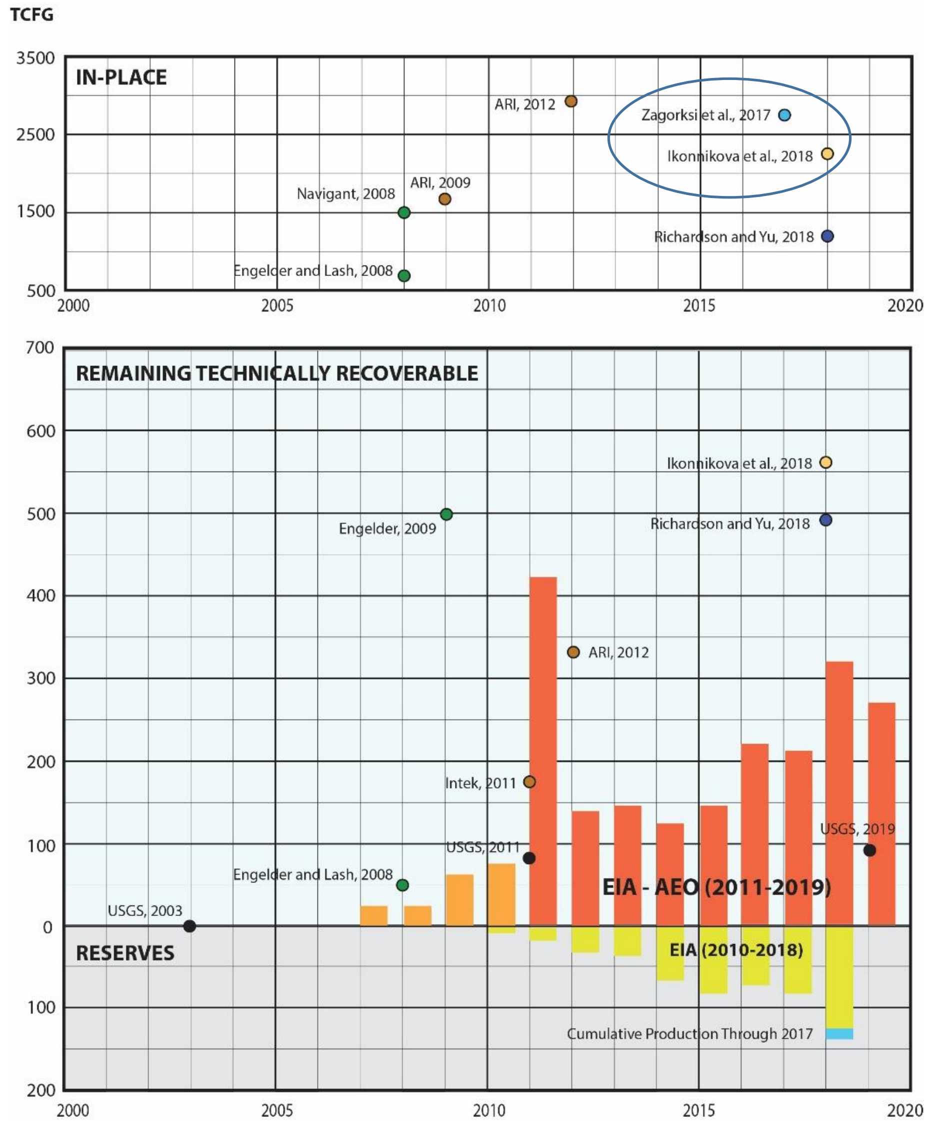


** most commonly assessed (often as remaining TRR) – but often includes inherent economic assumptions….*

Part 2: Marcellus Assessments

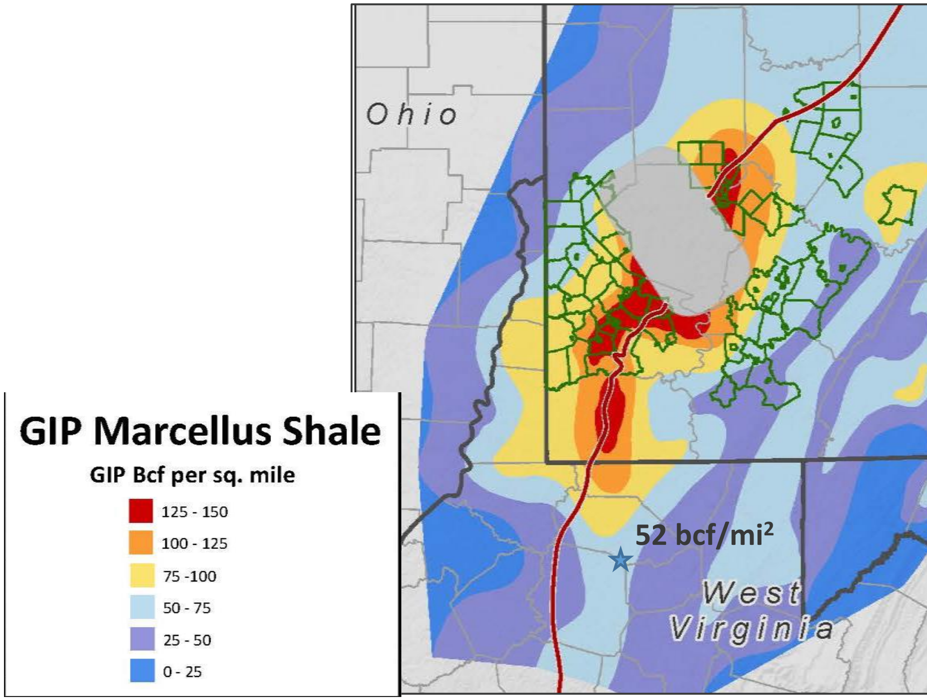
2000 - present

IN PLACE RESOURCES	**2,227 Tcf** (UT-BEG, 2018) **1,313 Tcf** (Richardson & Yu, 2018) **2,686 Tcf** (Zagorski et al., 2017) **2,912 Tcf** (ARI, 2012) **1,500 Tcf** (Navigant, 2008) **512 Tcf** (Lash and Engelder, 2008) **~250 Tcf** *(NPC, USGS, early 1990s)*
REMAINING TECHNICALLY-RECOVERABLE RESOURCES	**96 Tcf** (USGS, 2019) **263 Tcf** (EIA, 2019, 2018, 2017…) **560 Tcf** (UT-BEG, 2018) **492 Tcf** (Richardson & Yu, 2018) **~330 Tcf** (ARI, 2012) **84 Tcf** (USGS, 2011) **498 Tcf** (Engelder, 2009) **50 Tcf** (Engelder and Lash, 2008)
RESERVES	**124 Tcf** (EIA, 2018)
PLAY-SCALE RECOVERY EFFICIENCY	**25-30%** (UT-BEG, 2018) **37-48%** (Richardson & Yu, 2018) **9%** (OGJ, 2014) **11%** (ARI, 2012)
SMALL-SCALE RECOVERY EFFICIENCY	**10%** (Seals et al., 2017) from SRV **50%** (inferred from Industry data)

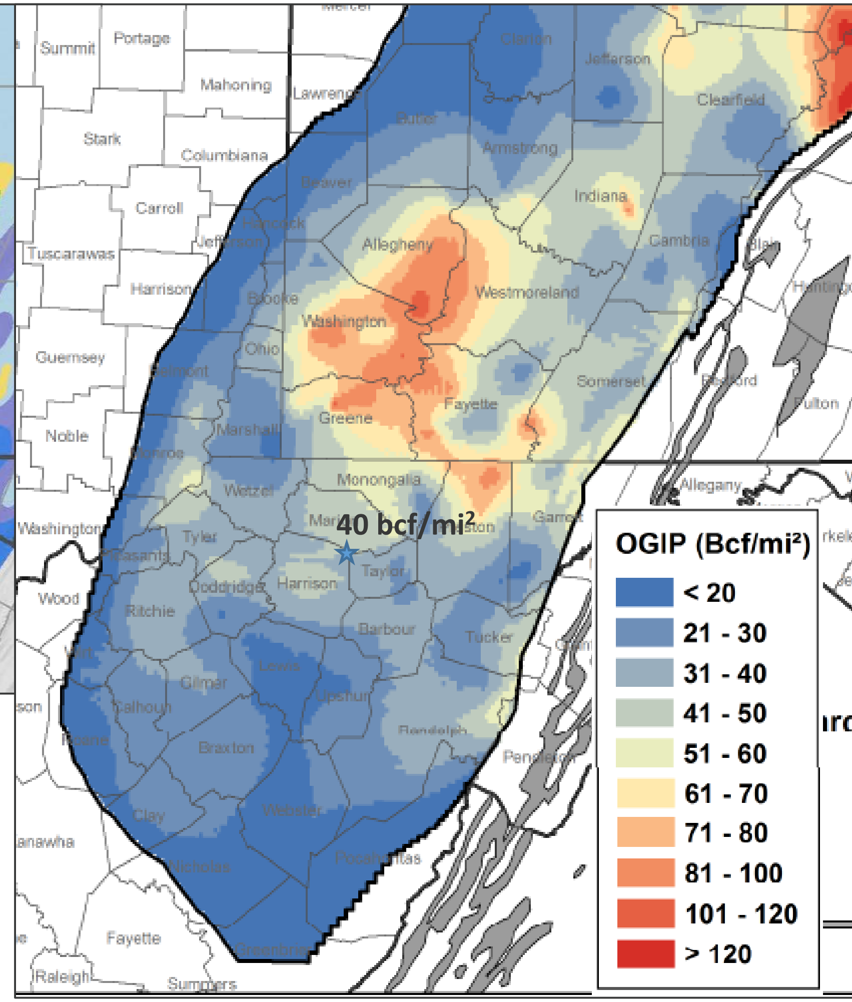


GIP/mi²: Public-Domain Marcellus Est.

Range Resources (2016, 2017) -- UT BEG (2018)



Zagorski et al., 2016



Ikonnikova et al., 2018

GIP/mi² estimates can be generated for any given spot on the map

Marcellus Shale TRR Assessments (Gas)

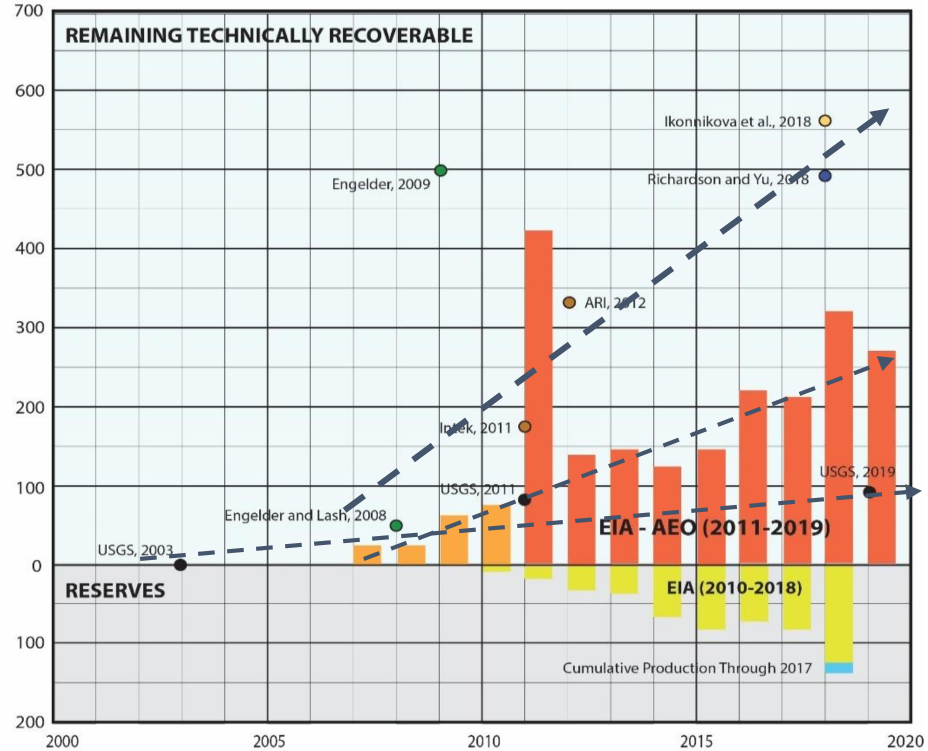
NATIONAL ENERGY TECHNOLOGY LABORATORY

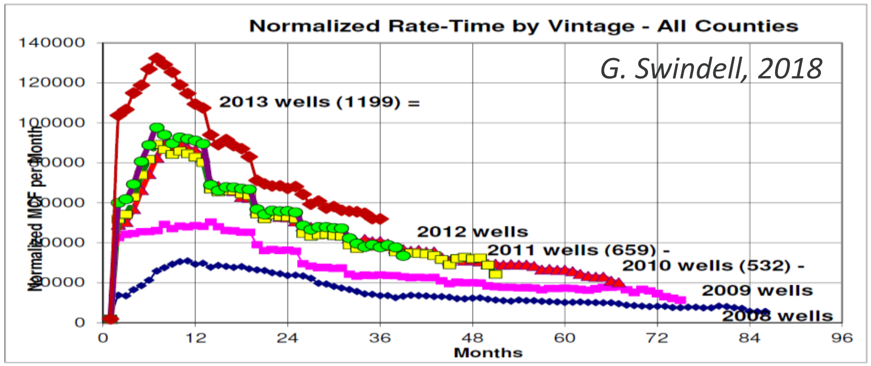
2000 - present

- TRR is the goal of public-domain assessments (**USGS, EIA**)
- Expected expansion is noted – but disparity between assessments appears to be increasing

---

- TRR = EUR/Well * Number of remaining well locations
- Because EUR is a **f**(technology) -- which is a **f**(time)… past well performance will understate future well performance; (particularly true in unconventionals)
- No mapped assessments of TRR to allow comparison to areal GIP/mi^2 data.





Quick USGS – EIA Comparison

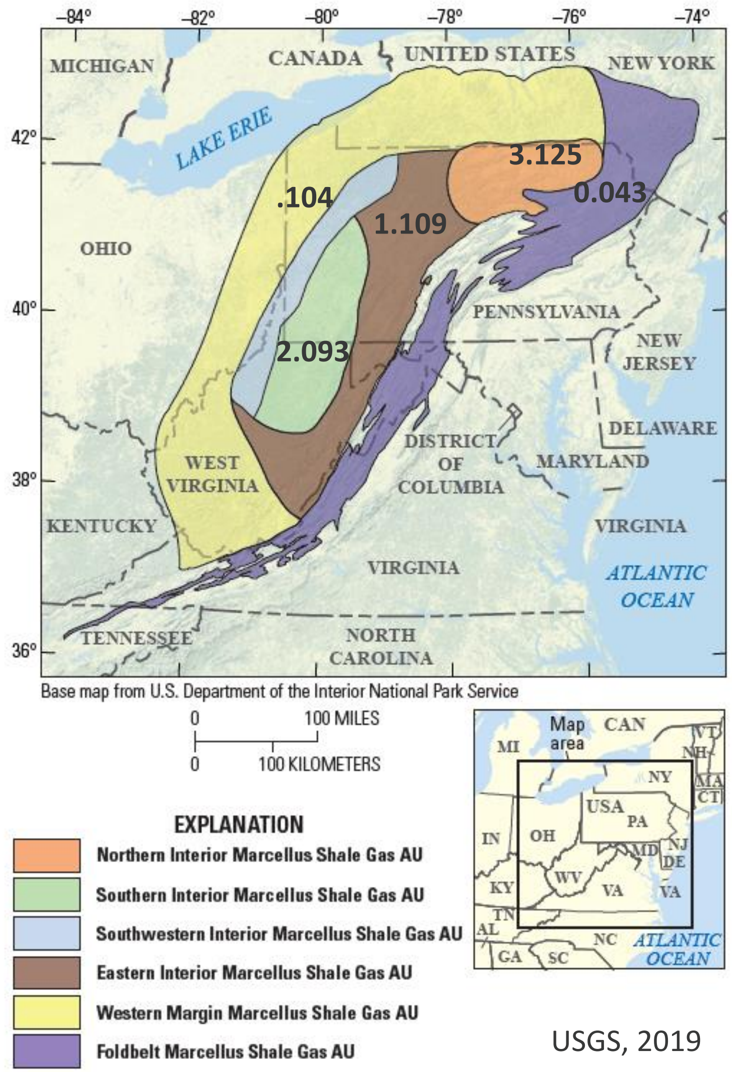
2019 Remaining TRR assessments

USGS (2019)   96.5 Tcf mean

- 11.4 million acres remaining productive
- Spacing is 1 well per 146.7 acres
- EUR = 2.093 bcf/well in N. WVa
- EUR is fixed.

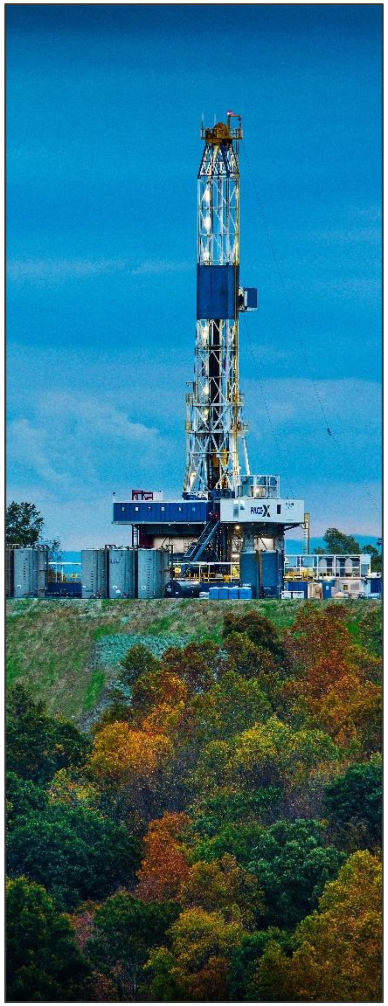
EIA (2019)   262.5 Tcf+ (2017)

- 18 million acres
- Spacing is 1 well per 148 acres
- EUR = 2.425 in N WVa.
- EUR allowed to grow (1%+/yr)



USGS, 2019

Summary Part 2: Status of Assessments



- General consensus on regional Marcellus GIP → 2,000 to 3,000 Tcf & two independent sources for GIP at any location
- No general consensus on regional Marcellus TRR → 90 to 560 Tcf
- Therefore, current information does not allow reasonable assignment of RE, nor provide any insight on how it might vary spatially….

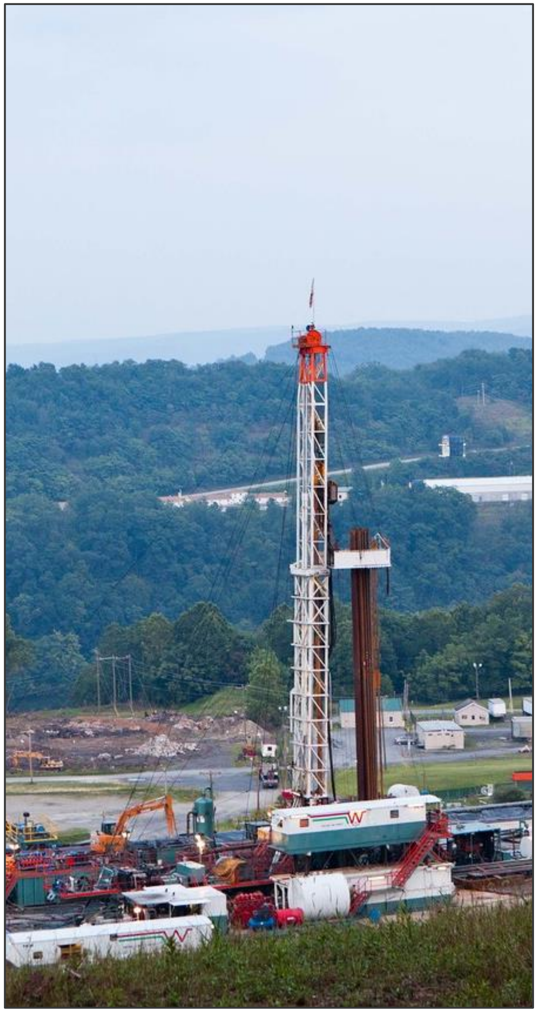
90 TRR / 3,000 GIP = **3%** ***to*** 560 TRR / 2,000 GIP = **28%**

(regional averages only)

- Potential sources for variances in TRR include:
  1. Selection of wells to use in calculation of future EUR
  2. Uncertainty in translating production data to EUR
  3. Determination of total play area…

Part 3: Approach to constrain RE

RE = EUR/In-Place IN WHAT SPECIFIC VOLUME…?



Well: RE = EUR/in-place in a single SRV

- *f* (geology, technology)
- Likely to yield highest but most variable, unconstrained RE

Pad(s): RF = Sum of EURs/in-place in a multi-well SRV

- *f* (geology, technology, well spacing, lease geometry)
- Often drilled over a short period of time by one operator using consistent approach and with goal to fully drain a specific area

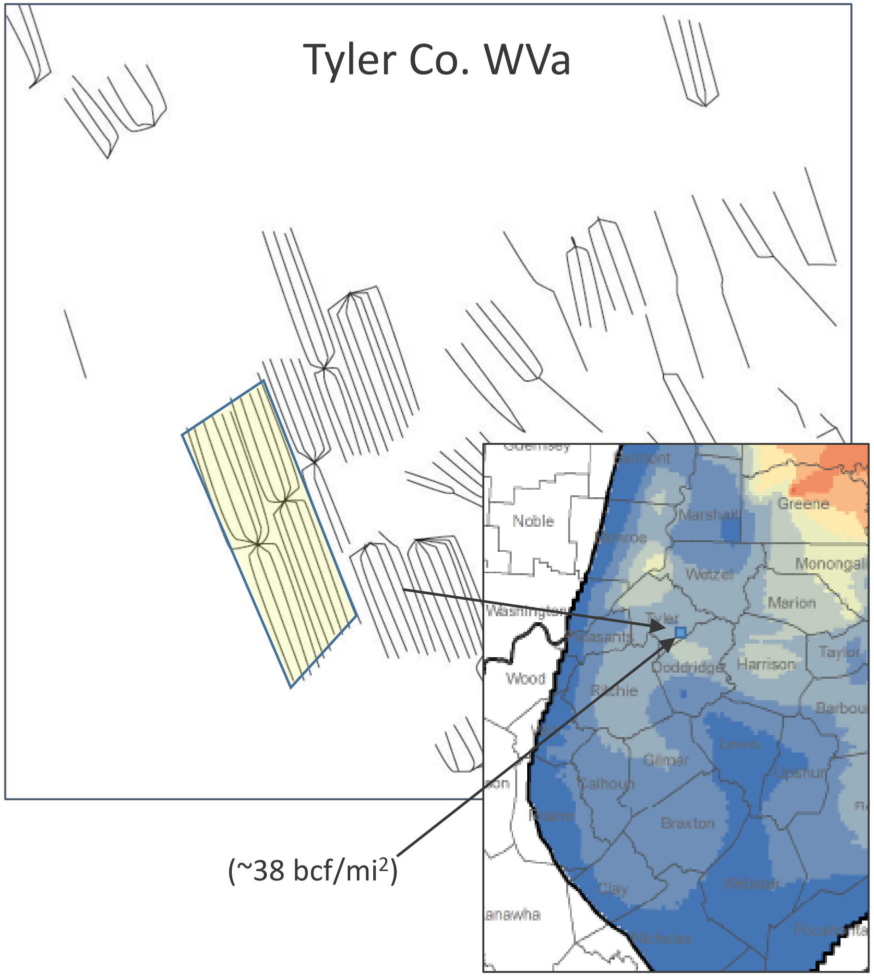
Play/Basin: RF = Sum of EURs/in-place in Play

- *f* (geology, technology, well spacing, lease geometry), plus variable
- … reservoir quality, pressure, etc….
- … operators, w/ different views on technology, spacing, etc…
- … regulatory environments…
- Hence lowest and least meaningful RE's… ("10%")

Recovery Efficiency: Approach

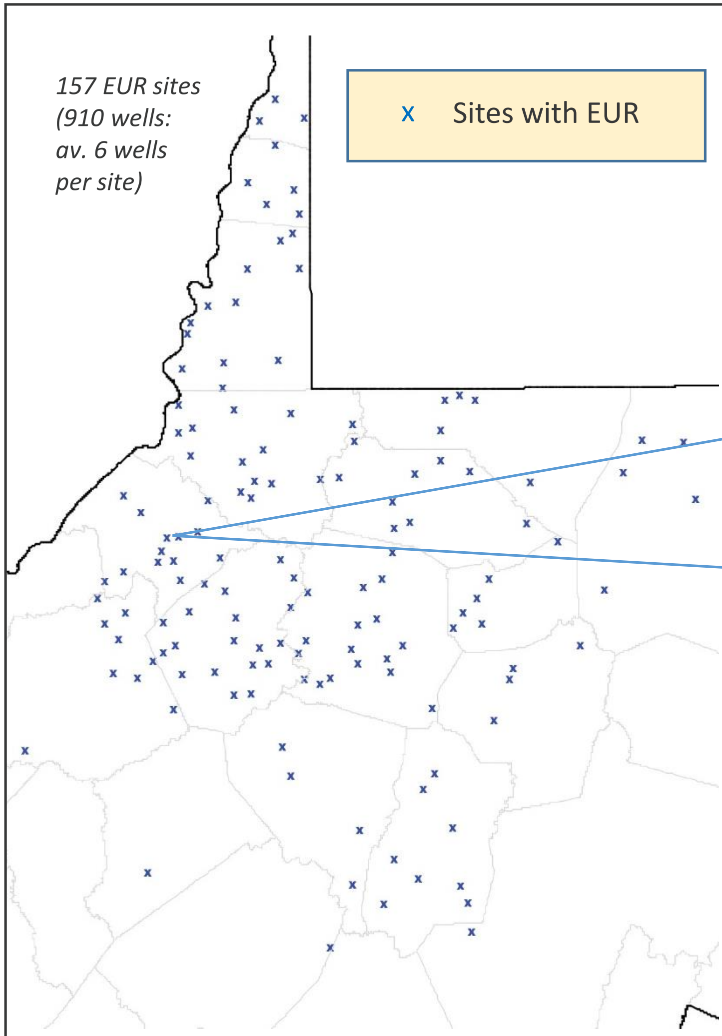
RE = EUR/GIP per unit area at Pad/Lease Scale

- Identify sites that appear to be fully developed (at likely ultimate spacing).
  - Common operator with common completion approach (vintage).
- Determine Total Area (mi^2) for each
  - = sum of lateral length X spacing
- Sum all well EURs → TRR for each
- Convert to TRR/mi^2
- Compare to two existing GIPs/mi^2 estimates for that location to calculate recovery efficiency.
- Repeat for 157 such sites and map…



Example EUR Datasets

Case Studies: Tyler Co. WVa

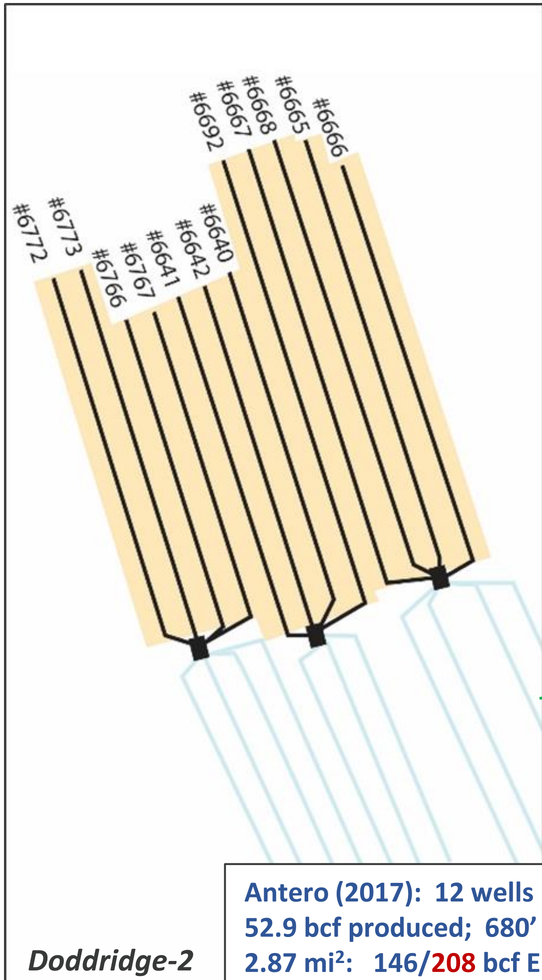


	A	B	C	D	E	G	J	K	M	N	O	P
1		API	Operator	County	Comp. Date	Horizontal Length	Mos.	Cum BCFGE	EUR Oil (BE)	EUR Gas (BE)	Total EUR	EUR B-Factor
701		4709502171	Antero	Tyler	7/6/2017	8456.12	18	3.4755				87
702		4709502265	Antero	Tyler	7/10/2017	8661.98	18	3.4744				29
703		4709502269	Antero	Tyler	6/28/2017	8322.19	18	3.6991				31
704	2	4709502270	Antero	Tyler	7/2/2017	8215.98	18	3.2945				13
705		4709502275	Antero	Tyler	6/23/2017	8310.48	18	2.9973				42
706		4709502306	Antero	Tyler	6/19/2017	7610.06	18	3.6471				97
707		4709502307	Antero	Tyler	6/15/2017	13293.68	18	5.9688				.3
708		4709502308	Antero	Tyler	7/14/2017	7280.16	18	3.3652				41
709		4709502277	Antero	Tyler	11/26/2016	11433.99	25	2.2657				97
710		4709502254	Antero	Tyler	12/13/2016	11578.84	25	2.2787				73
711		4709502293	Antero	Tyler	12/7/2016	10746.95	25	1.9439				29
712		4709502294	Antero	Tyler	12/2/2016	10538.3	25	2.5938				.6
713	3	4709502304	Antero	Tyler	11/19/2016	10409.26	25	4.6904				46
714		4709502335	Antero	Tyler	12/6/2016	11026.09	25	2.4507				0
715		4709502336	Antero	Tyler	12/12/2016	10935.71	25	2.6784				12
716		4709502337	Antero	Tyler	12/1/2016	10753.61	25	1.9164				0
717		4709502338	Antero	Tyler	11/26/2016	10778.84	25	2.4011				51
718		4709502276	Antero	Tyler	11/20/2016	10463.7	25	2.3603				33
719		4709502172	Antero	Tyler	4/17/2016	10926.43	33	5.0148				2
720		4709502173	Antero	Tyler	4/23/2016	10594.72	33	4.9445				83
721		4709502174	Antero	Tyler	4/23/2016	10154.78	33	5.9219				49
722	4	4709502169	Antero	Tyler	4/4/2016	11587.76	33	5.2221				31
723		4709502181	Antero	Tyler	4/18/2016	12574.76	33	5.7807				75
724		4709502182	Antero	Tyler	4/11/2016	12231.12	33	6.1115				47
725		4709502183	Antero	Tyler	4/2/2016	11531.59	33	5.8985				09
726		4709502032	EQT	Tyler	2/13/2013	6716.91	31	2.8445				2
727	5	4709502176	EQT	Tyler	7/15/2015	6706.18	27	2.1931				17
728		4709502177	EQT	Tyler	7/15/2015	8129.39	28	2.777				92
729		4709502178	EQT	Tyler	8/1/2015	7175.51	27	2.1002				37
730		4709502348	Antero	Tyler	11/22/2017	8708.24	8	0.8676				91
731		4709502349	Antero	Tyler	11/22/2017	8531.25	8	0.8543				2
732	6	4709502350	Antero	Tyler	3/27/2018	9518.81	8	1.6132				2
733		4709502354	Antero	Tyler	4/17/2018	9175.34	8	1.474				2
734		4709502372	Antero	Tyler	3/21/2018	9168.16	8	1.6399				2
735		4709502374	Antero	Tyler	3/19/2018	9024.46	8	1.9611				97
736		4709502040	Triad Hunter	Tyler	11/14/2013	5370.96	49	3.8866				68
737	7	4709502041	Triad Hunter	Tyler	11/14/2013	5952	49	4.202				42
738		4709502042	Triad Hunter	Tyler	11/13/2013	6268.67	49	4.1283				57
739		4709502043	Triad Hunter	Tyler	11/12/2013	7043.81	49	4.8255				87
740		4709502096	Jay-Bee	Tyler	4/26/2014	7467.73	56	3.8174				2
741	8	4709502097	Jay-Bee	Tyler	4/22/2014	6790.28	56	3.8667				11
742		4709502098	Jay-Bee	Tyler	4/22/2014	7118.45	56	4.0166				73
743		4709502282	Antero	Tyler	9/14/2017	8960.45	14	2.0524				2
744		4709502283	Antero	Tyler	1/31/2018	8939.27	11	2.1307				82
745		4709502284	Antero	Tyler	9/6/2017	8843.14	14	2.3805				39
746		4709502285	Antero	Tyler	9/11/2017	9828.66	14	2.8865				47

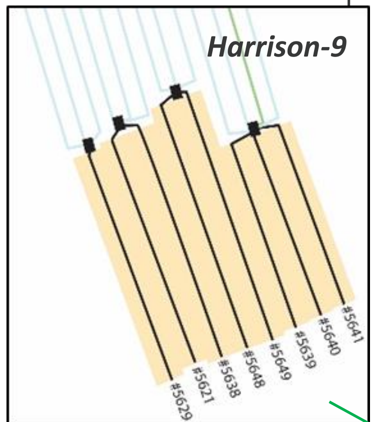
Select Area Summaries | Play A Wells | Vintage Ohio River | Play B Wells | Vintage - Tyler Co | Vintage NW Dodd Co. | Vintage - SW Doddridge

Example EUR sites

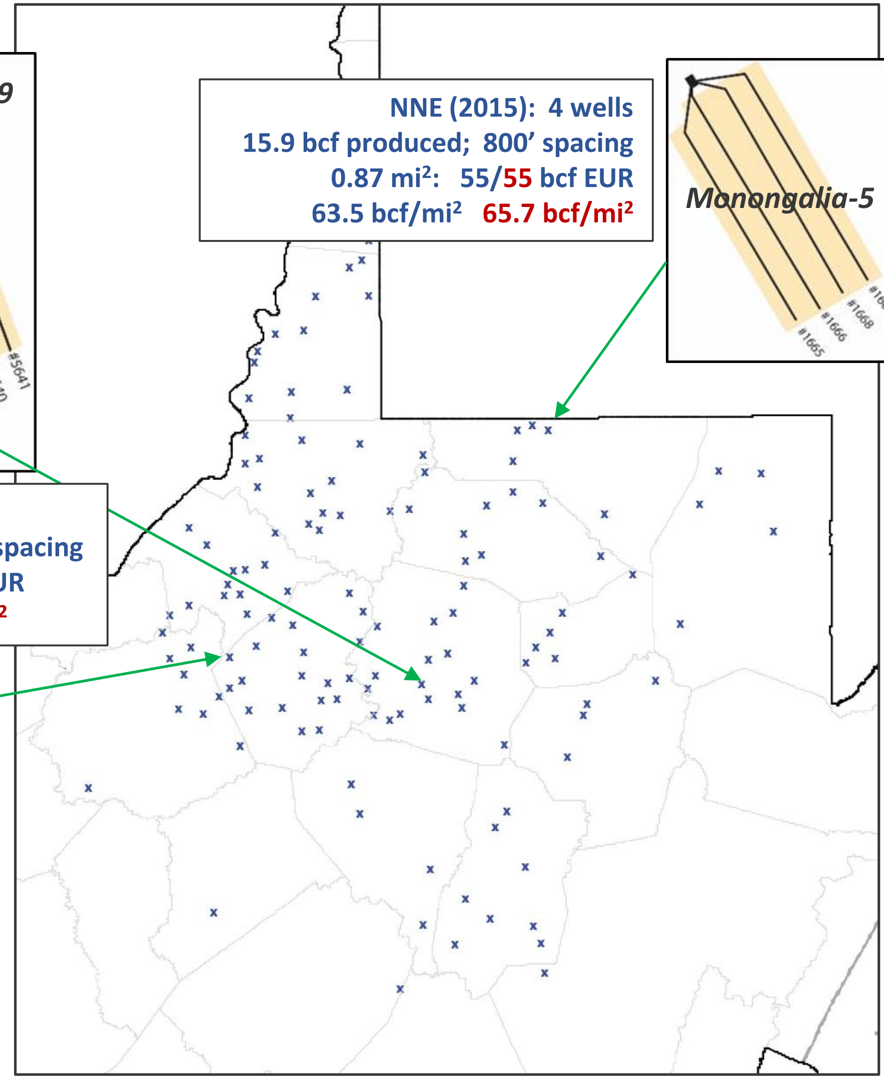
3 of 157 studied



Antero (2017): 12 wells
52.9 bcf produced; 680’ spacing
2.87 mi^2: 146/**208** bcf EUR
51.1 bcf/mi^2 **75.2 bcf/mi^2**



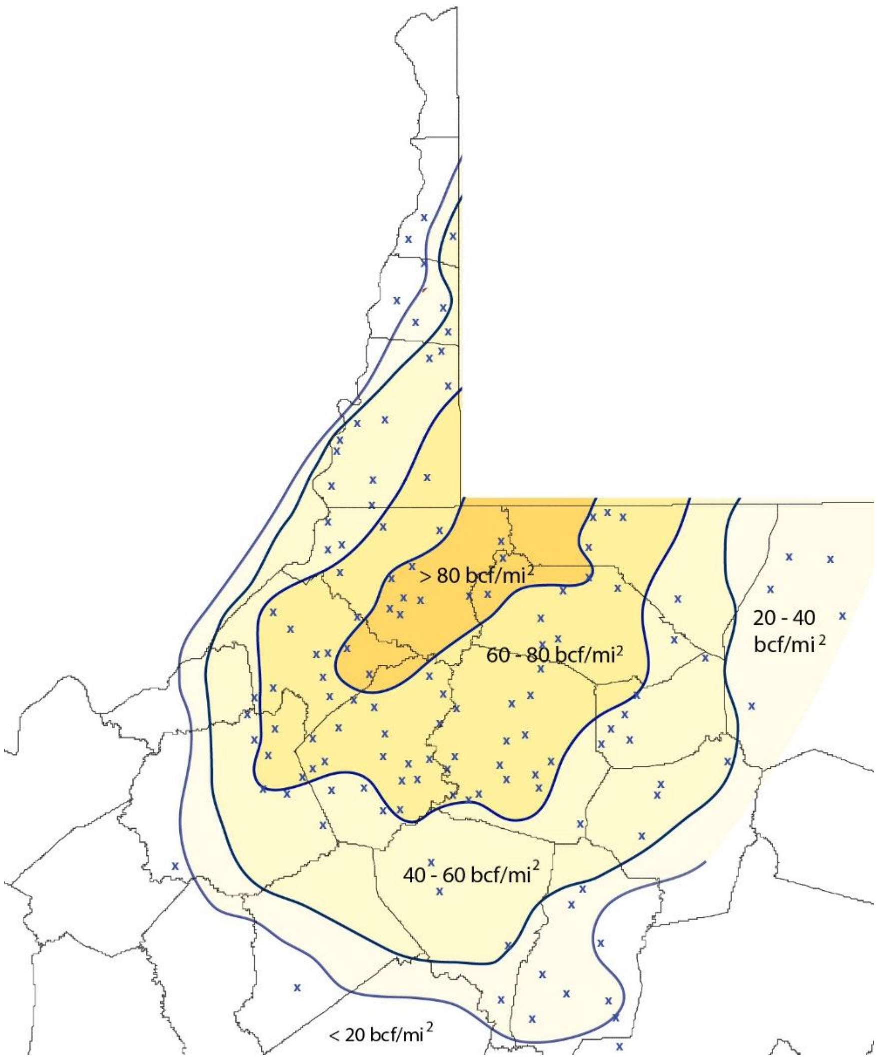
Antero (2013): 8 wells
44.9 bcf produced; 705’ spacing
1.70 mi^2: 105/**108** bcf EUR
52.0 bcf/mi^2 **64.1 bcf/mi^2**

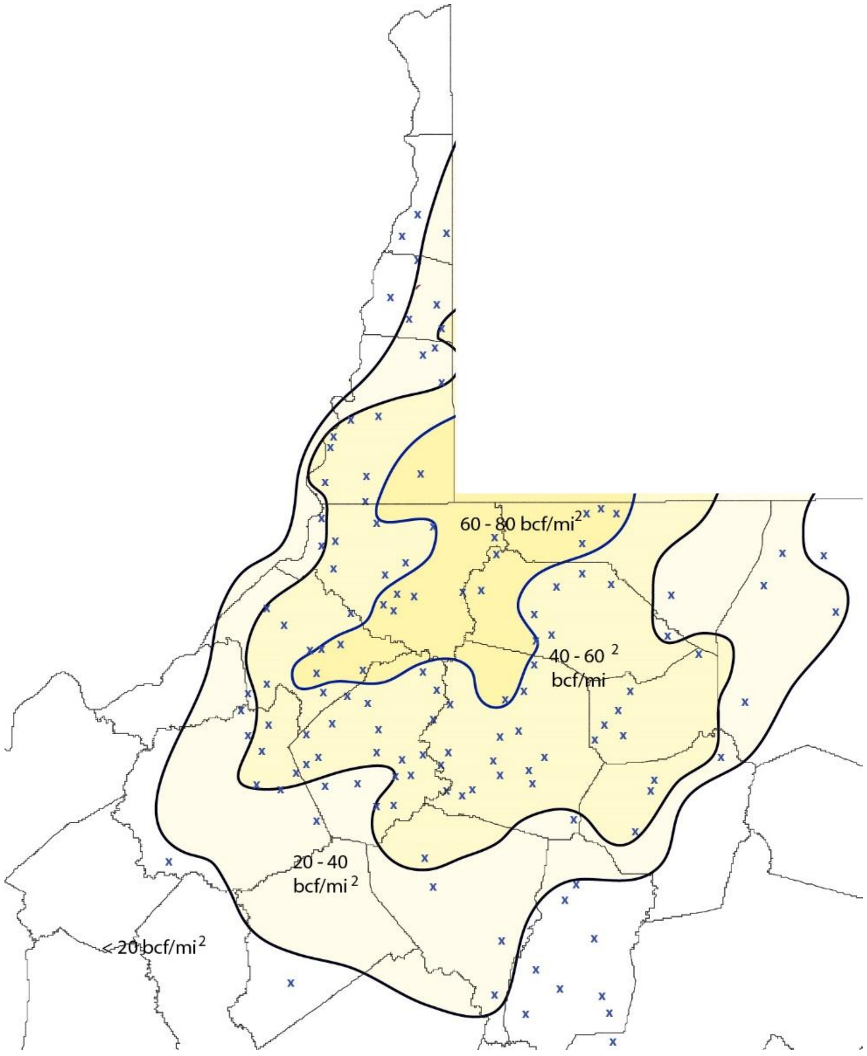


NNE (2015): 4 wells
15.9 bcf produced; 800’ spacing
0.87 mi^2: 55/**55** bcf EUR
63.5 bcf/mi^2 **65.7 bcf/mi^2**

Part 4: Initial Results

Recovery per mi² using alternative EUR sources with well life = 50 yr

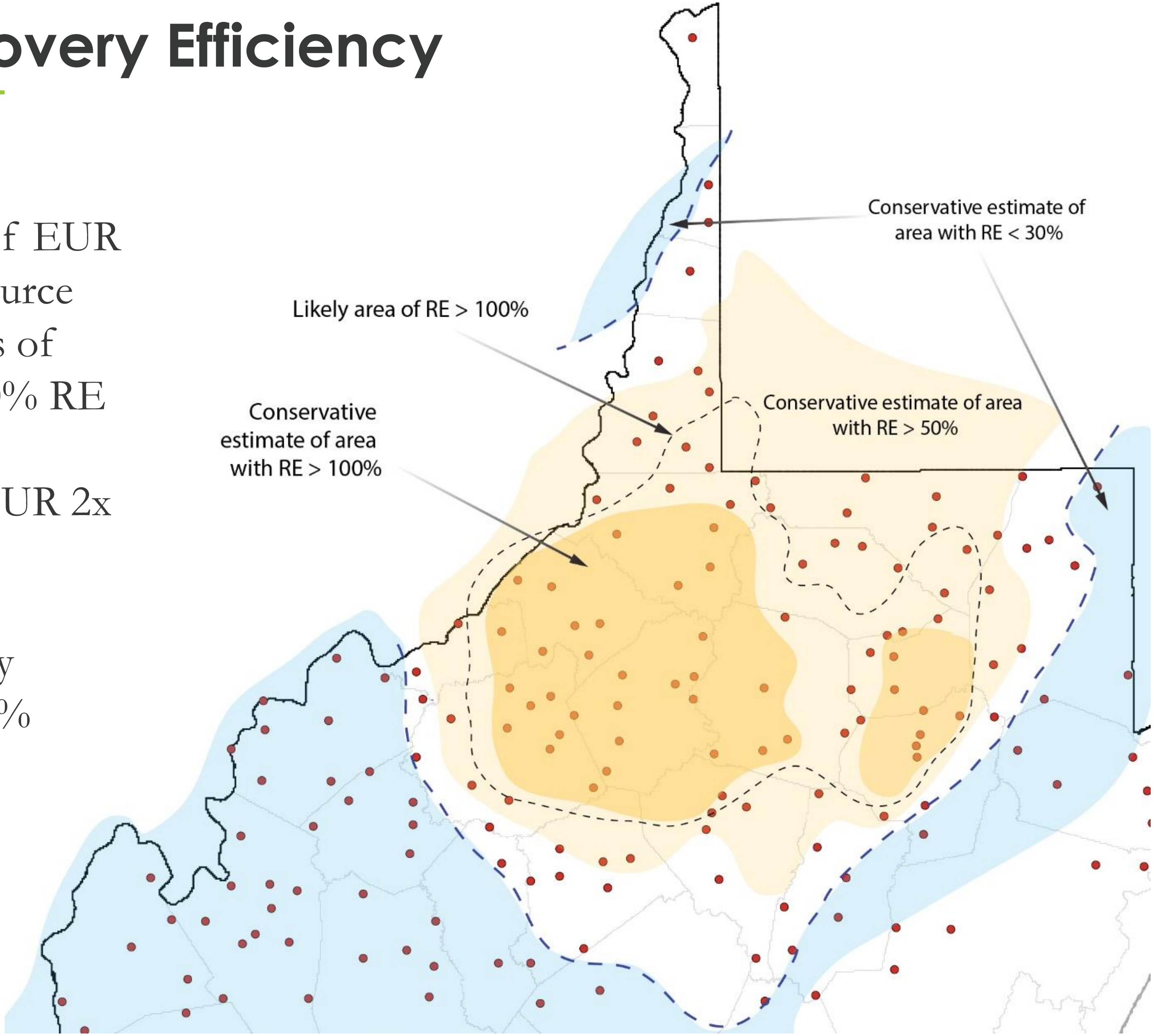




Results: Recovery Efficiency

Initial (Impossible) Results

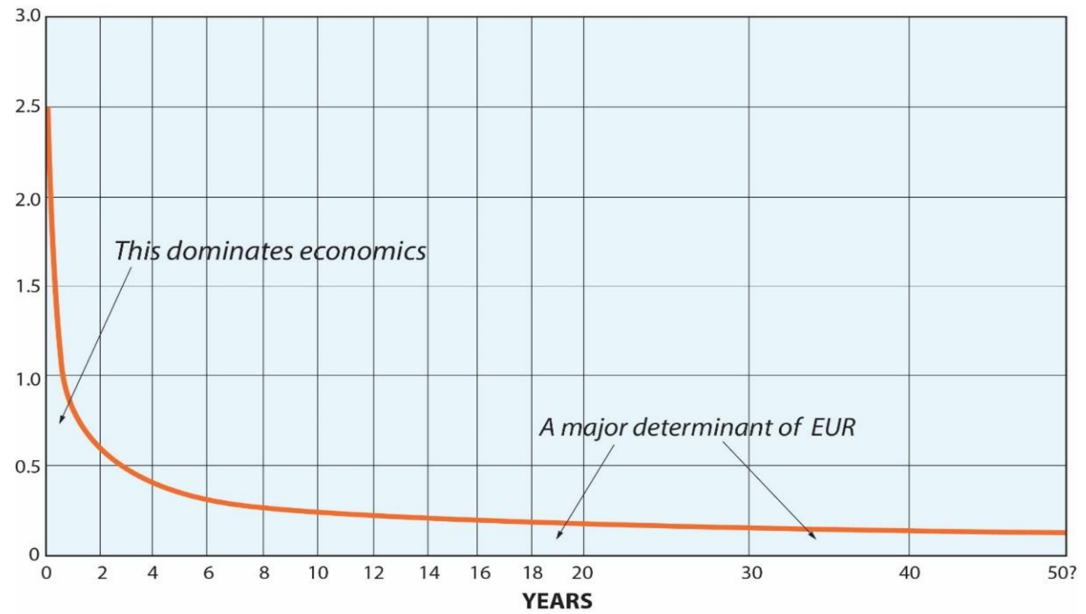
- All permutations of EUR source and GIP source result in large areas of the play with >100% RE
- Some areas have EUR 2x or 3x GIP
- Virtually entire play area with RE > 50%

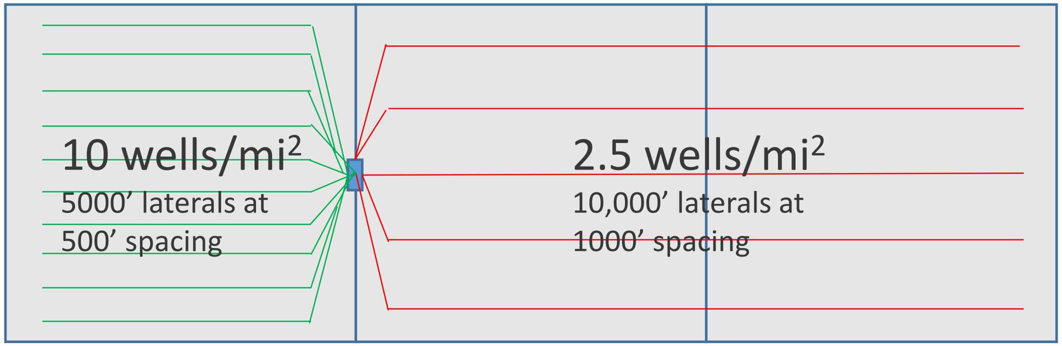


Part 5: Explanation: EUR too high?

Uncertainties: Reservoir Behavior, Well Life Assumption, and Spacing

- EUR approaches differ, but nature of decline is generally agreed upon…
- Ultimate recovery is not yet observed for Marcellus wells
  - EURs will become increasingly reliable with time and experience.
- A primary source of uncertainty…how long will the wells produce? (20 years? 50 years?).
- Another source of confusion… variable spacing and lateral lengths complicate conversion of EUR/well into EUR/mi^2
- Two independent EUR sources used.





Explanation: GIP too low?

A very likely culprit

- GIP assessments (ex. Zagorski et al., 2016) acknowledge conservative nature of GIP values…
- The simple GIP equations are anything but simple in the shale context…

GIP (total) = GIP (free) + GIP (adsorbed)

GIP(free) = Volume (Area x Thickness) x Porosity x HC Saturation x FVF

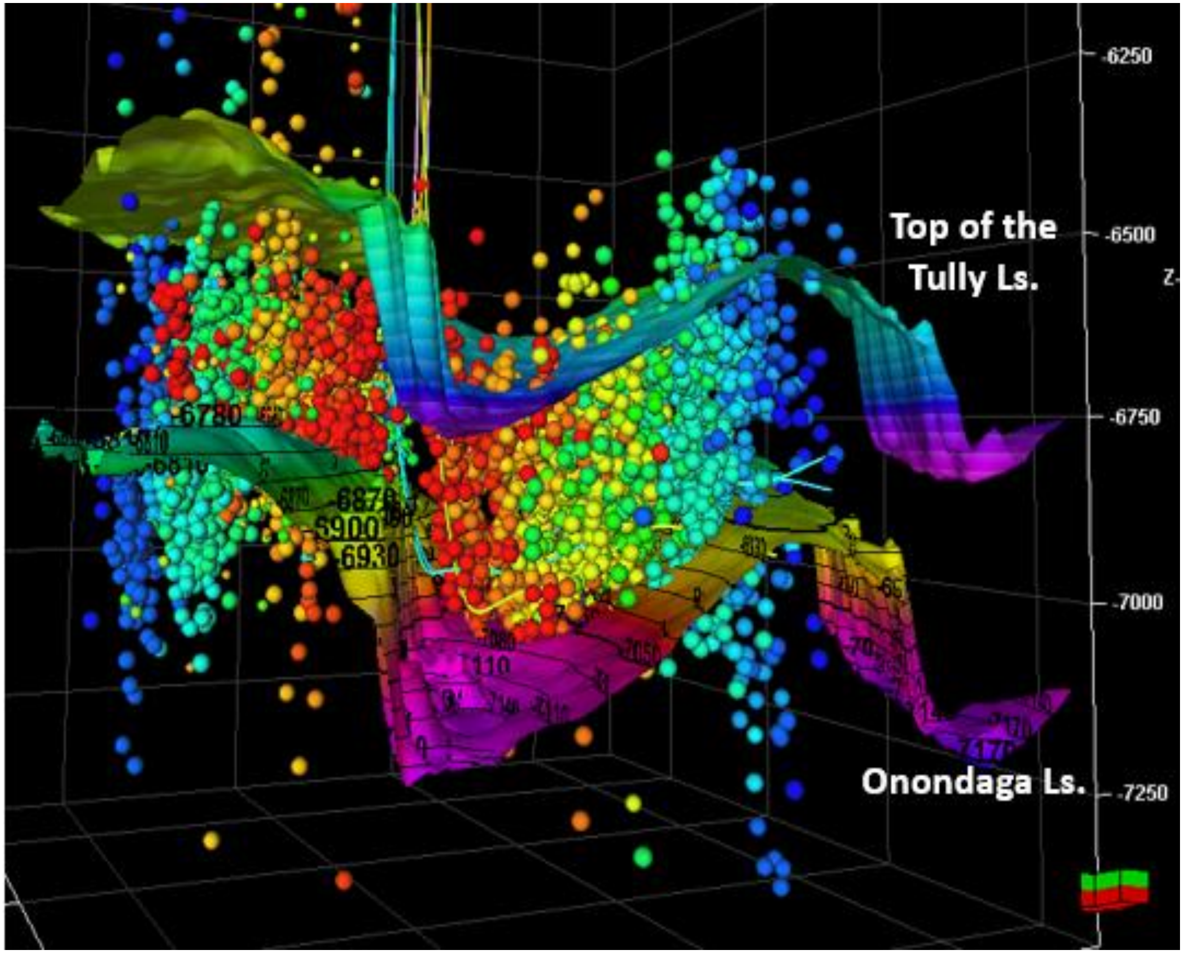
GIP(adsorbed) = Volume (Area x Thickness) x Density x Gas Content (isotherm)

- Common practice generally results in a conservative treatment for each GIP parameter

Volume: What is H? (thickness)

GIP(free) = Volume (Thickness x Area) x Porosity x HC Saturation x FVF

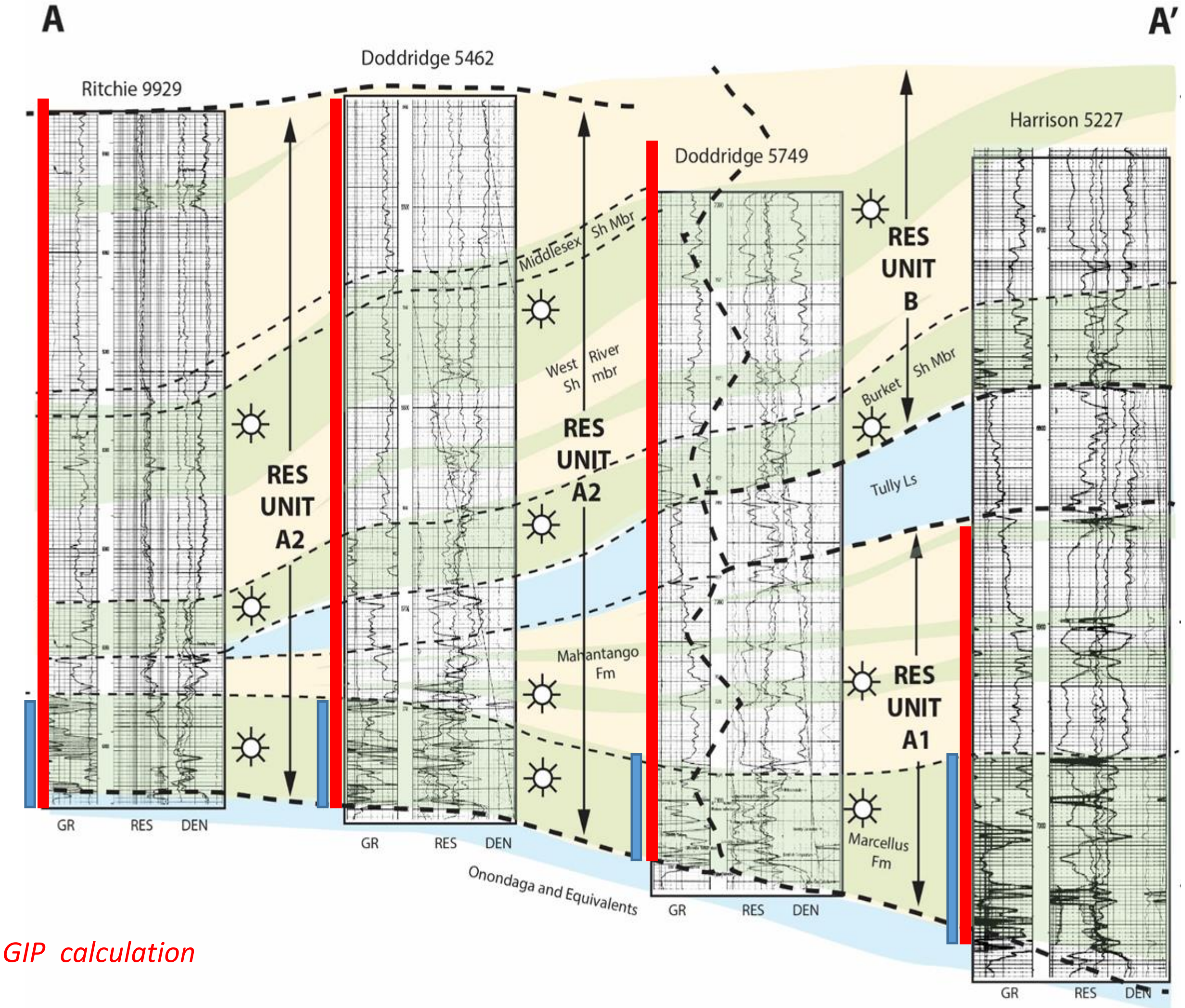
- Gradational vertical contacts between pay and non-pay. There is no “non-pay”
- Stimulation and production readily extend beyond target unit’s lithostratigraphic boundaries



GR Cross-section

North Central West Virginia

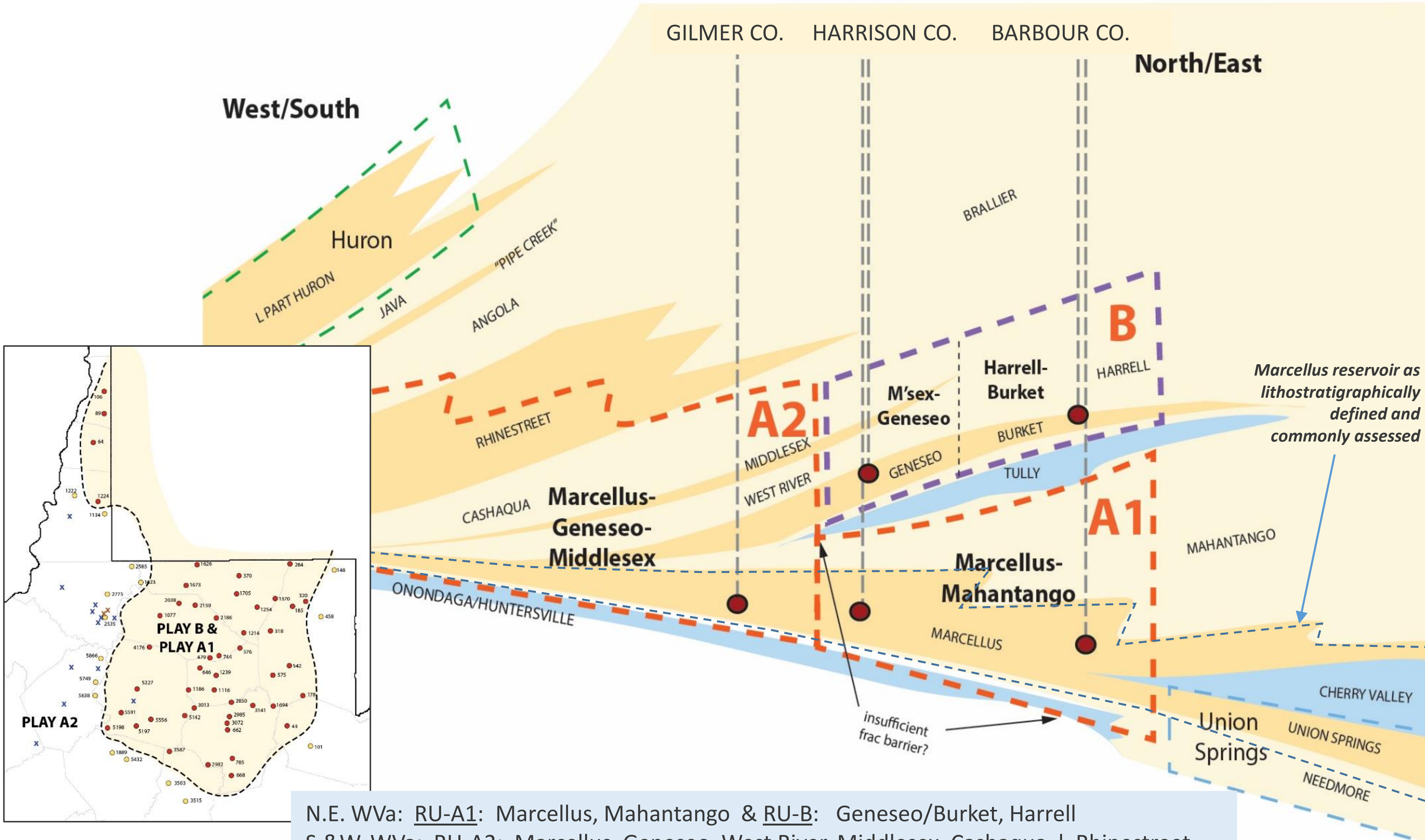
- For this study, we extend 300' above the top of the Marcellus.
- UNLESS there is a strong upper frac barrier (Tully both thick and separated from the Marcellus)
- Assume lower frac barrier is good unless reported otherwise (ex. Braxton Co.)



Modified "H" for Marcellus Reservoir Unit GIP calculation

Standard "H" for Marcellus GIP calculation

WV Shale "Reservoir Units"

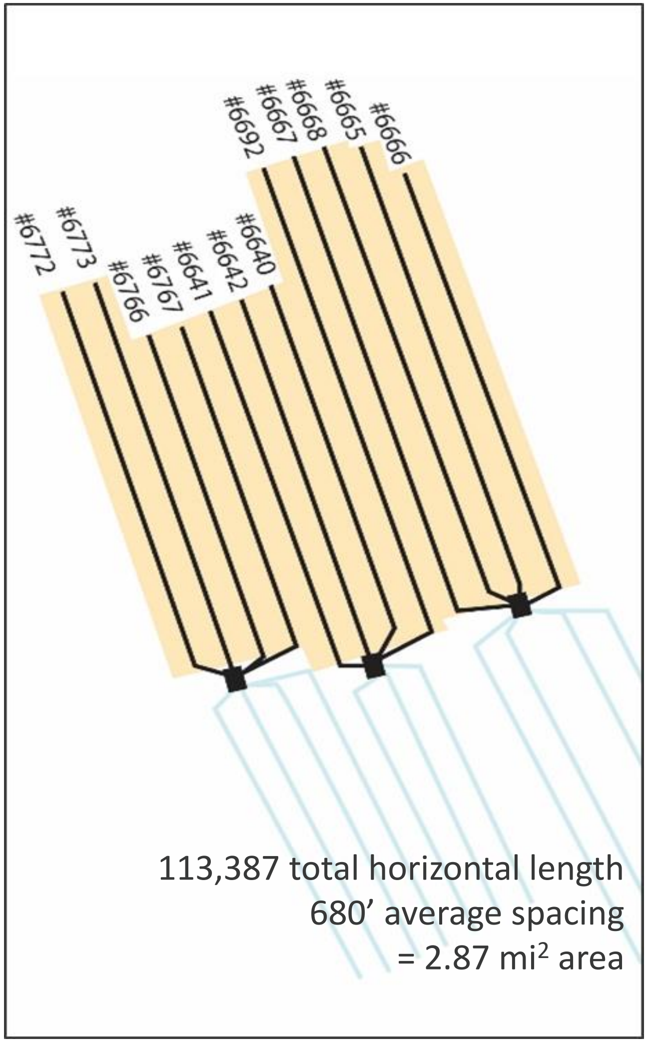


N.E. WVa: RU-A1: Marcellus, Mahantango & RU-B: Geneseo/Burket, Harrell
S.&W. WVa: RU-A2: Marcellus, Geneseo, West River, Middlesex, Cashaqua, l. Rhinestreet

Volume: What is Area?

GIP(free) = Volume (Thickness x Area) x Porosity x HC Saturation x FVF

- Area = spacing x lateral length.
- Length calculation is meant to include all the acreage that has been removed from further consideration as future drilling target.*
- Lateral extent of volume within a multi-well development is constrained by the next well laterally.
  - Where wells are drilled at a common or similar level (not vertically stacked)



Porosity

GIP(free) = Volume (Thickness x Area) x Porosity x HC Saturation x FVF

- Complex to estimate from logs
  - multiple modes and scales of porosity
  - dynamic porosity with gas generation & pressure reduction
  - kerogen correction needed: kerogen density is variable
- Perhaps not readily determined from standard core analysis
  - fine fracture porosity?
  - in situ behavior difficult to duplicate in the lab…
- Density logs can read to 20% or more…
  - set local porosity maxima as measured in in-gauge boreholes.
  - use density porosity both uncorrected and with kerogen correction…

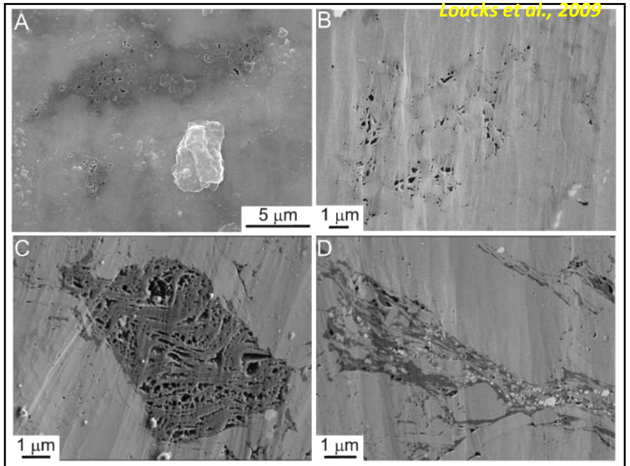
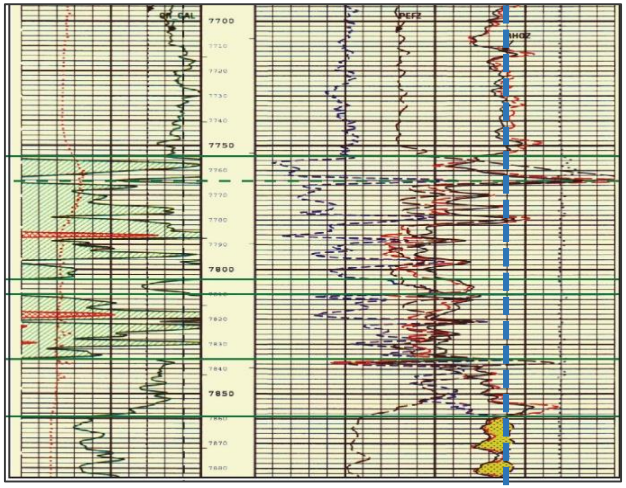


FIG. 5.—Nanopores associated with organic matter in the Barnett Shale. A) Elliptical to complexly rounded nanopores in an organic grain. Darker materials are organics. BSE image. Blakely #1, 2,167.4 m. B) Angular nanopores in a grain of organic matter. SE image. Blakely #1, 2,167.4 m. Accelerating voltage = 10 kV; working distance = 6 mm. C) Rectangular nanopores occurring in aligned convoluted structures. SE image. T.P. Sims #2, ~ 2,324 m. Accelerating voltage = 2 kV; working distance = 3 mm. D) Nanopores associated with disseminated organic matter. Carbou-rich grains are dark gray; nanopores are black. SE image. T.P. Sims #2, ~ 2,324 m. Accelerating voltage = 2 kV; working distance = 2 mm.

GR ≠ Vsh due to High U etc..

Den Por ≠ Eff Por due to kerogen +++



Other Key Parameters

GIP(free) = Volume (Thickness x Area) x Porosity x HC Saturation x FVF

GIP(adsorbed) = Volume (Area x Thickness) x Density x Gas Content (isotherm)

Saturation is just as messy

- Not readily calculated from logs (corrections needed for V_{sh} and V_{ker} (which require core)
- Not readily determined from cores - S_w exaggerated by drilling-emplaced fluids (Douds et al., 2017).
- Assumption = fix at low value (i.e. 15%?)

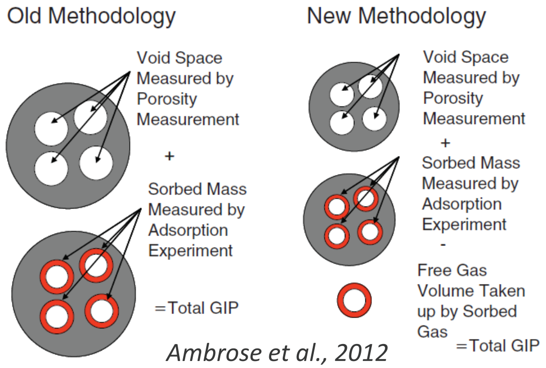
Formation Volume Factor (FVF)

- Converts volumes at depth to volumes at STP
- In Situ P and T are complex to measure
- May be complex local pressure distributions…
- Complicated by complex hydrocarbon chemistries and thermodynamics in nano-scale pore spaces

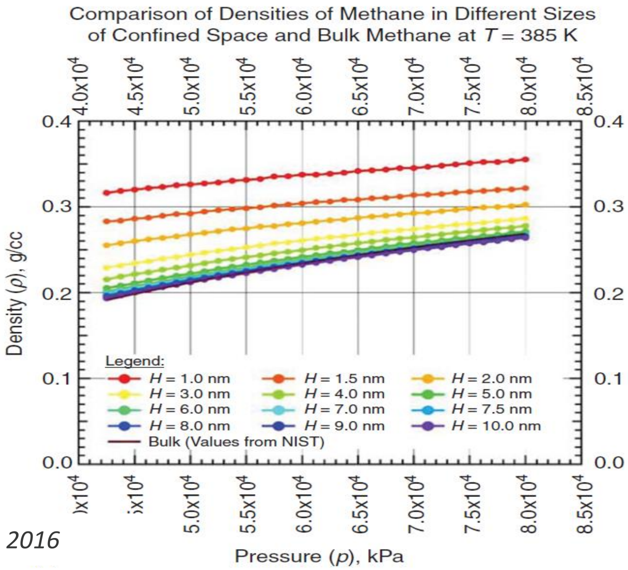
Adsorbed gas content (scf/ton)

- Poorly known; Few public domain datapoints.
- Generally assumed through analogues.

First public domain gas content measurement from Marcellus Shale – 1979 DOE EGSP Program



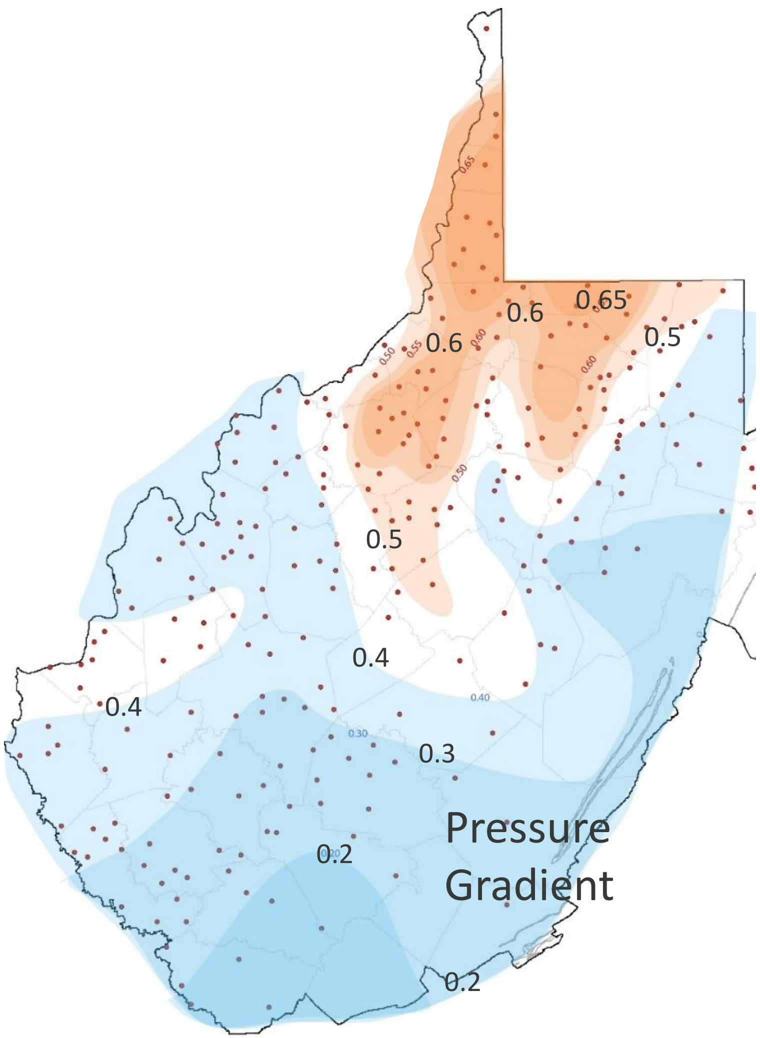
Ambrose et al., 2012



Pikatbunkate et al., 2016

Part 6: New WVGES-NETL GIP Estimation

Update of WVGES, AAPG 2013.



1. **Volume:** Expansion to include flow units **(+++). This is likely a major source of GIP underestimation in WV**
2. **Pressure/Temperature:** WVGES Oil and Gas (as reported by operator) new data. **(++)**
3. **Porosity:** From Logs: bulk density with variable grain density. Alternative with and without variable kerogen density correction. **(+)**
4. **Saturation:** Set at consistent low value (15%)? **(+)**
5. **Formation Volume Factor:** Gas density correction for small pores **(+)** and Ambrose correction **(-)** deferred at present… (need pore size distribution information to implement)
6. **Adsorbed Gas:** TOC from logs from multiple methods (GR, DEN, RES) converted to GC; calibration to EGSP/MSEEL data **(working…)**
7. **Multiple Scenarios to be run to assess sensitivity to assumptions (Sw, Adsorbed gas, RU height, etc…)**

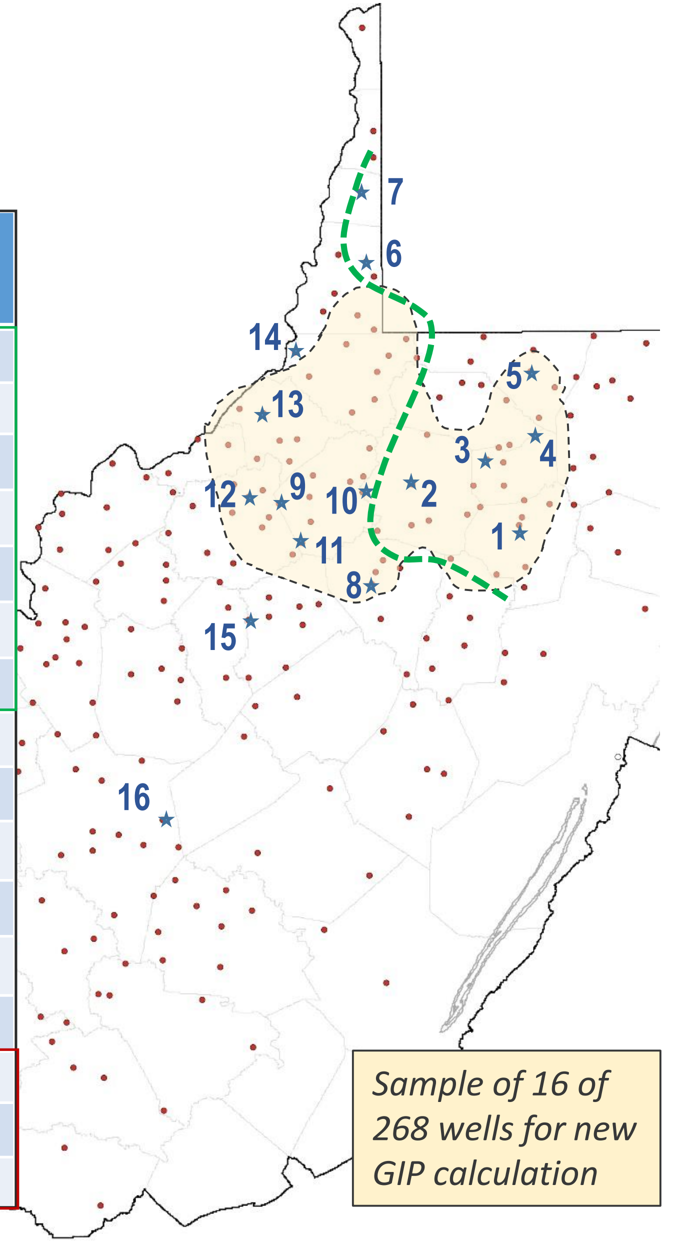
Preliminary (!) GIP/RE Results

Play A1/A2 only; Marcellus Reservoir Unit

County	Well	Ave Pub. GIP*	Ave Est. EUR*	Est RE	WVGS GIP* Case A	Case A RE	WVGS GIP* Case B	Case B RE	Case B Marcellus Share of RU GIP
1 - Barbour	662	36	48	133%	65	74%	58	82%	81%
2 – Harrison	5227	48	61	127%	138	44%	123	50%	66%
3 – Taylor	646	44	45	102%	133	34%	119	38%	69%
4 – Taylor	576	38	44	116%	135	24%	123	27%	63%
5 – Monongalia	1705	47	50	107%	137	36%	123	41%	65%
6 – Marshall	1224	58	40	69%	85	47%	75	53%	72%
7 – Ohio	64	63	33	52%	109	30%	97	34%	76%
8 – Lewis	3703	33	55	182%	110	55%	95	63%	48%
9 – Doddridge	2909	33	69	209%	183	38%	166	42%	44%
10 – Doddridge	5638	47	51	109%	129	40%	113	45%	41%
11 – Doddridge	5644	30	43	143%	128	34%	112	38%	42%
12 – Ritchie	4832	27	45	167%	194	23%	181	25%	54%
13 - Tyler	1121	29	62	214%	201	31%	189	33%	38%
14 – Wetzel	644	43	27	63%	159	17%	147	18%	54%
15 – Gilmer	4332	25	13	52%	103	13%	89	15%	43%
16 - Kanawha	5307	~10	N/A		52		47		34%

Case A: *Sw = 0.15/0.35; H(A2) = 300'; Porosity = No Correction; FVF = No Correction; Adsorbed Gas = "conservative"*

Case B: *Includes initial Porosity (Kerogen) Correction.*



Ex. Doddridge 5644 GIP

~ 43 bcf/mi^2 EUR from "Marcellus wells"

~112 bcf/mi^2 GIP in "Reservoir Unit" @ 300' SRV

GIP per unit at 300' SRV — Zagorski et al., 2016

46.9 bcf/mi^2 in Marcellus — **35 bcf/mi^2**

2.0 bcf/mi^2 in Mahantango

30.1 bcf/mi^2 in Geneseo

25.7 bcf/mi^2 in West River

3.6 bcf/mi^2 in Middlesex

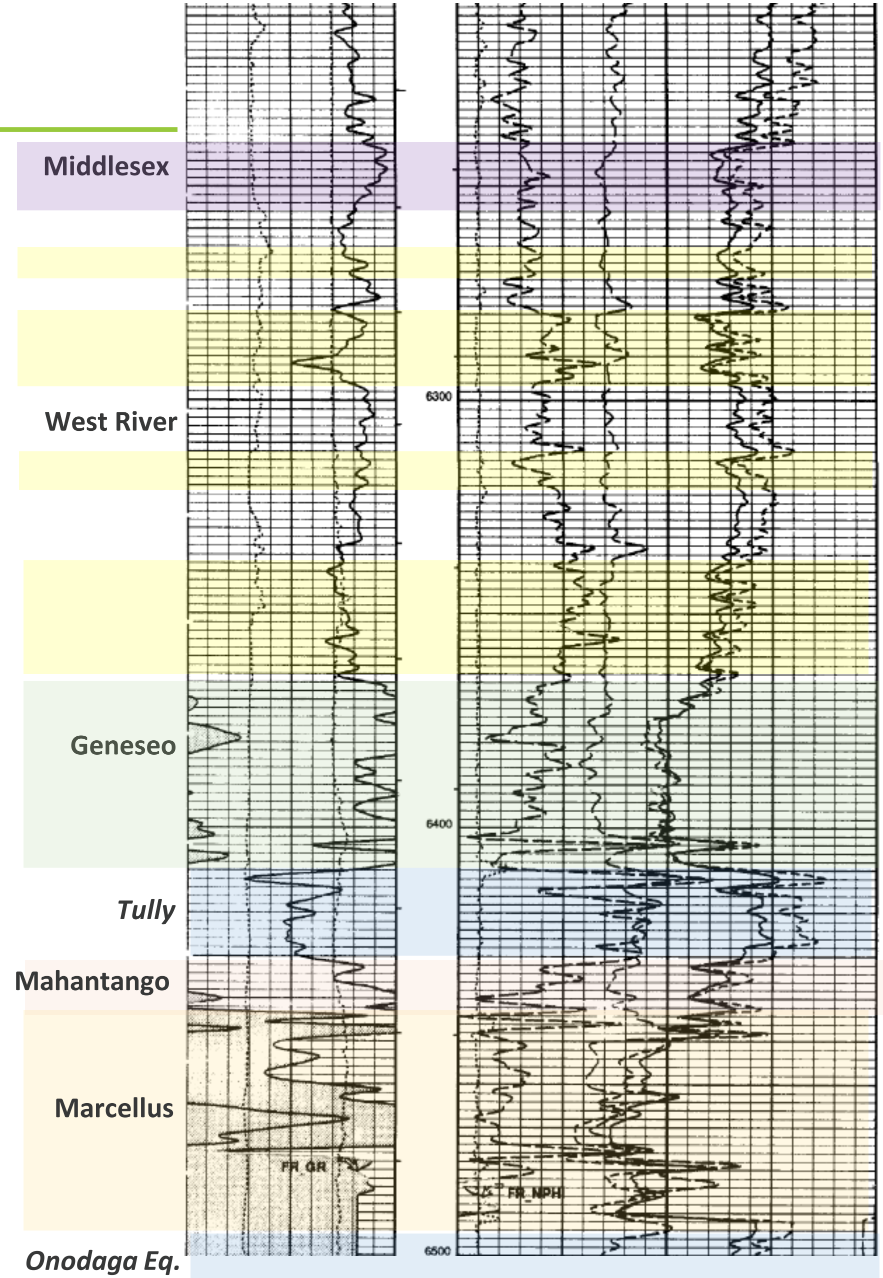
3.7 bcf/mi^2 in Cashaqua

} **40 bcf/mi^2**

58% of GIP is in non-Marcellus units.

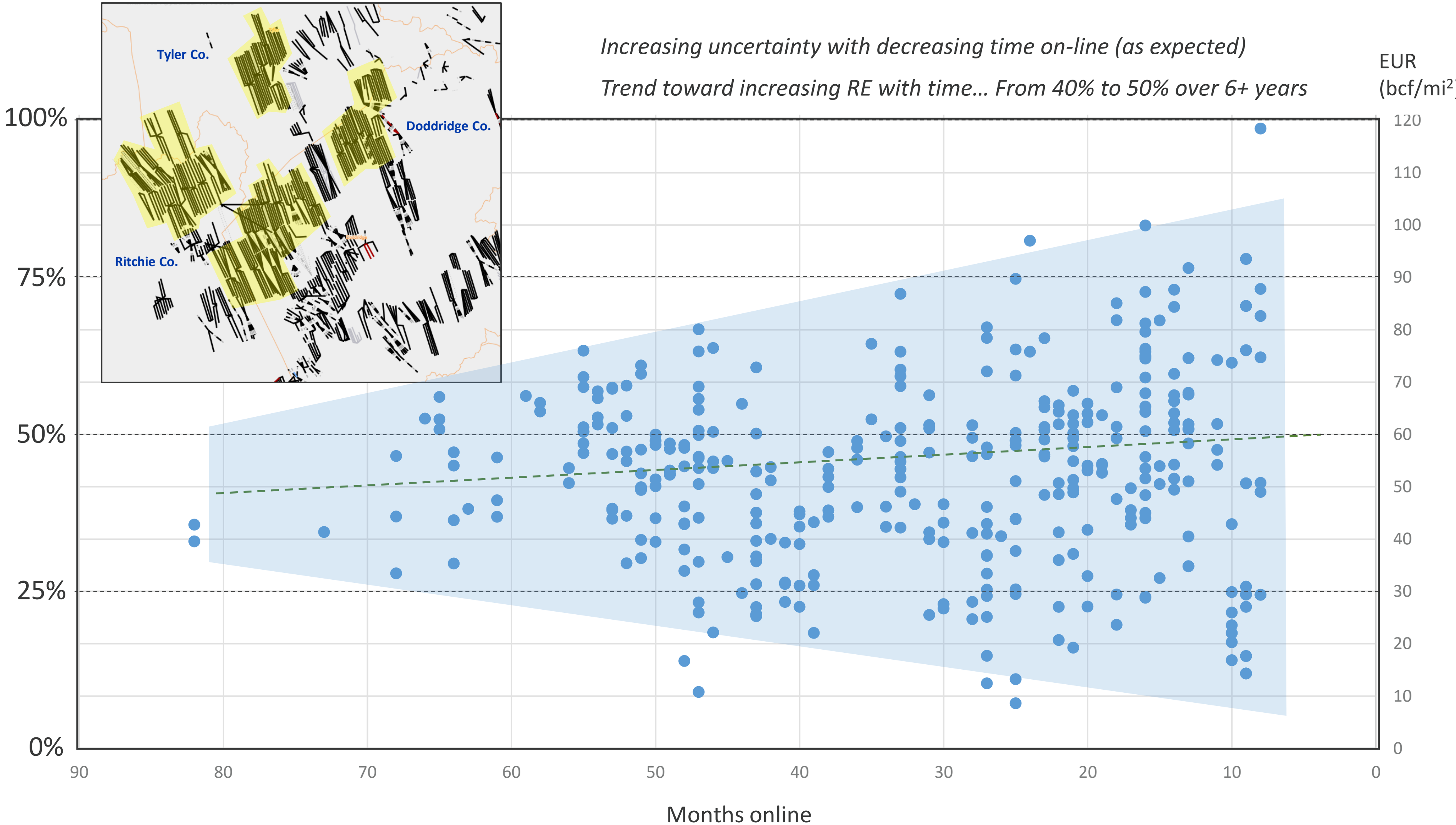
38% RE from Reservoir Unit … on average.

Likely implies larger RE from Marcellus proper



Add'l Results: RE with Time

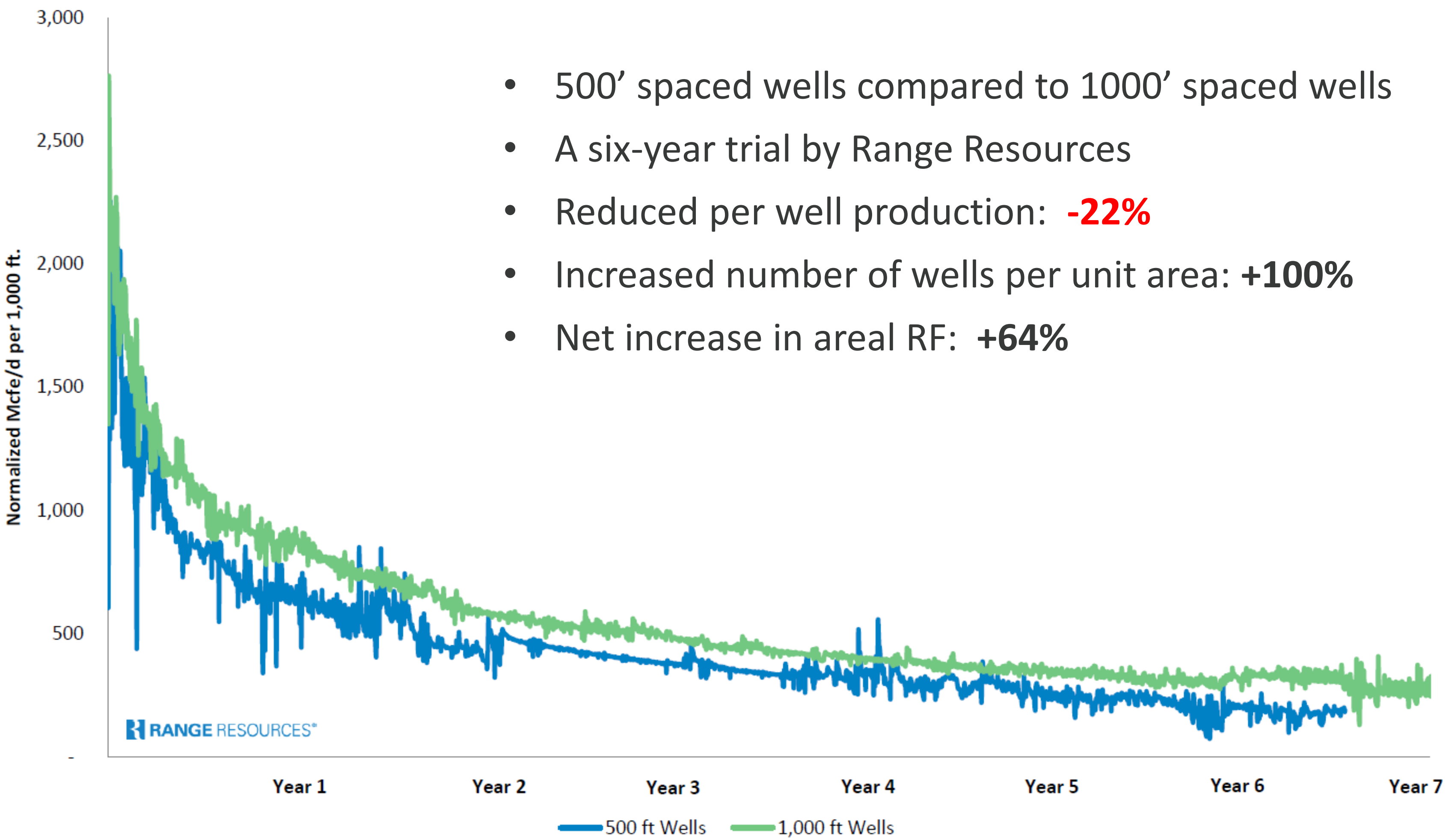
365 wells in Doddridge-Tyler-Ritchie Co.: Play A2: Assuming 120 bcf/mi² GIP



Add'l Results: Spacing

1,000' compared to 500' well spacing: Marcellus Shale: Range Resources

- 500' spaced wells compared to 1000' spaced wells
- A six-year trial by Range Resources
- Reduced per well production: **-22%**
- Increased number of wells per unit area: **+100%**
- Net increase in areal RF: **+64%**



Spacing Examples

Most "efficient" not necessarily the most economic

NE Marshall Co.: HG Energy (2014-2017)

- 5 wells; 39,864' @ 750' = 1.06 mi^2 Est EUR = 51.8 bcf/mi^2
- 7 wells: 55,496' @ 600' = 1.12 mi^2 Est EUR = 70.1 bcf/mi^2

W. Marshall Co.: HG Energy (2014-2015)

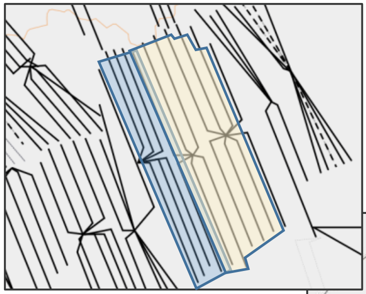
- 6 wells; 57,736' @ 742' = 1.54 mi^2 Est EUR = 23.1 bcf/mi^2
- 6 wells; 39,740 @ 500' = 0.72 mi^2 Est EUR = 40.6 bcf/mi^2

C. Doddridge Co.: EQT (2015)

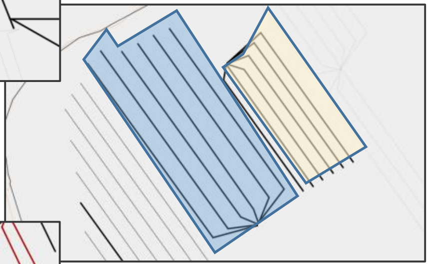
- 12 wells; 84,843' @ 980' = 2.99 mi^2 Est EUR = 36.5 bcf/mi^2
- 6 wells; 39,264' @ 760' = 1.07 mi^2 Est EUR = 64.1 bcf/mi^2

Ritchie Co: Antero (2016-2017)

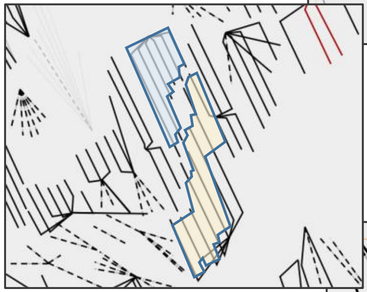
- 12 wells; 109,783' @ 1000' = 3.94 mi^2 Est EUR = 46.4 bcf/mi^2
- 8 wells; 63,236' @ 670' = 1.52 mi^2 Est EUR = 79.9 bcf/mi^2



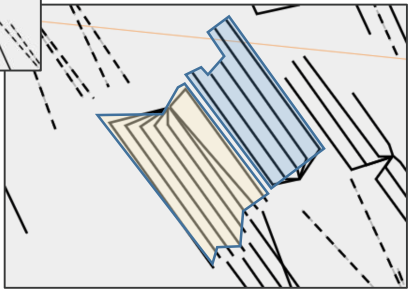
+35%



+76%



+76%



+72%

Summary: Marcellus RE in WV

KEY FINDINGS:

1. RE appears very high (>100%) over large areas using extant estimates of 50-yr EURs and GIPs.
2. Hypothesis #1: low GIP is primary factor driving this erroneous result.
3. Hypothesis #2: limited reservoir volume is primary cause of low GIP
4. Extending volume to 300' (or Frac Barrier) does not fully address the problem…porosity and gas saturation underestimation likely need to be factored (to arrive at 50% RE…)
5. EURs will need to be continuously refined/monitored…
6. Preliminary data indicate general increase in RE with time.
7. RE improves with reduced well spacing. (However, spacing has a strong impact on costs and economics).

Thank You

northeast
NATURAL ENERGY

WVGES
GEOLOGY UNDERLIES IT ALL

NATIONAL ENERGY TECHNOLOGY LABORATORY