



Integrating 100 Years of Research in the Mesaverde-Mancos Group Transition, Piceance Basin, Colorado, USA

Bryan McDowell

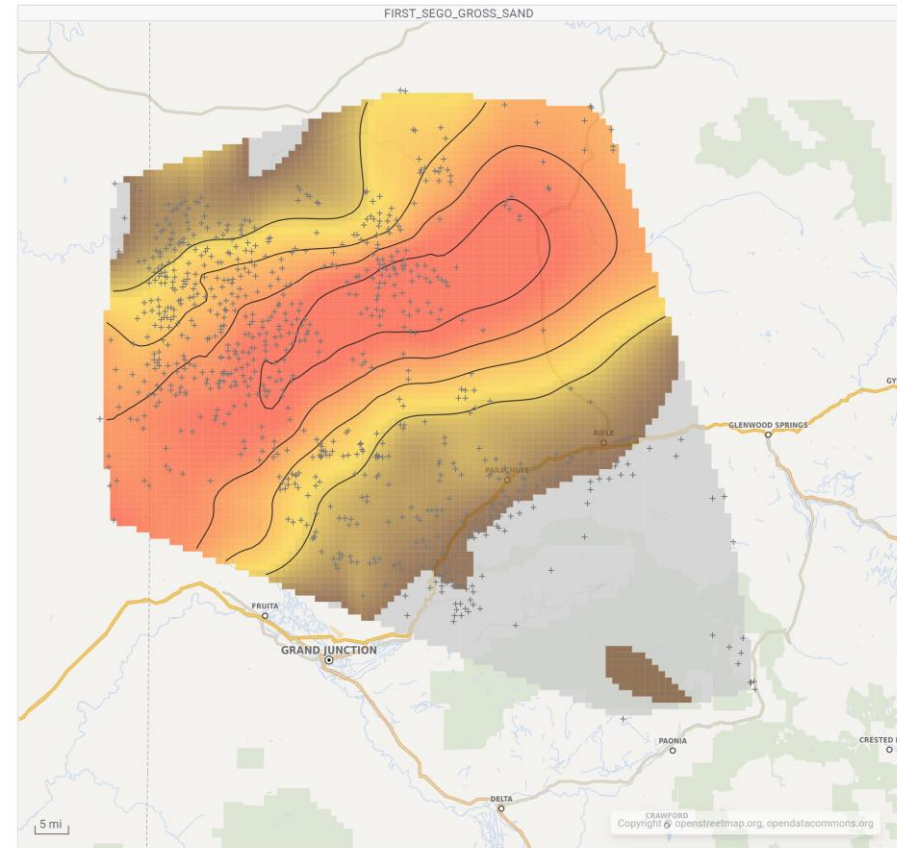
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Agenda

- Introduction
- Workflow
- Proof-of-Concept
- Results (Preview)
- Conclusions

Map chart



Introduction

The Problem (1/2)

- Geologic datasets are increasingly easier to access due to ongoing digitization efforts by:
 - Geologic surveys
 - Professional societies
 - Regulatory agencies
 - Academia
- Although more accessible, utilization is still difficult due to the inherent nature of geologic data:
 - Heavily text-based
 - Commonly embedded within figures
 - Rarely tabulated

The Problem (2/2)

- As researchers, we are often left with highly-fragmented datasets of varying quality/content that are not easily compiled/manipulated
- As a result, when working in highly-researched areas, such as the Rocky Mountains, we are often “...*drowning in information but starved for knowledge.*” (Naisbit, 1982)
- Luckily, advances in business analytics tools enable geoscientists to integrate data much faster/easier
 - Examples: TIBCO Spotfire, Tableau, Microsoft PowerBI, etc.
 - However, these tools are slowly being adopted by the community

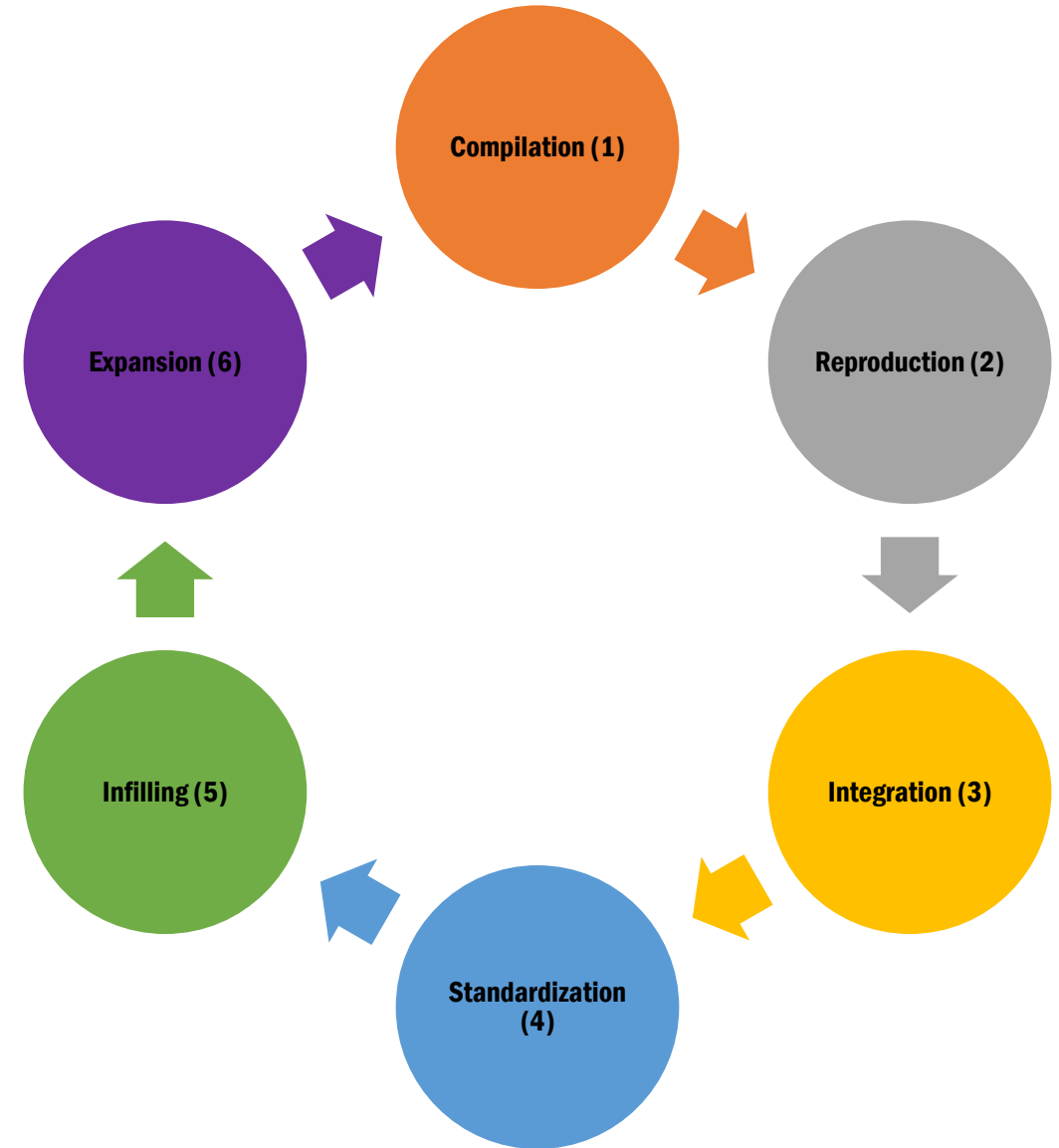
Data Mining

- We should leverage what is already available to:
 - Save time/money (e.g., don't reinvent the wheel)
 - Promote integration with other studies
- To illustrate the point, we will present...
 1. A step-by-step workflow for integrating existing data
 2. A case study on gross sandstone distribution in Campanian-aged stratigraphic units in the Piceance Basin (Colorado/Utah)
- Please note:
 - This is not rocket science – it's a logical methodology to highlight errors

Workflow

Workflow

1. Compile previous work
2. Reproduce previous work
3. Integrate outcrop + subsurface data
4. Standardize interpretations
5. Infill existing dataset with new data
6. Expand AOI



List of Steps

- Steps:

1. Compile data in initial AOI
2. Re
3. In
su
4. Standardize interpretations
5. Infill existing dataset with new data
6. Expand AOI
7. Repeat

Let's see this in action



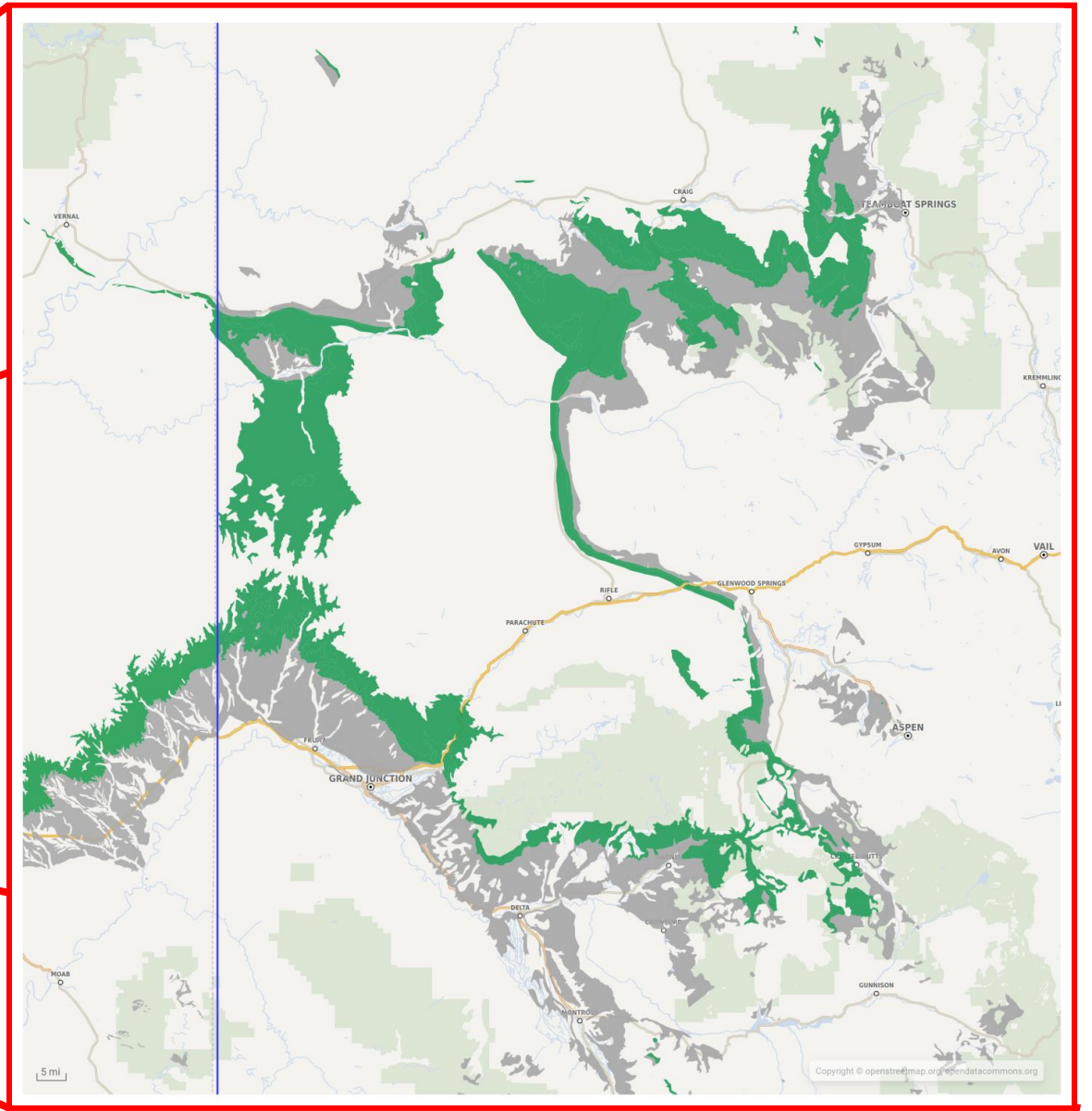
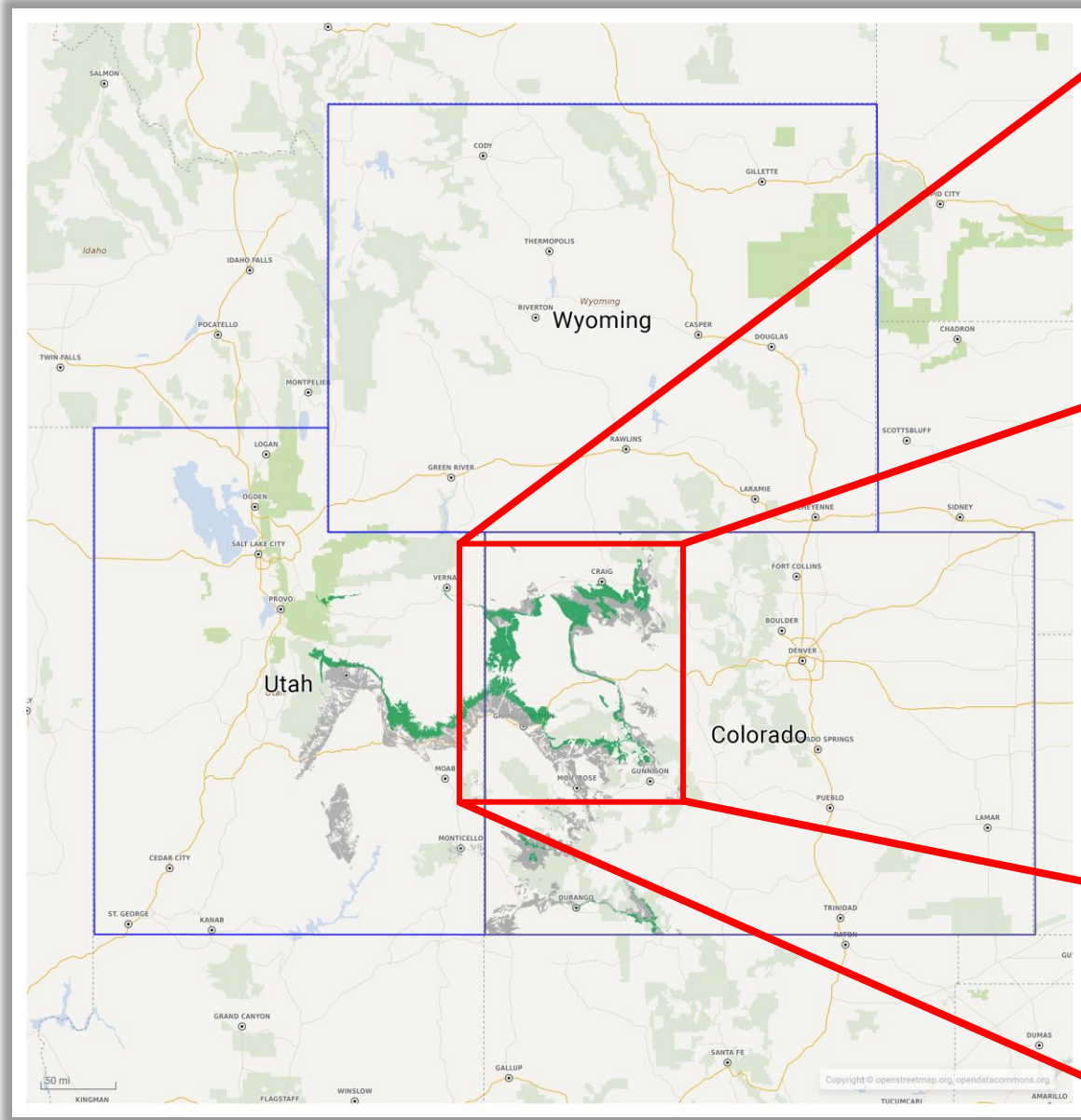
Proof-of-Concept (POC)

Castlegate Sandstone

- Late Cretaceous (Campanian) stratigraphic unit
 - Focus of extensive sequence stratigraphic studies:
 - Van Wagoner et al. (1990); Van Wagoner (1995); Yoshida et al. (1996); McLaurin & Steel (2000); Miall & Arush (2000)
- Found in outcrop in two areas:
 - Northern area
 - Margins of the NE Uinta-NW Piceance basins
 - Southern area
 - Margins of the SE Uinta-SW Piceance basins

Castlegate Sandstone (cont.)

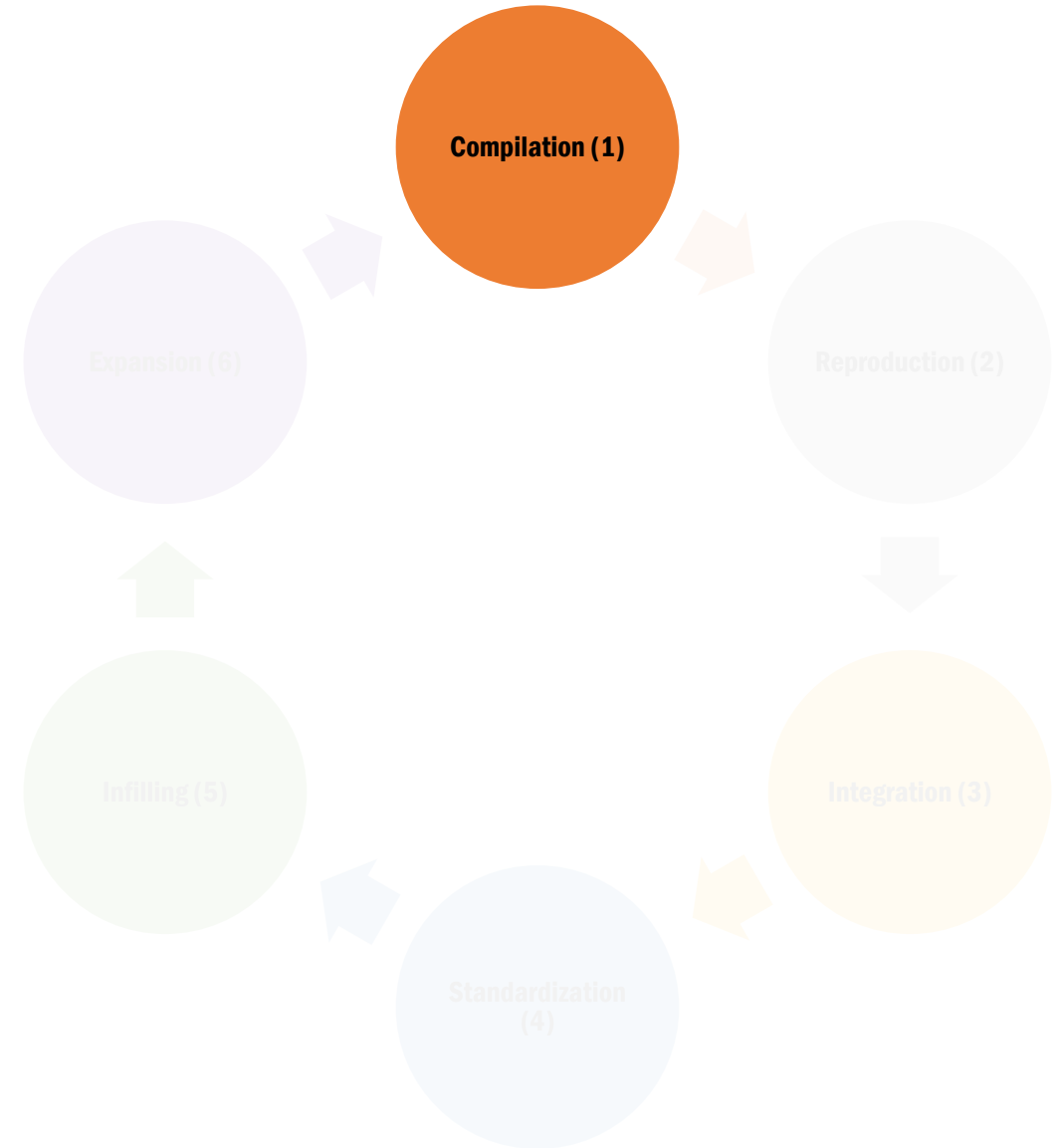
- The transition from fluvial to marine depositional environments has been widely studied
 - However, these studies usually stop where the sandstone facies end
- Age-equivalent mudstones and siltstones are present throughout the basin but are difficult to correlate



POC – Compilation

1. Compile previous work

2. Reproduce previous work
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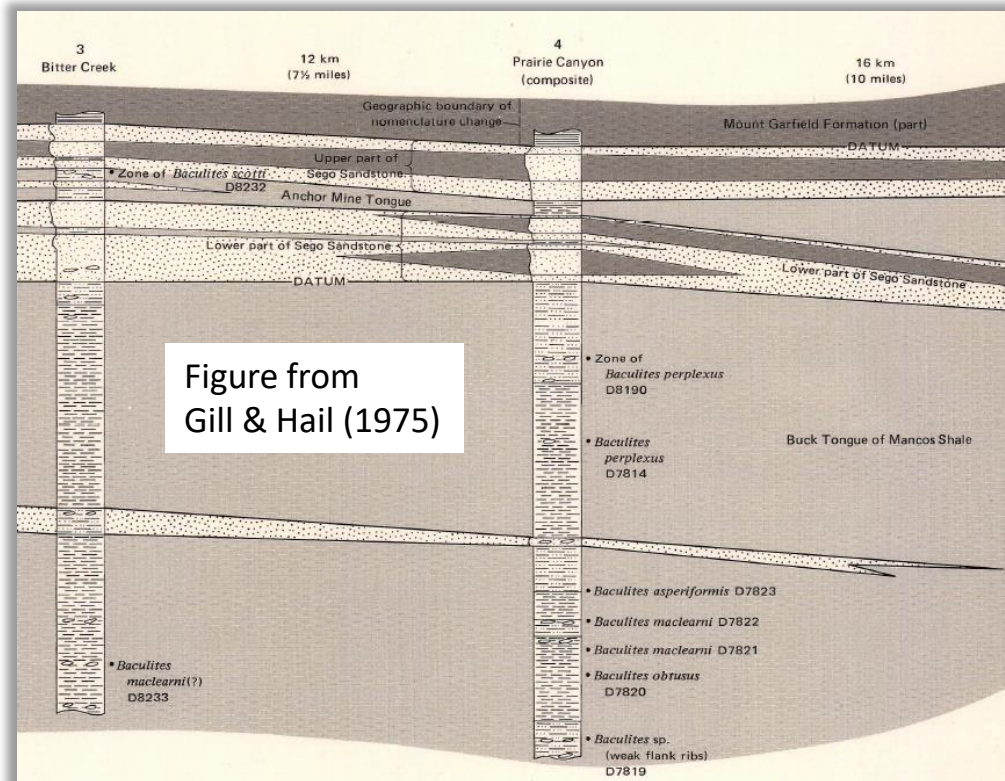


Data Compilation

- Literature search for:
 - Ammonite localities
 - Stratigraphic sections
 - Subsurface correlations
 - Geologic maps
- Compile/convert text- and figure-based data into tables
 - Microsoft Excel is a simple/cheap option for data tables
 - TIBCO Spotfire or Tableau is great for integrating data for dynamic visualizations

Data Conversion

Original Form



New Form

List of Stratigraphic Sections

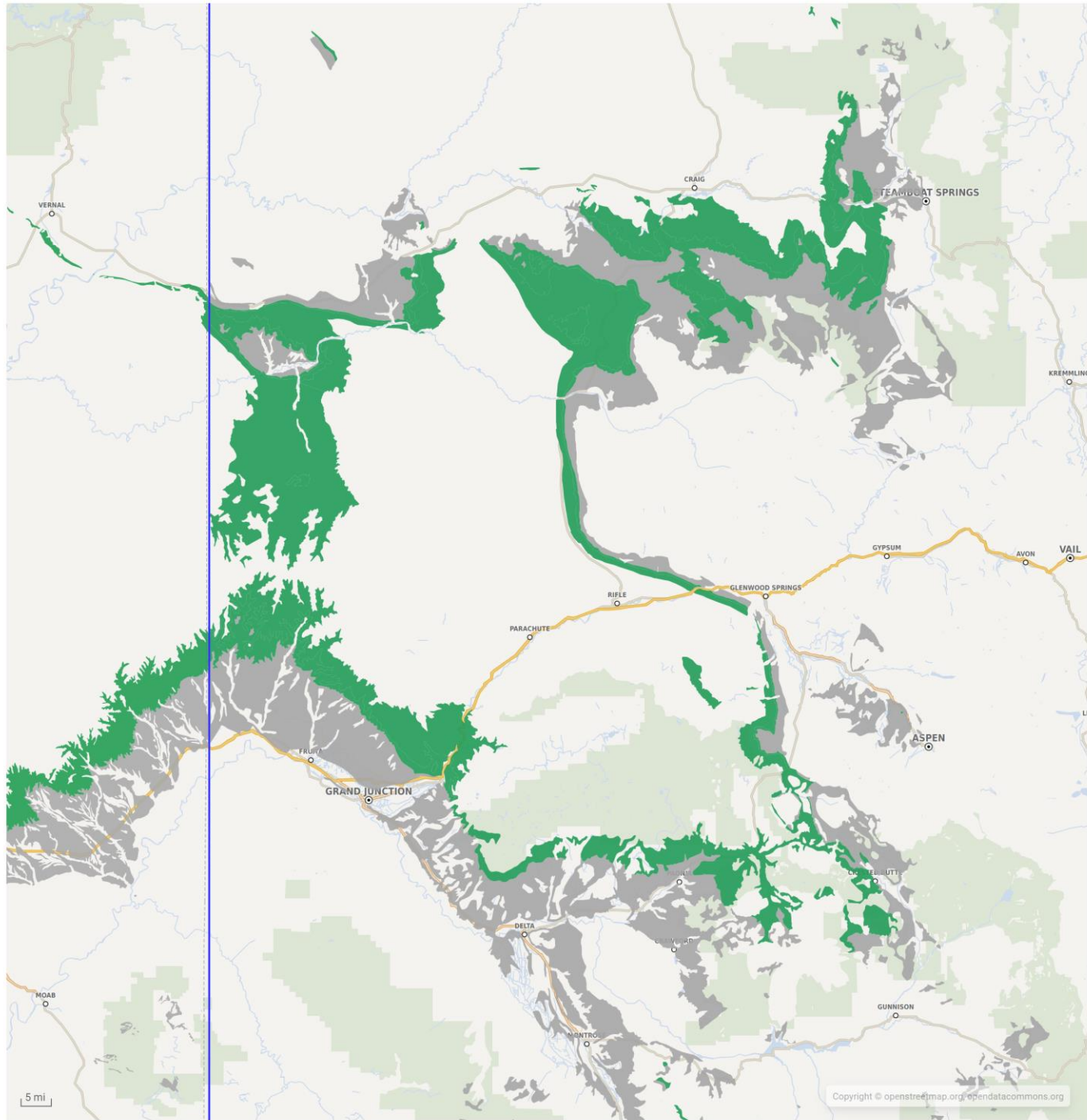
	A	E	F	G	H	I	J	K	N	O
1	Author(s)	Strat Section	State	County	Section	Township	Range	Qtr Sec	Latitude	Longitude
94	Gill & Hail (1975)	Bitter Creek (above top Castlegate)	Utah	Grand	9	17S	25E	W1/2	39.34287	-109.15914
95	Gill & Hail (1975)	Bitter Creek (below top Castlegate)	Utah	Grand	16	17S	25E	E1/2	39.32846	-109.14974
109	Gill & Hail (1975)	Prairie Canyon (composite) (above top Castlegate)	Colorado	Garfield	30	7S	104W	SW1/4	39.42125	-109.03631
110	Gill & Hail (1975)	Prairie Canyon (composite) (below top Castlegate)	Colorado	Garfield	18	8S	104W	NE1/4	39.37135	-109.02574

List of Geologic Units

	A	B	C	D
1	Author(s)	Strat Section	Reported Geologic Unit	Interpreted Geologic Unit
520	Gill & Hail (1975)	Bitter Creek (above top Castlegate)	Neslen Formation	Neslen Fm
521	Gill & Hail (1975)	Bitter Creek (above top Castlegate)	Upper part of Sego Sandstone	Upper Sego Sandstone
522	Gill & Hail (1975)	Bitter Creek (above top Castlegate)	Anchor Mine Tongue of Mancos Shale	Anchor Mine Tongue
523	Gill & Hail (1975)	Bitter Creek (above top Castlegate)	Lower part of Sego Sandstone	Lower Sego Sandstone
524	Gill & Hail (1975)	Bitter Creek (above top Castlegate)	Buck Tongue of Mancos Shale	Buck Tongue
526	Gill & Hail (1975)	Bitter Creek (below top Castlegate)	Main body of Mancos Shale (part)	Mancos Shale (sub-Castlegate)
672	Gill & Hail (1975)	Bitter Creek (below top Castlegate)	Castlegate Sandstone	Castlegate Sandstone
673	Gill & Hail (1975)	Prairie Canyon (composite) (above top Castlegate)	Mount Garfield Formation (part)	Iles Fm
674	Gill & Hail (1975)	Prairie Canyon (composite) (above top Castlegate)	Upper part of Sego Sandstone	Upper Sego Sandstone
675	Gill & Hail (1975)	Prairie Canyon (composite) (above top Castlegate)	Anchor Mine Tongue of Mancos Shale	Anchor Mine Tongue
676	Gill & Hail (1975)	Prairie Canyon (composite) (above top Castlegate)	Lower part of Sego Sandstone	Lower Sego Sandstone
678	Gill & Hail (1975)	Prairie Canyon (composite) (above top Castlegate)	Buck Tongue of Mancos Shale	Buck Tongue
987	Gill & Hail (1975)	Prairie Canyon (composite) (below top Castlegate)	Main body of Mancos Shale (part)	Mancos Shale (sub-Castlegate)
1012	Gill & Hail (1975)	Prairie Canyon (composite) (below top Castlegate)	Castlegate Sandstone	Castlegate Sandstone

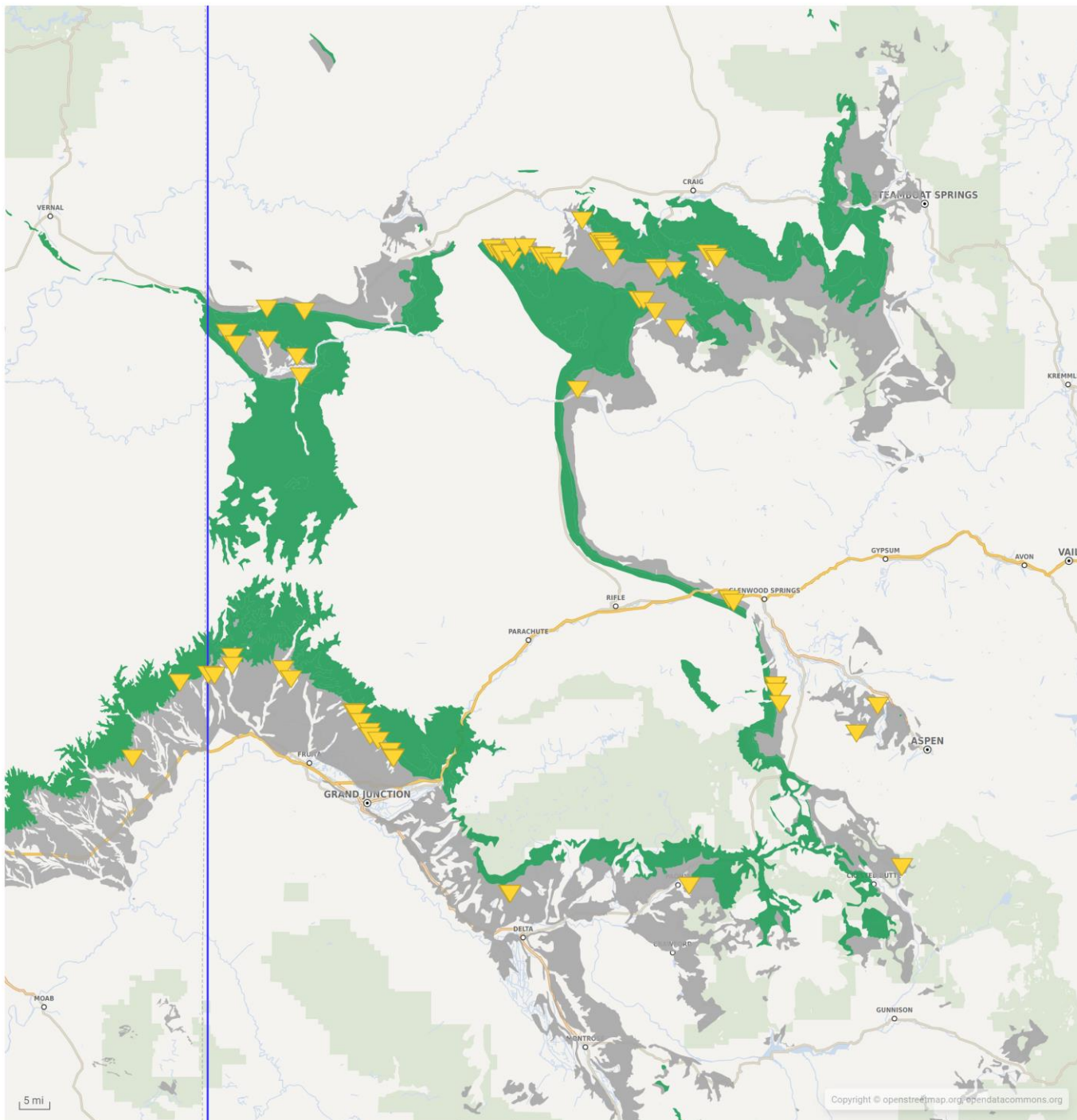
Data Tables

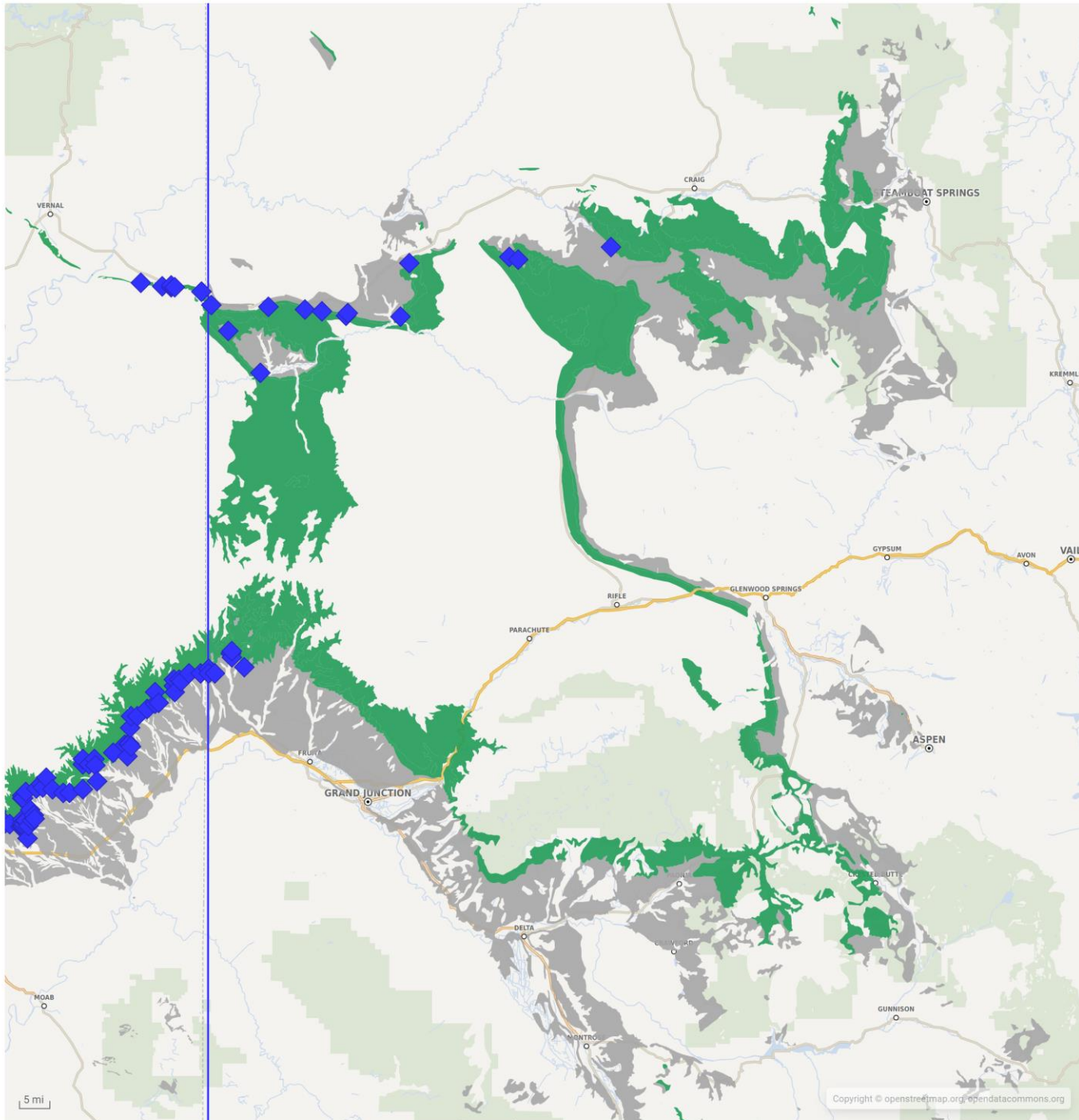
1. *Ammonite Fossil Locality Index*
2. *Stratigraphic Section Index*
 - And its corresponding *Geologic Unit Index*
3. *Subsurface Correlation Index*
 - And its corresponding *Geologic Unit Index*
4. *Geologic Map Index*
 - And its corresponding *Geologic Unit Index*



Ammonite Localities

- *Baculites asperiformis* fossil localities
- Data from USGS Denver Paleontology Collection

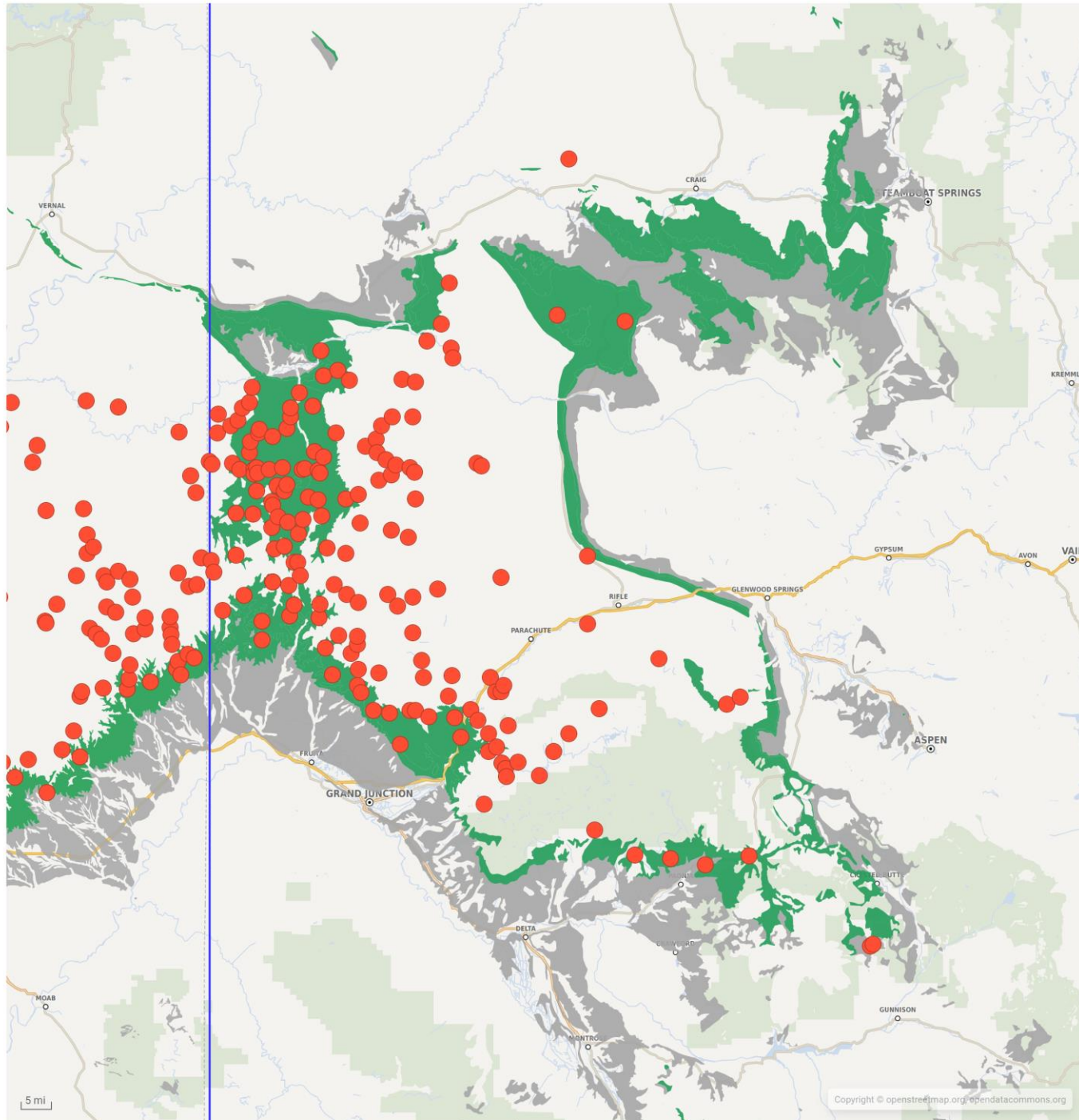




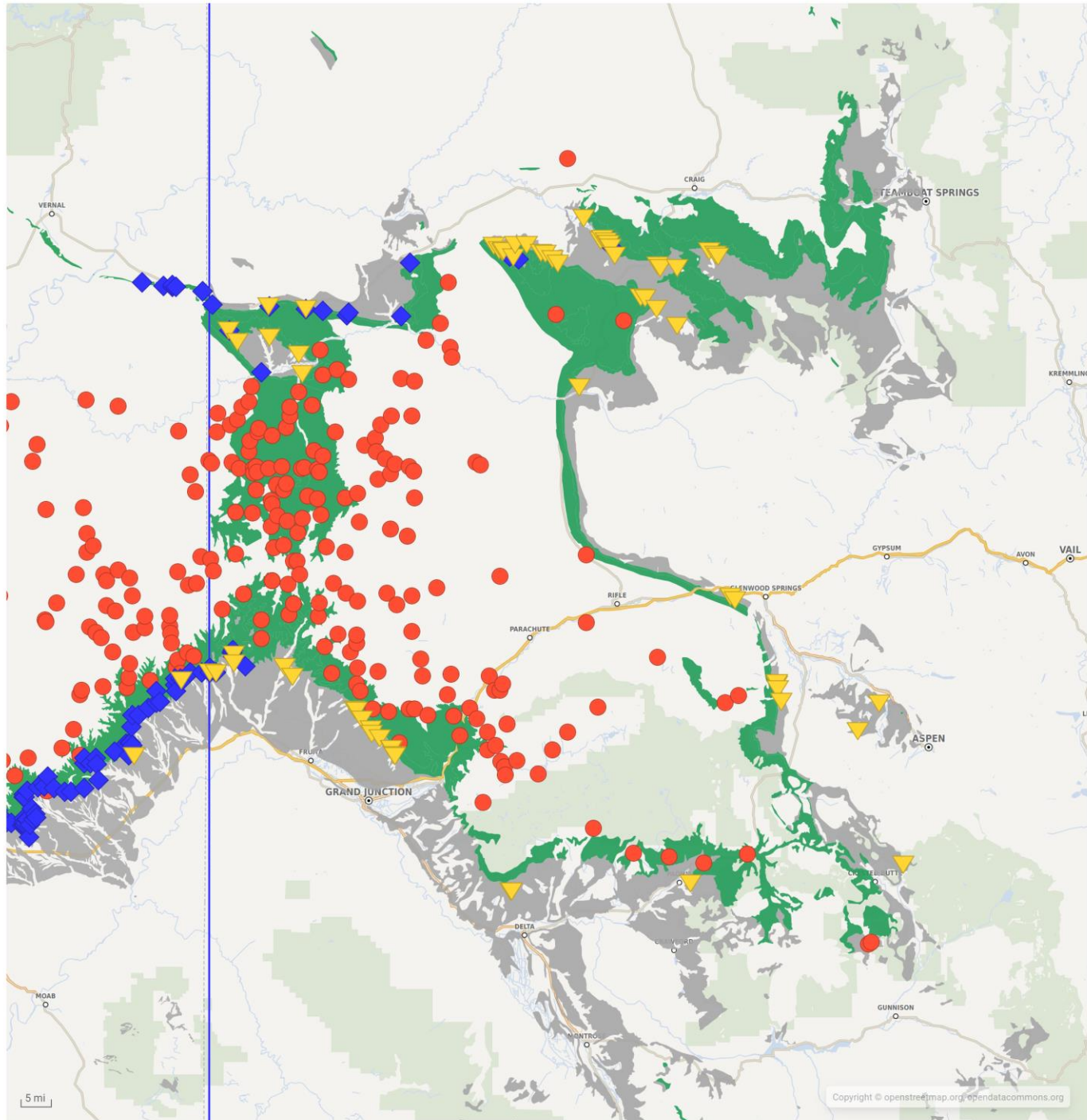
Stratigraphic Sections

- Young (1955)
- Gill & Hail (1975)
- Franczyk (1989)
- Van Wagoner et al. (1990)
- Van Wagoner (1991)
- Van Wagoner (1995)

Subsurface Correlations



- Finley et al. (1983)
- Johnson (1986)
- Johnson (1987)
- Franczyk (1989)
- Johnson (1989)
- Cole et al. (1997)
- Hettinger & Kirschbaum (2002, 2003)
- Dubiel (2003)
- Johnson (2003a)
- Johnson (2003b)
- Patterson et al. (2003)
- Hampson (2010)
- Schwendeman (2011)
- Rogers (2012)
- Anna (2012)

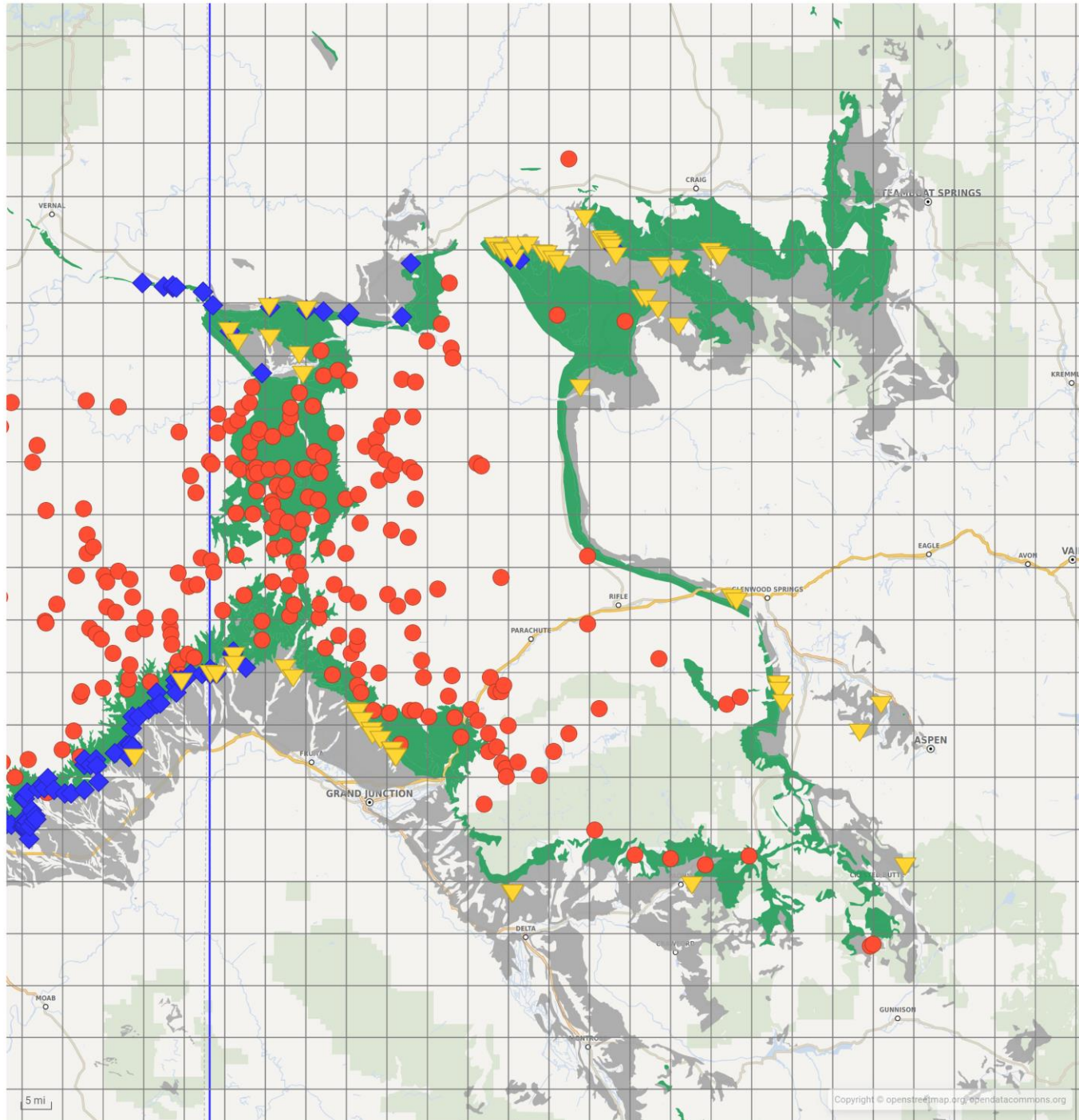


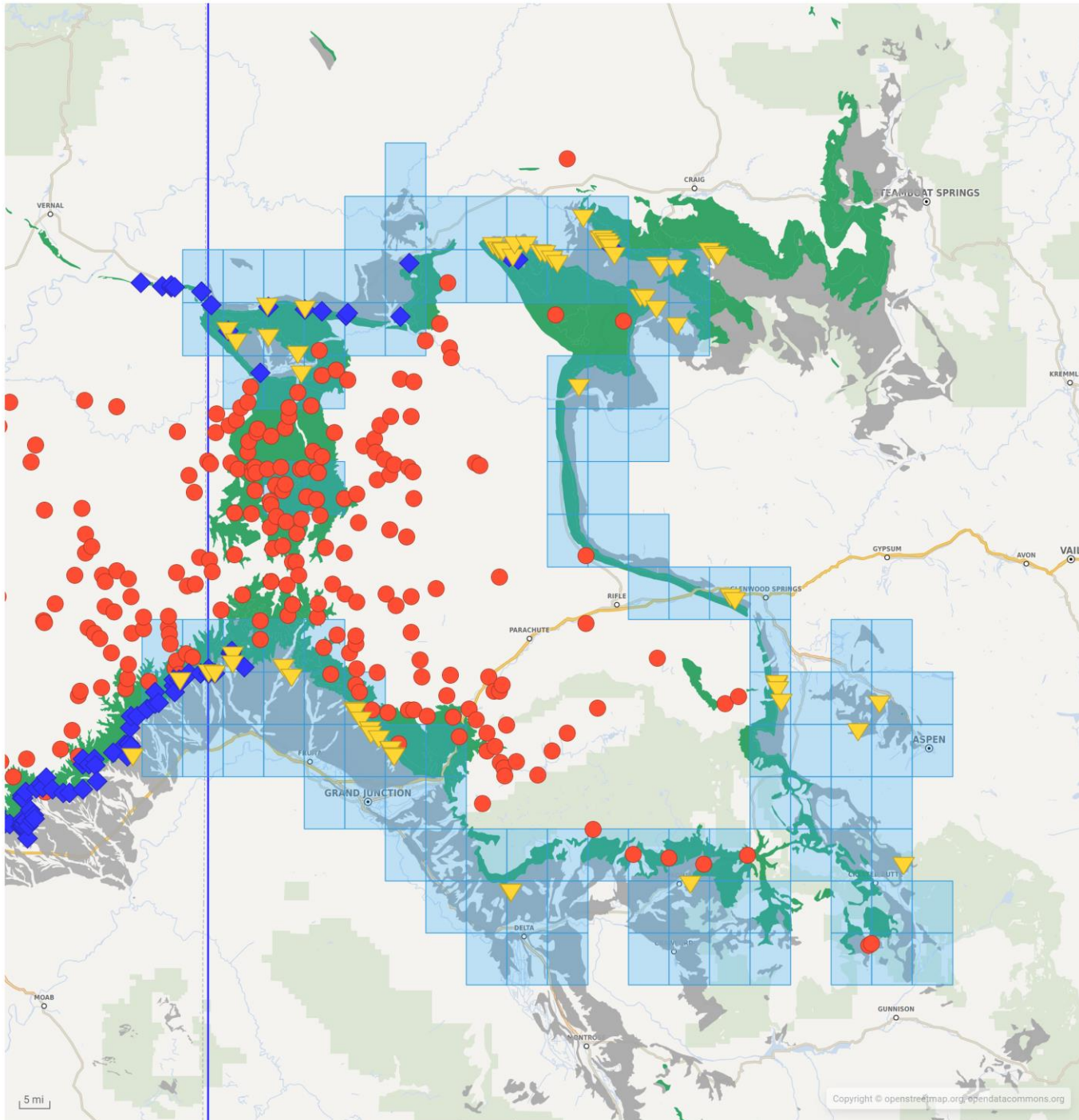
Initial Area-of-Interest

- Outlines areal extent of previously published data

USGS Quadrangles

- Subdivide area by USGS quadrangles



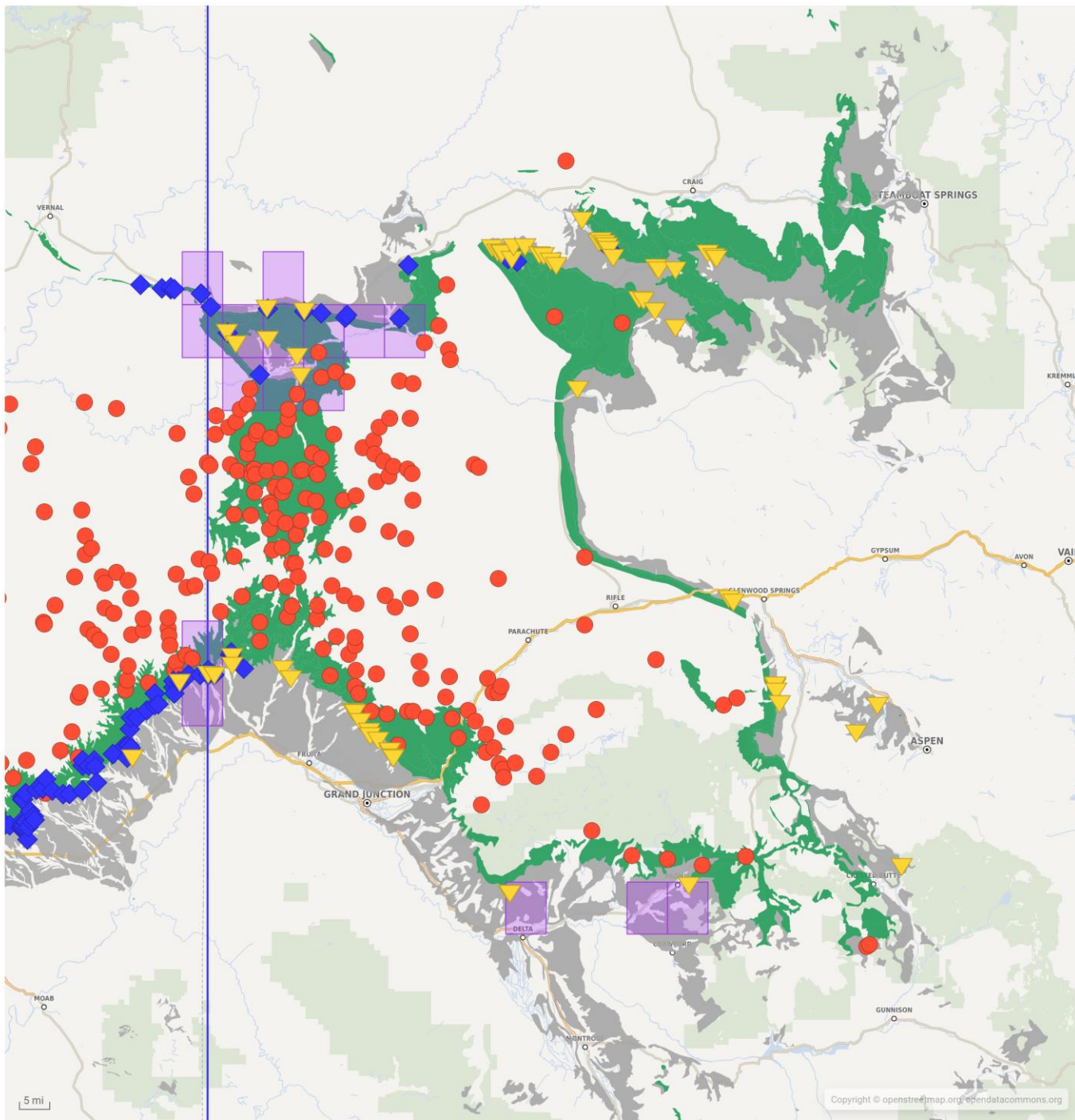


USGS Quadrangles

- Index all quadrangles with age-equivalent geologic units
- Final dataset:
 - 165 quadrangles
 - 98 publications
 - 1,067 geologic units

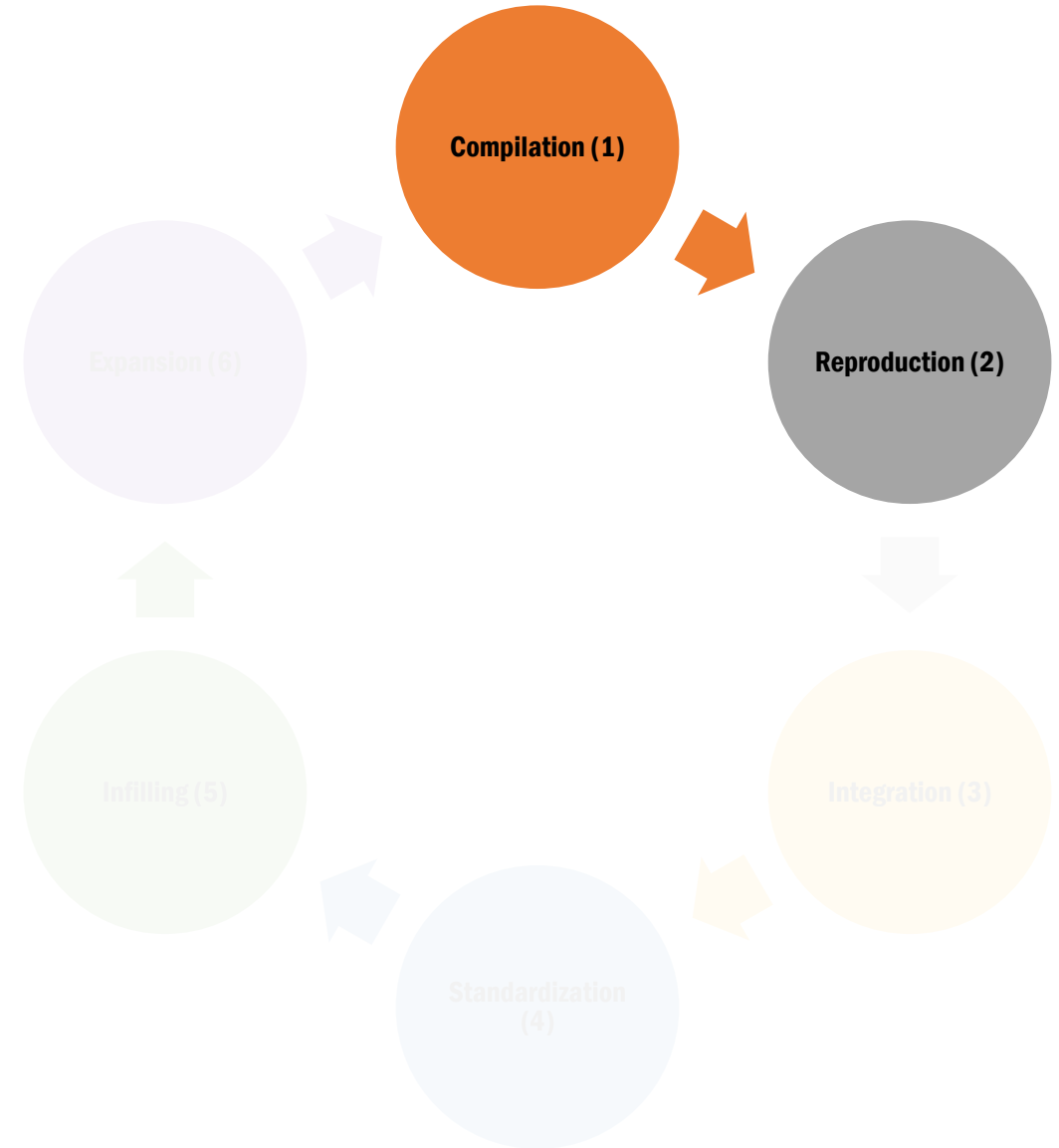
USGS Quadrangles

- Quadrangles with Castlegate Sandstone explicitly described

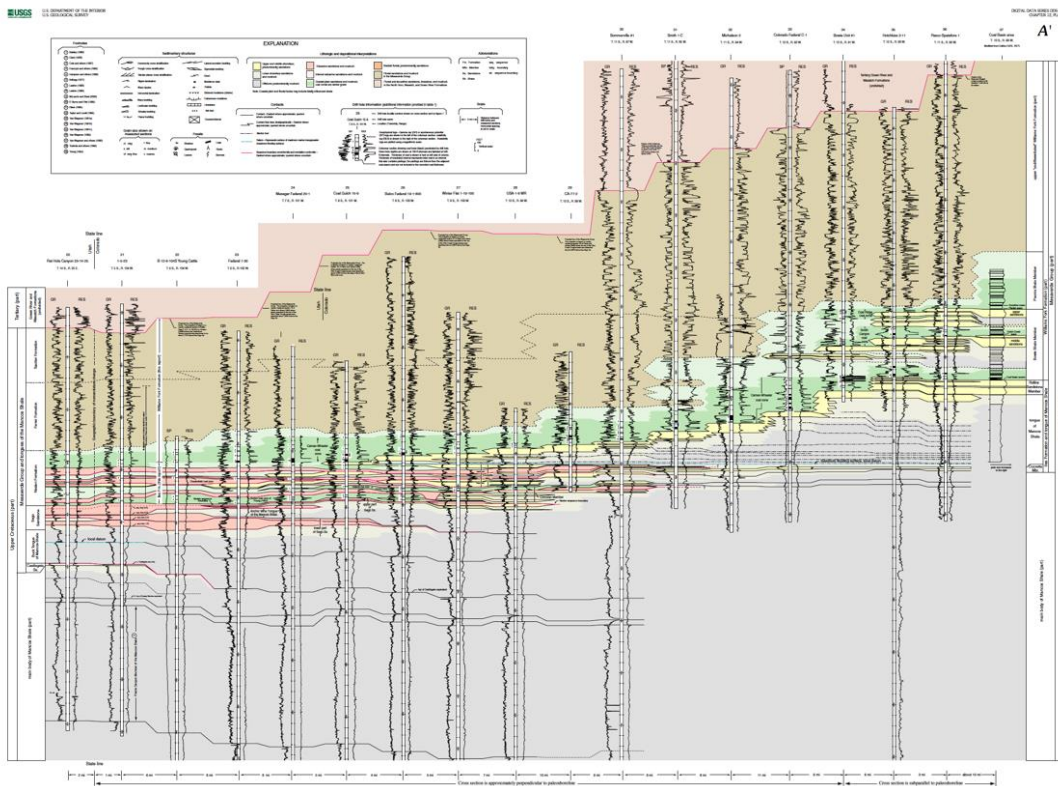


POC – Reproduction

1. Compile previous work
- 2. Reproduce previous work**
3. Integrate outcrop + subsurface data
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Reproduce Previous Subsurface Correlations



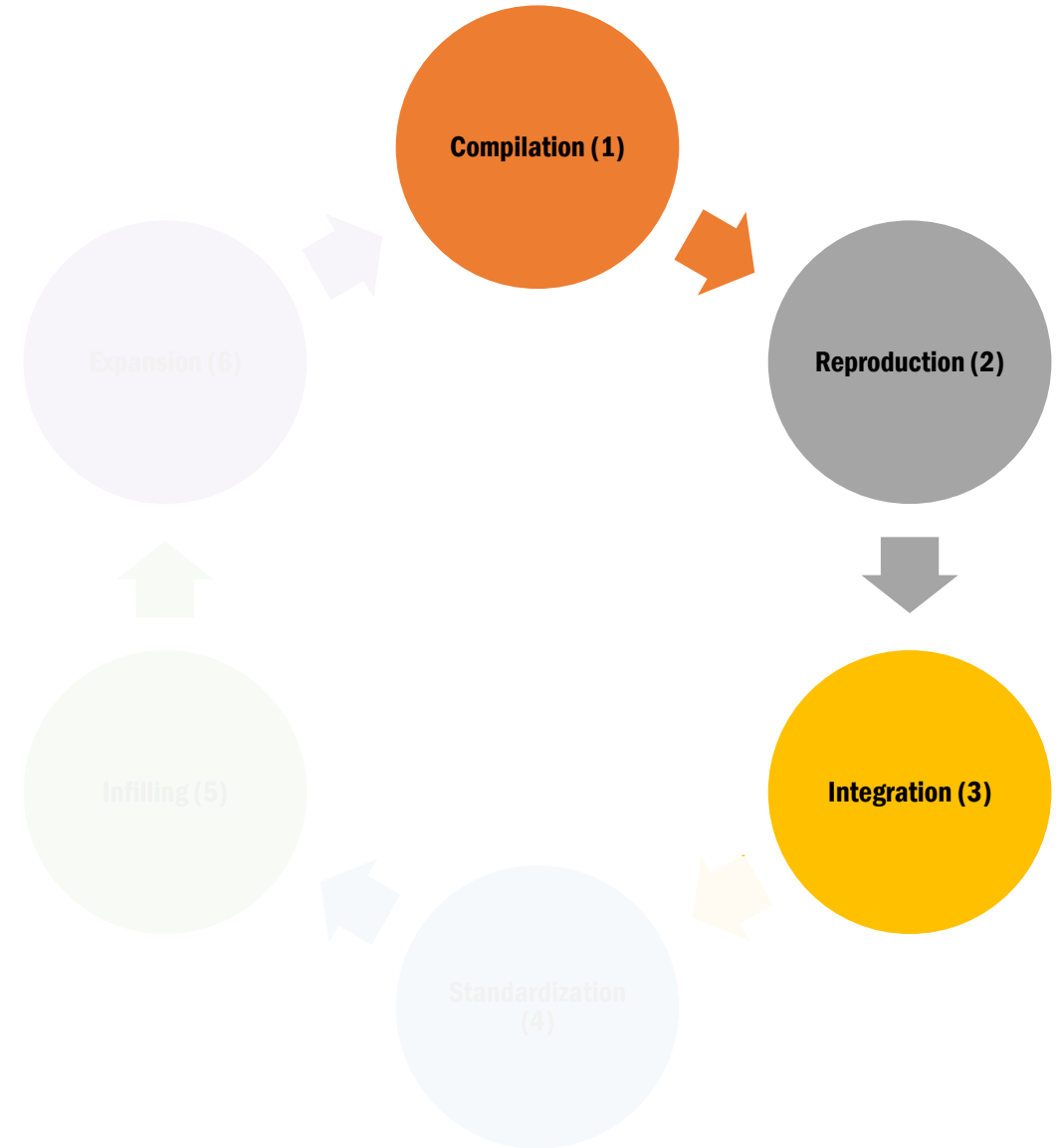
Replicating Correlations

- Assume all correlations are correct at first
- Pick tops for all wells before adding new data

Figure from Hettinger & Kirschbaum (2003)

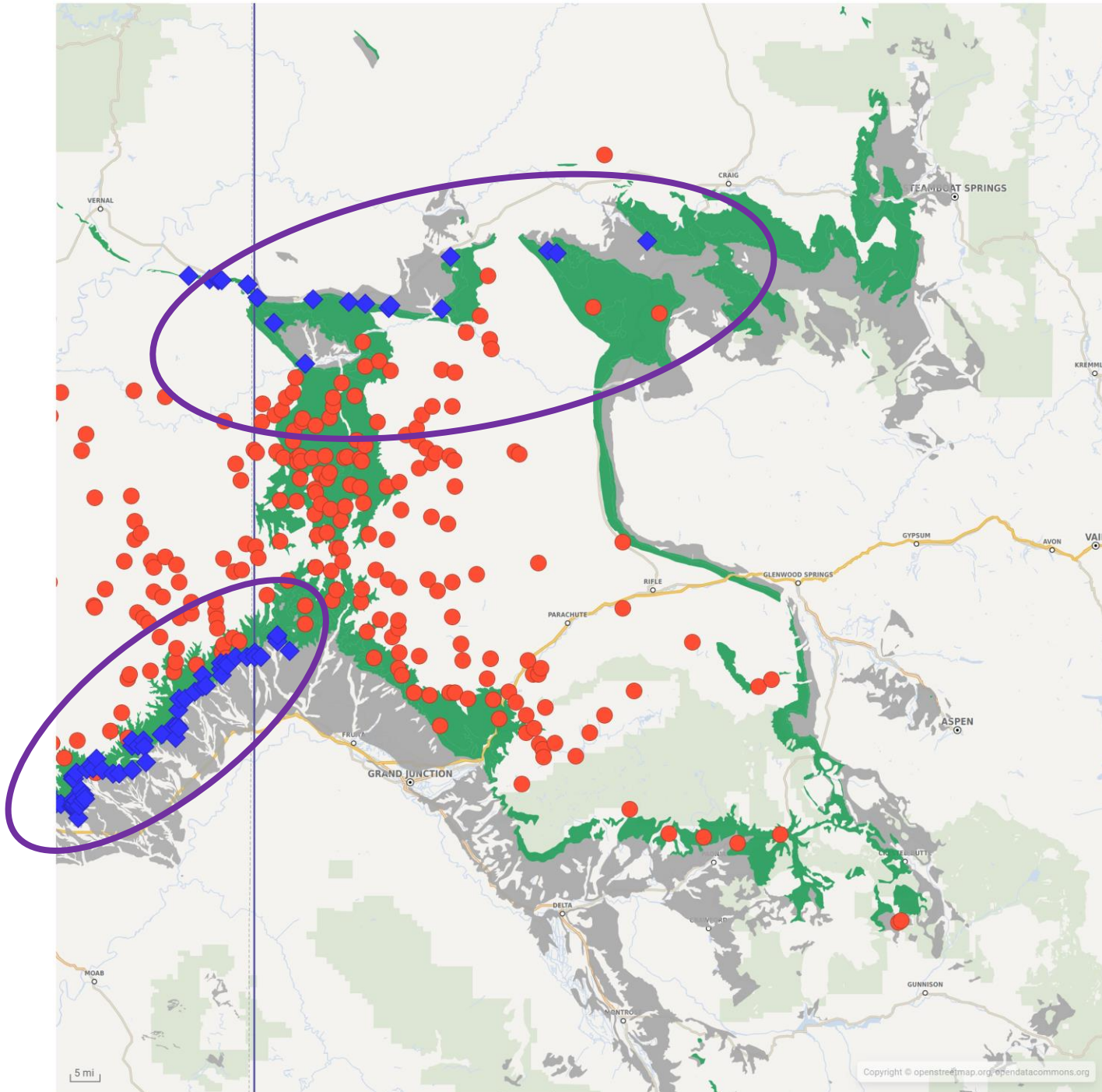
POC – Integration

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Outcrop-to-Subsurface Integration

- Compare-and-contrast well logs to nearby strat sections and geologic maps whenever possible



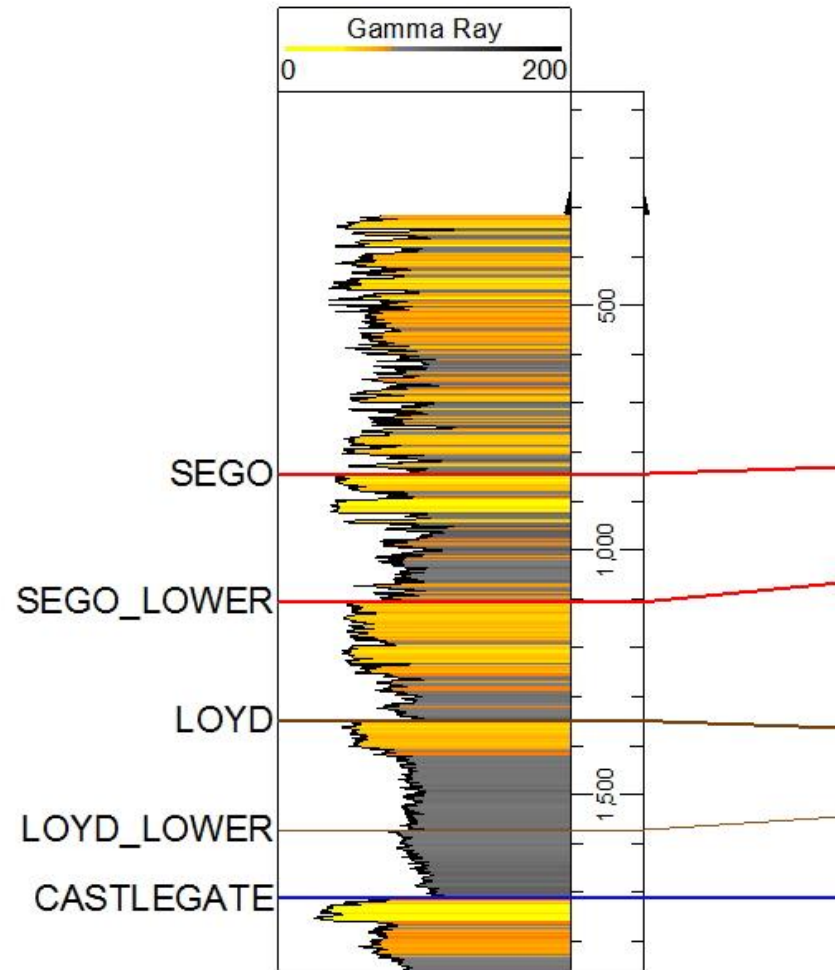
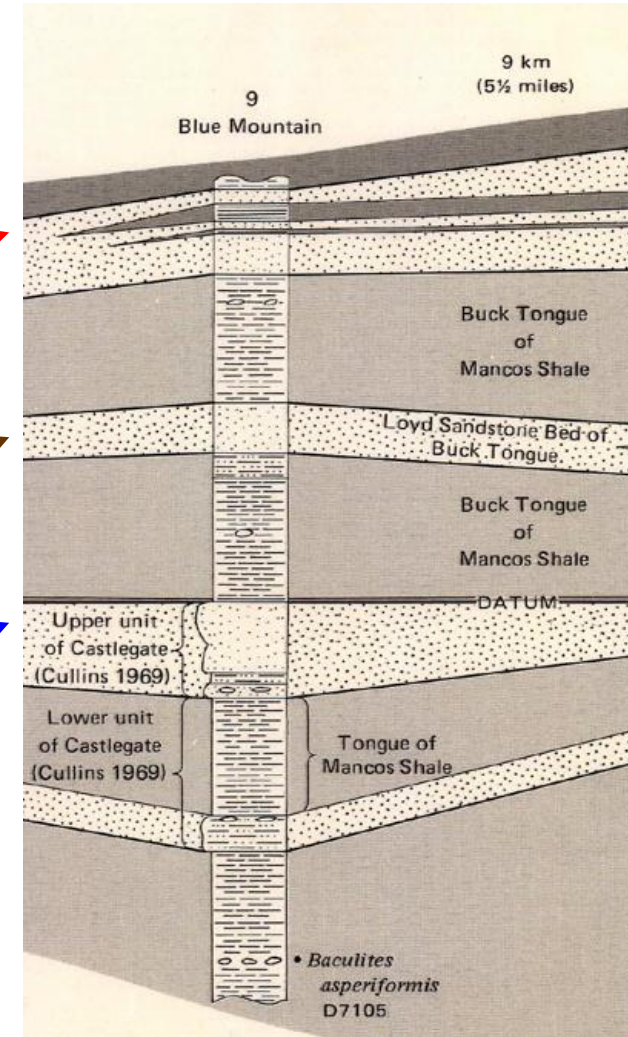
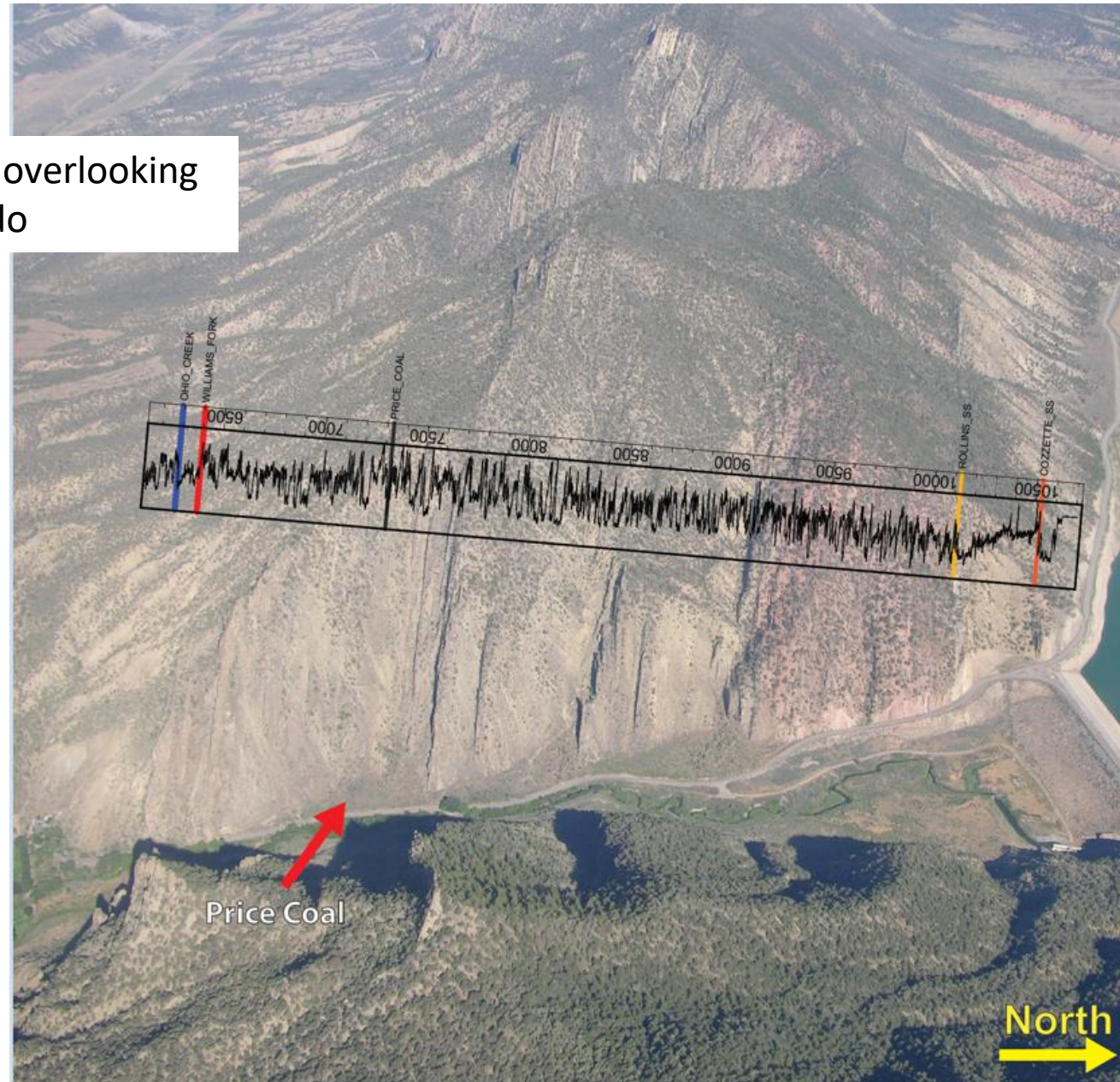


Figure from Gill & Hail (1975)

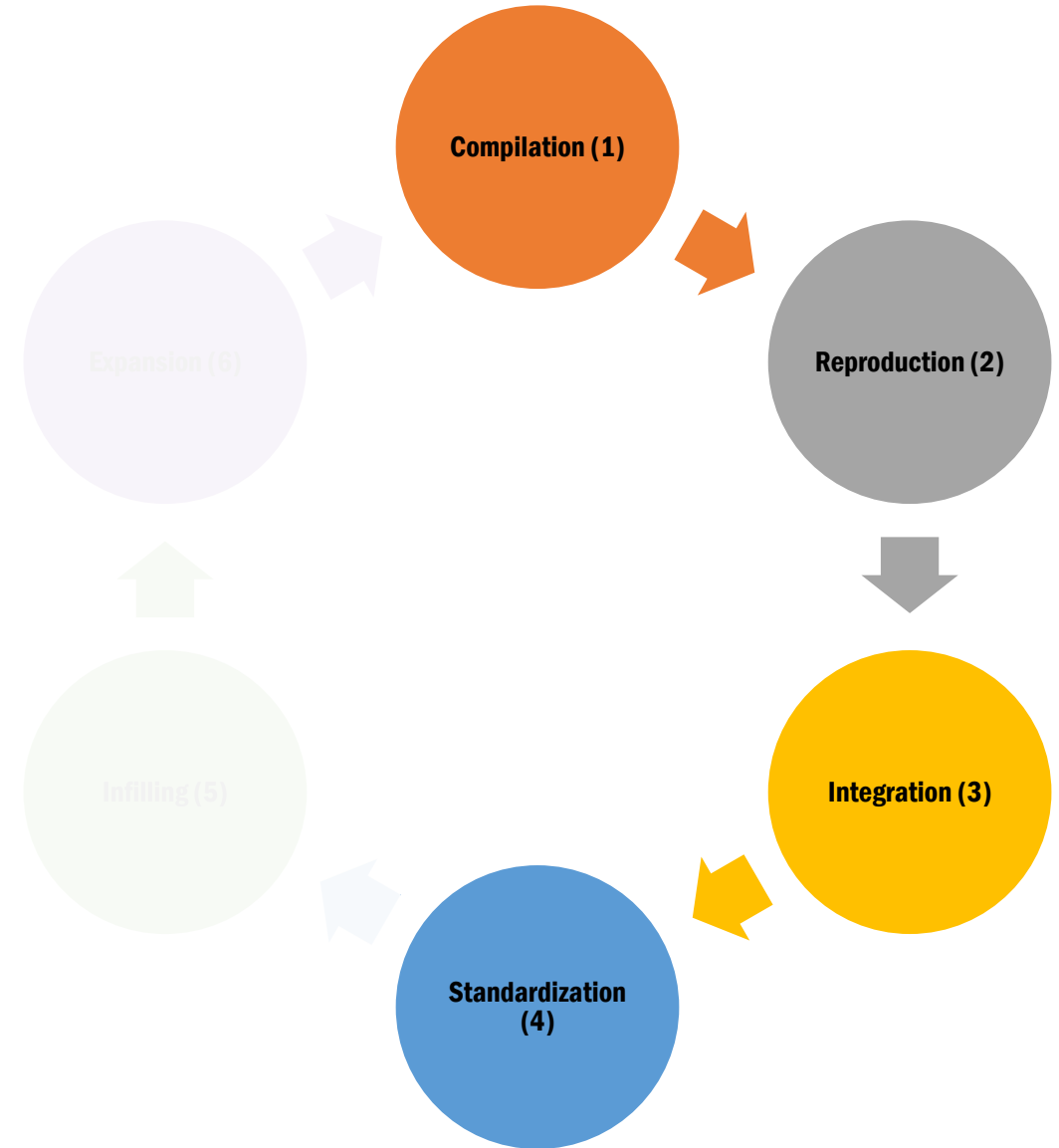


* Photo from Steve Cumella overlooking
NW cut of Rifle Gap, Colorado



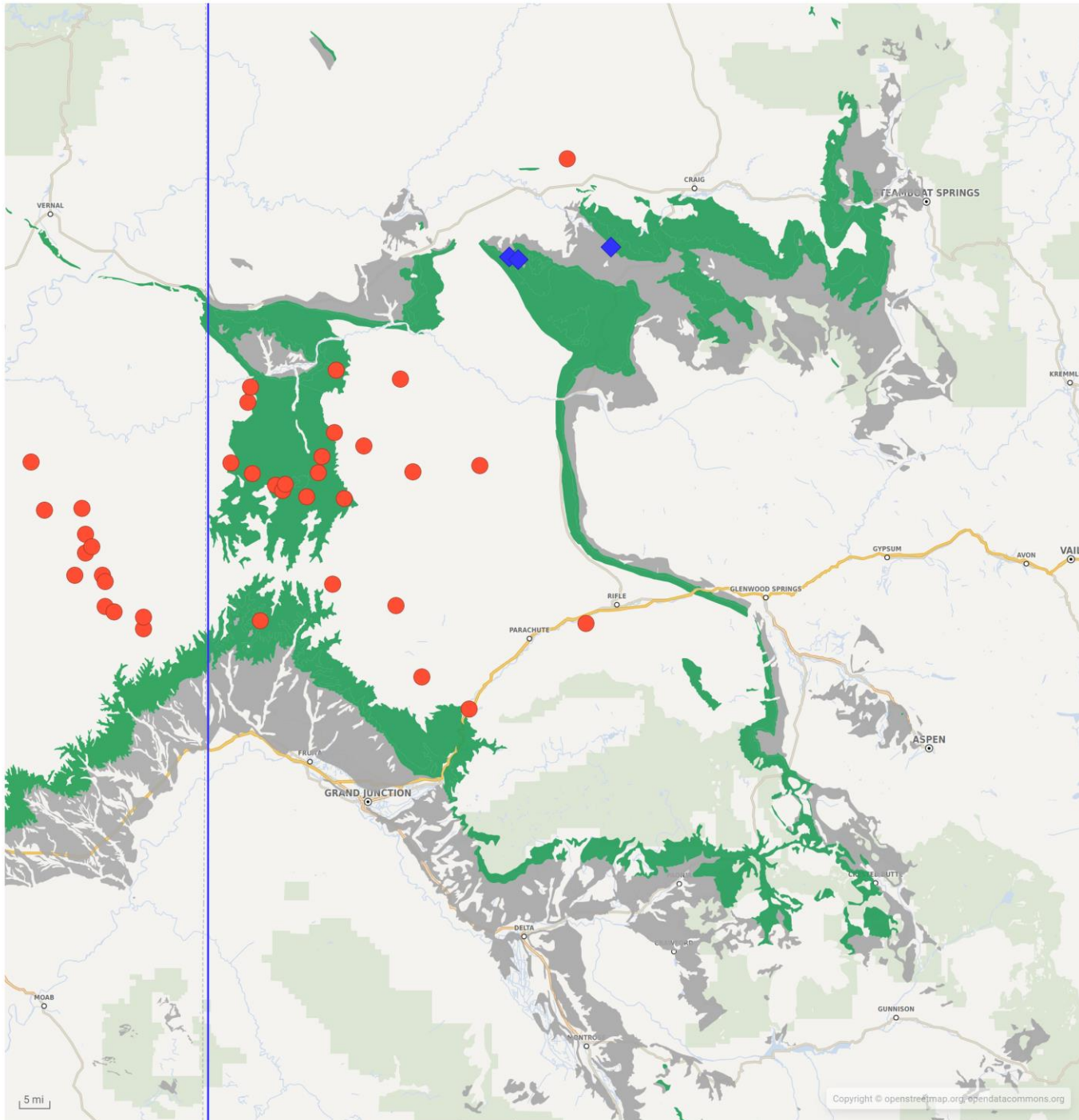
POC – Standardization

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Standardization

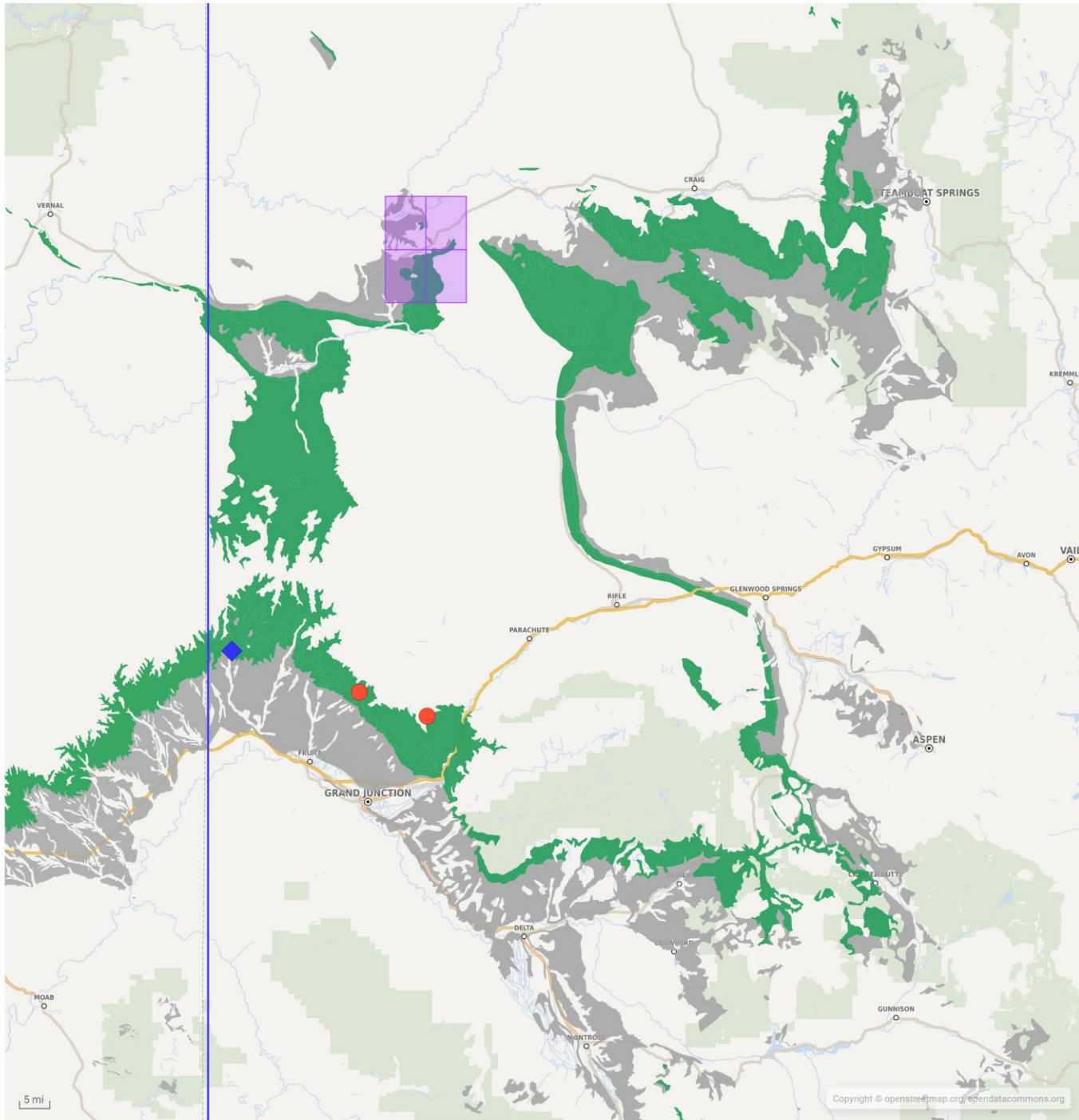
- Classify published data into three categories:
 1. *True positives*
 2. *False positives*
 3. *False negatives*



False Positive Data

- Strat sections
 - Gill & Hail (1975)
- Subsurface correlations
 - Finley et al. (1983)
 - Johnson (2003b)
 - Patterson et al. (2003)
 - Anna (2002)

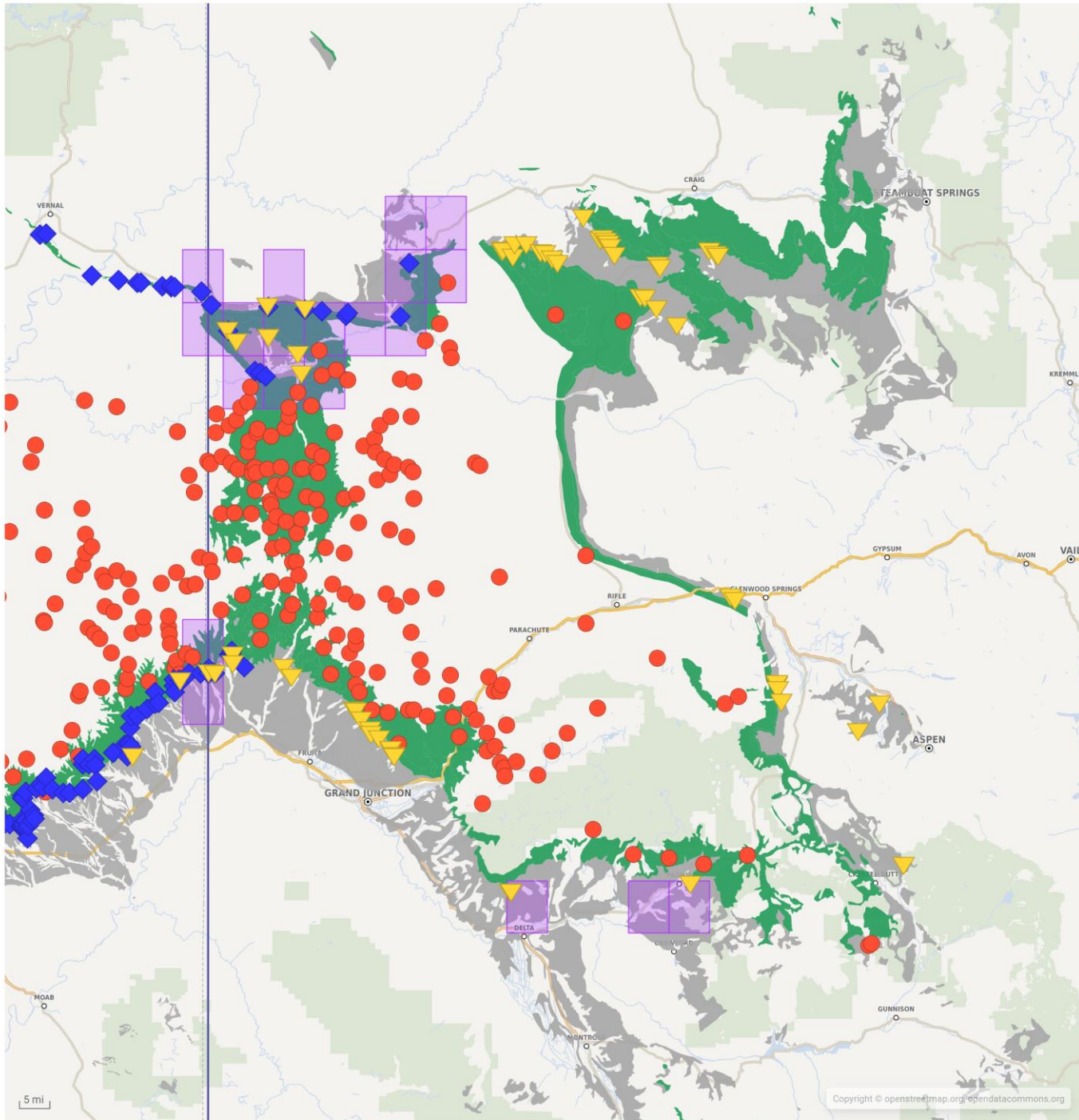
**** False Positives are removed ****



False Negative Data

- Strat sections
 - Fischer (1960)
- Subsurface correlations
 - Anna (2012)
- Geologic maps
 - Dyni (1968)

**** False Negatives are added ****

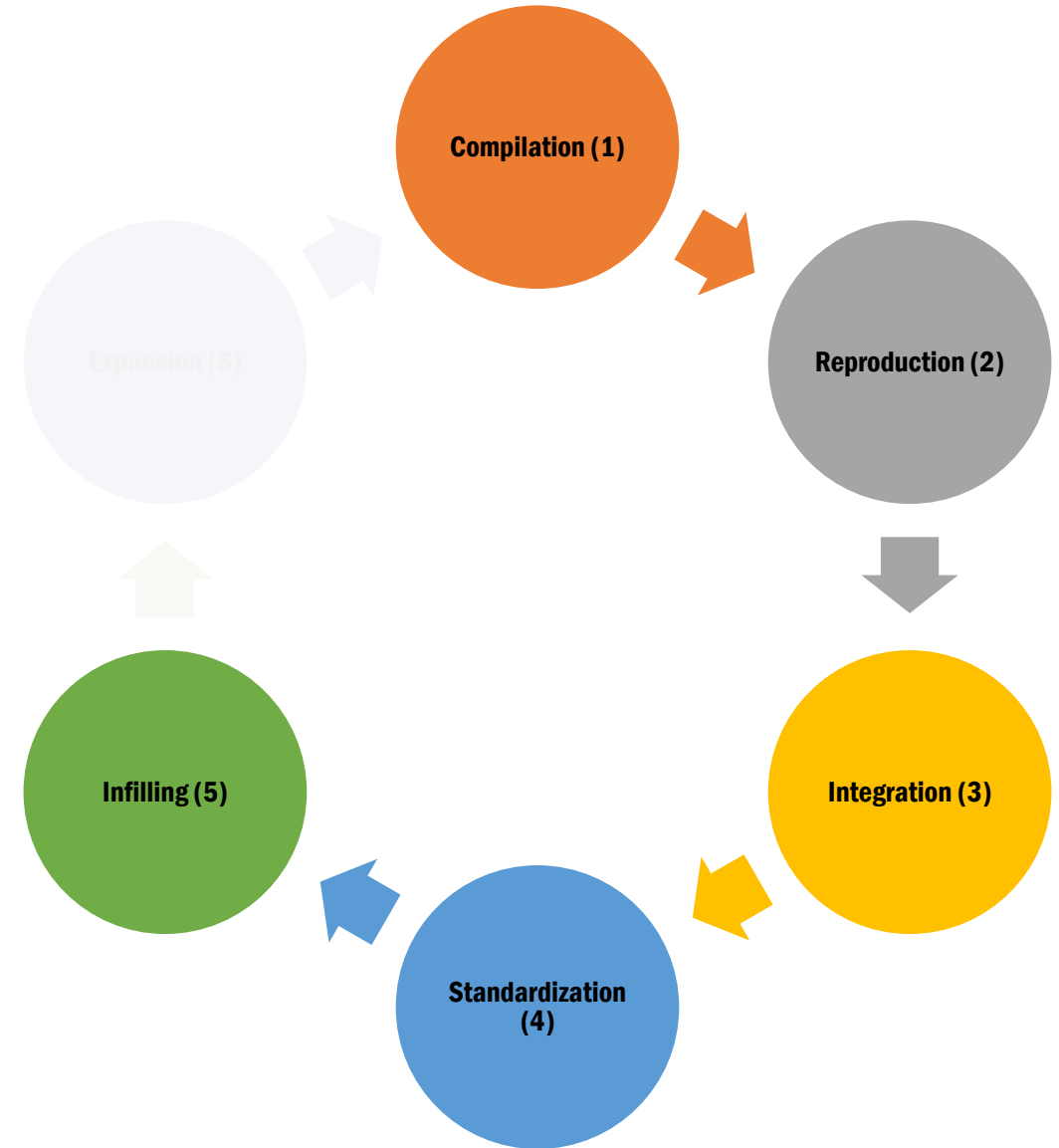


Standardized Dataset

- Sourced purely from existing publications

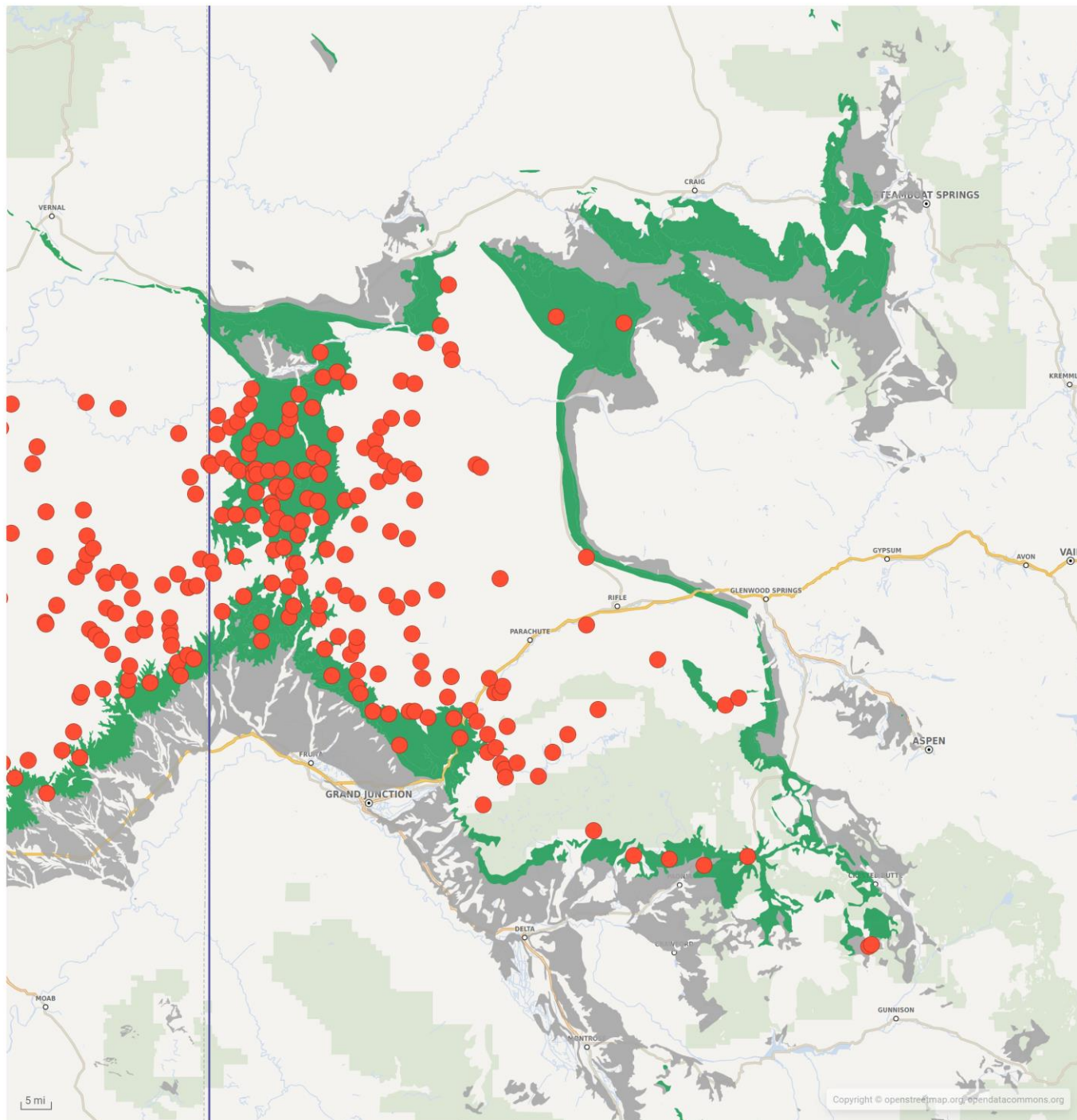
POC – Infilling

1. Compile previous work
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4. Standardize interpretations
- 5. Infill existing dataset with new data**
6. Expand AOI



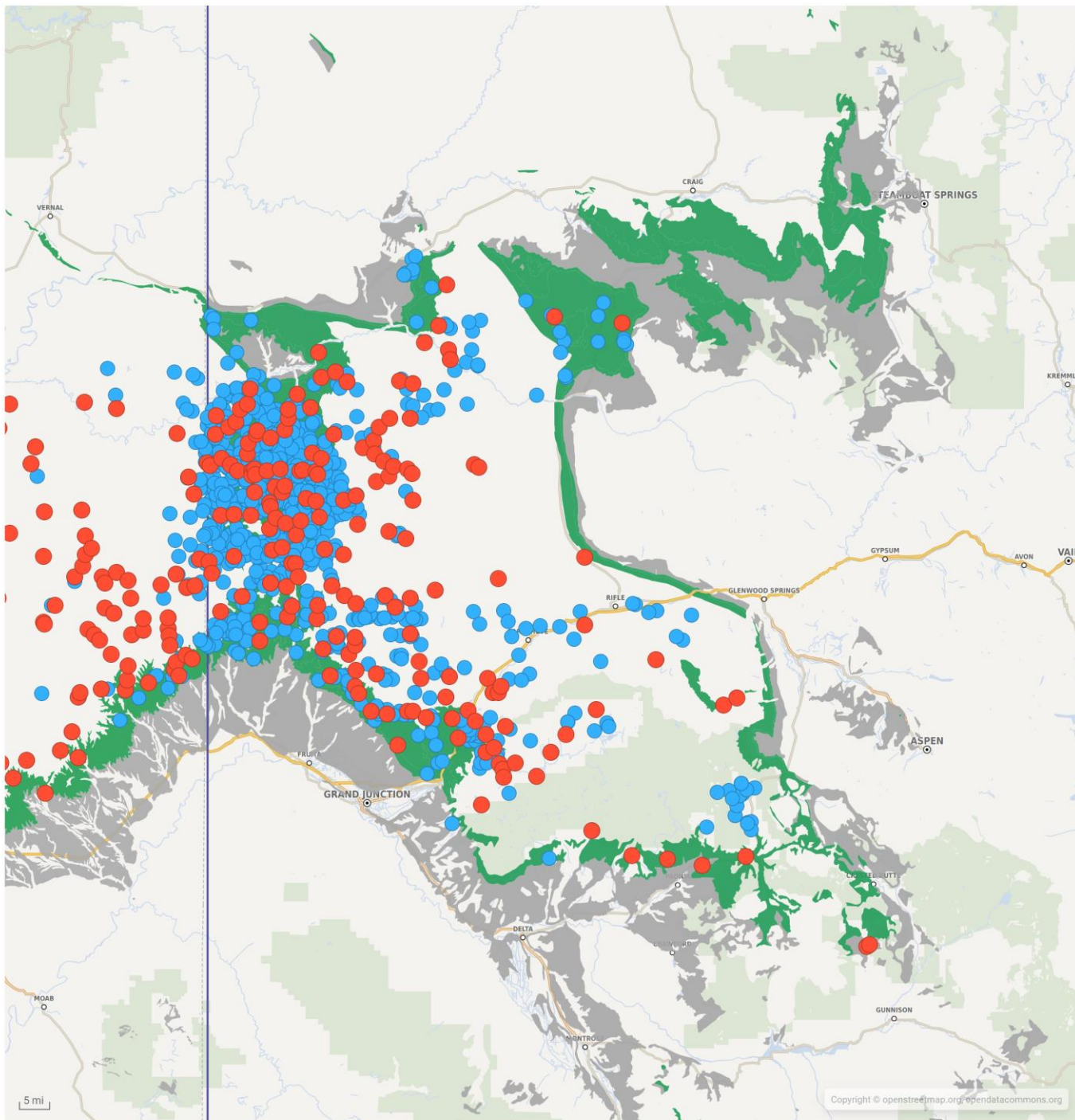
Areal Infilling

- Initial well count (e.g., seed wells)



Areal Infilling

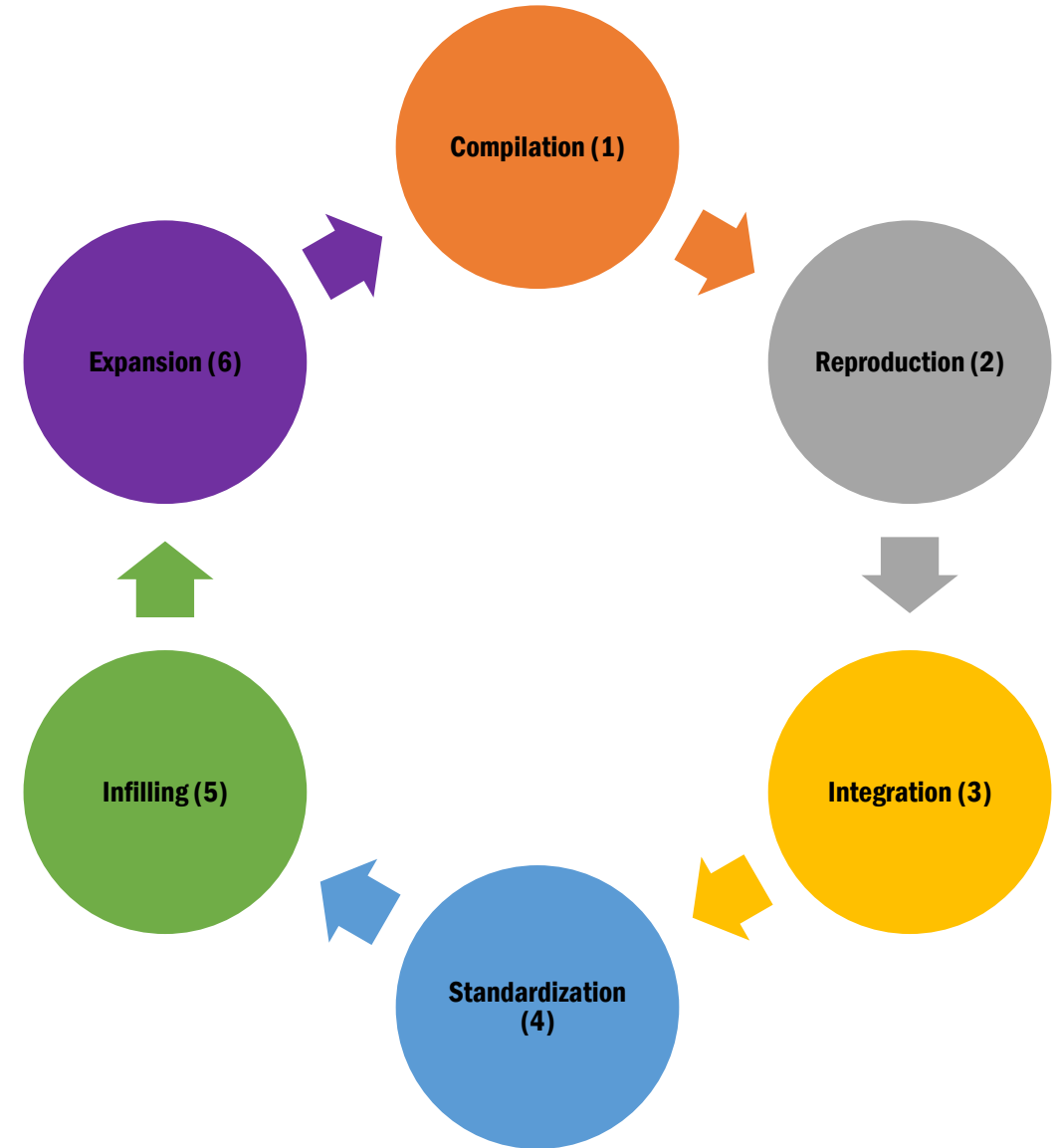
- Based on well log availability

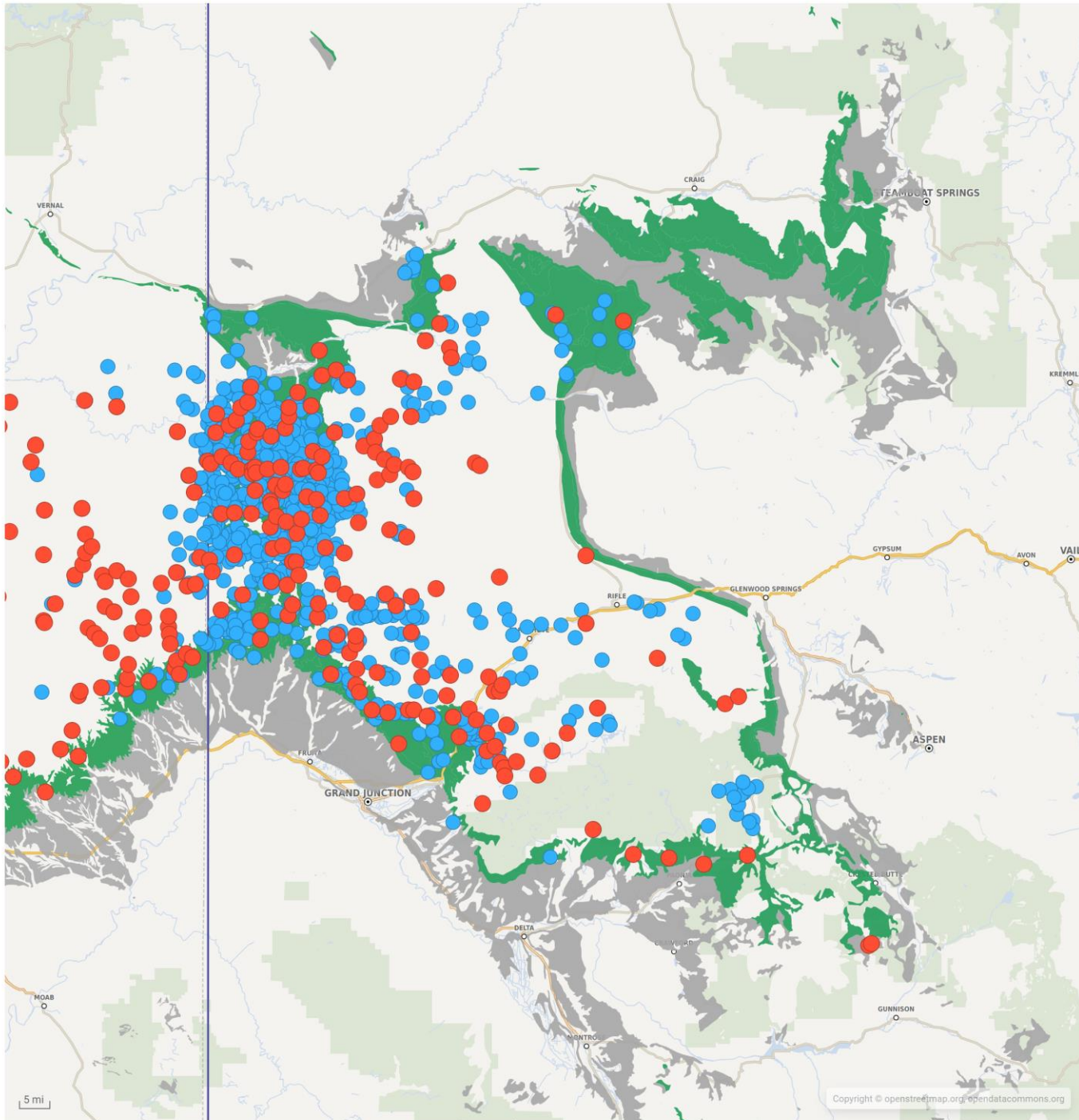


POC – Expansion

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3. Integrate outcrop + subsurface data
4. Standardize interpretations
5. Infill existing dataset with new data

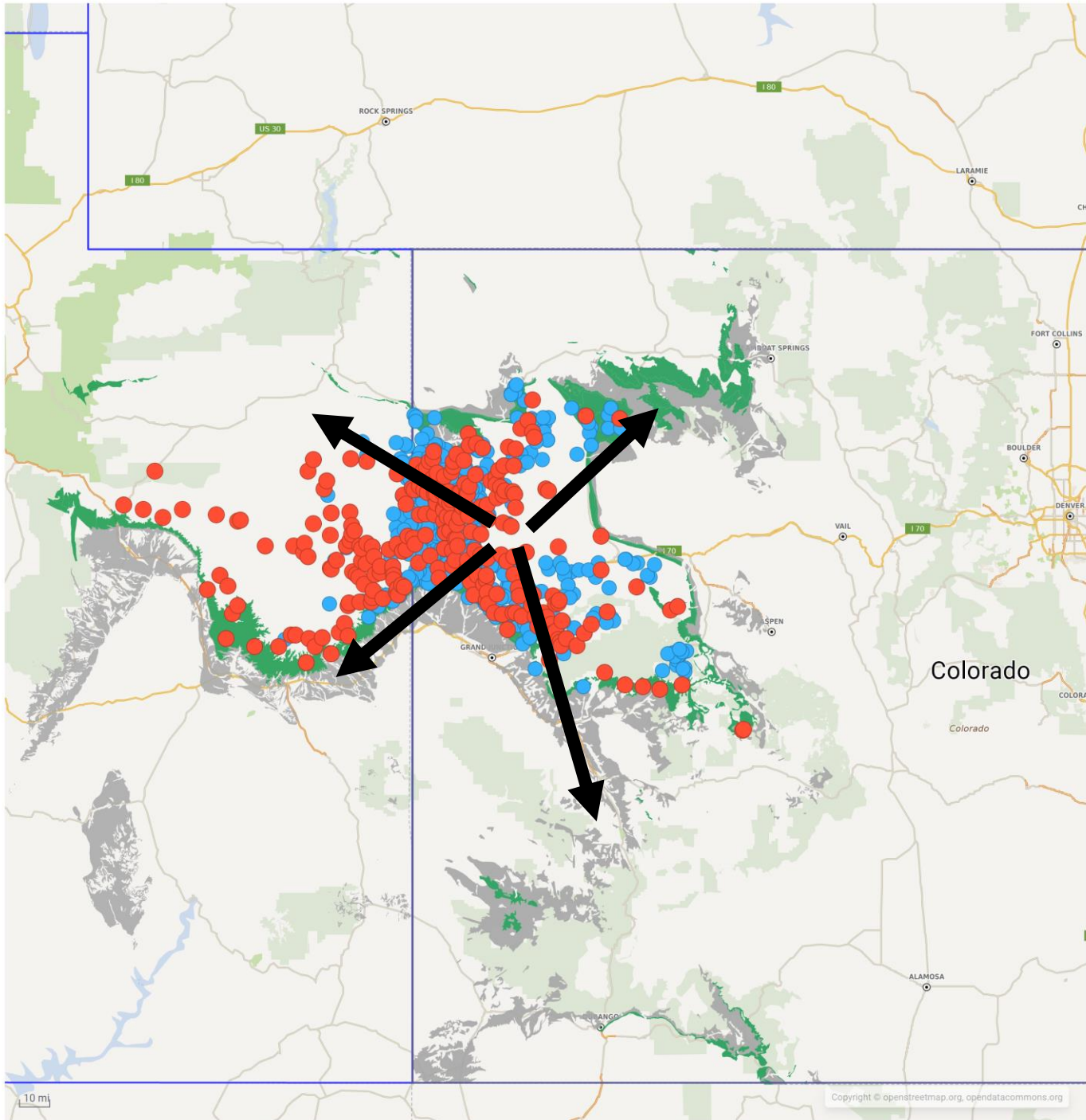
6. Expand AOI





Areal Expansion

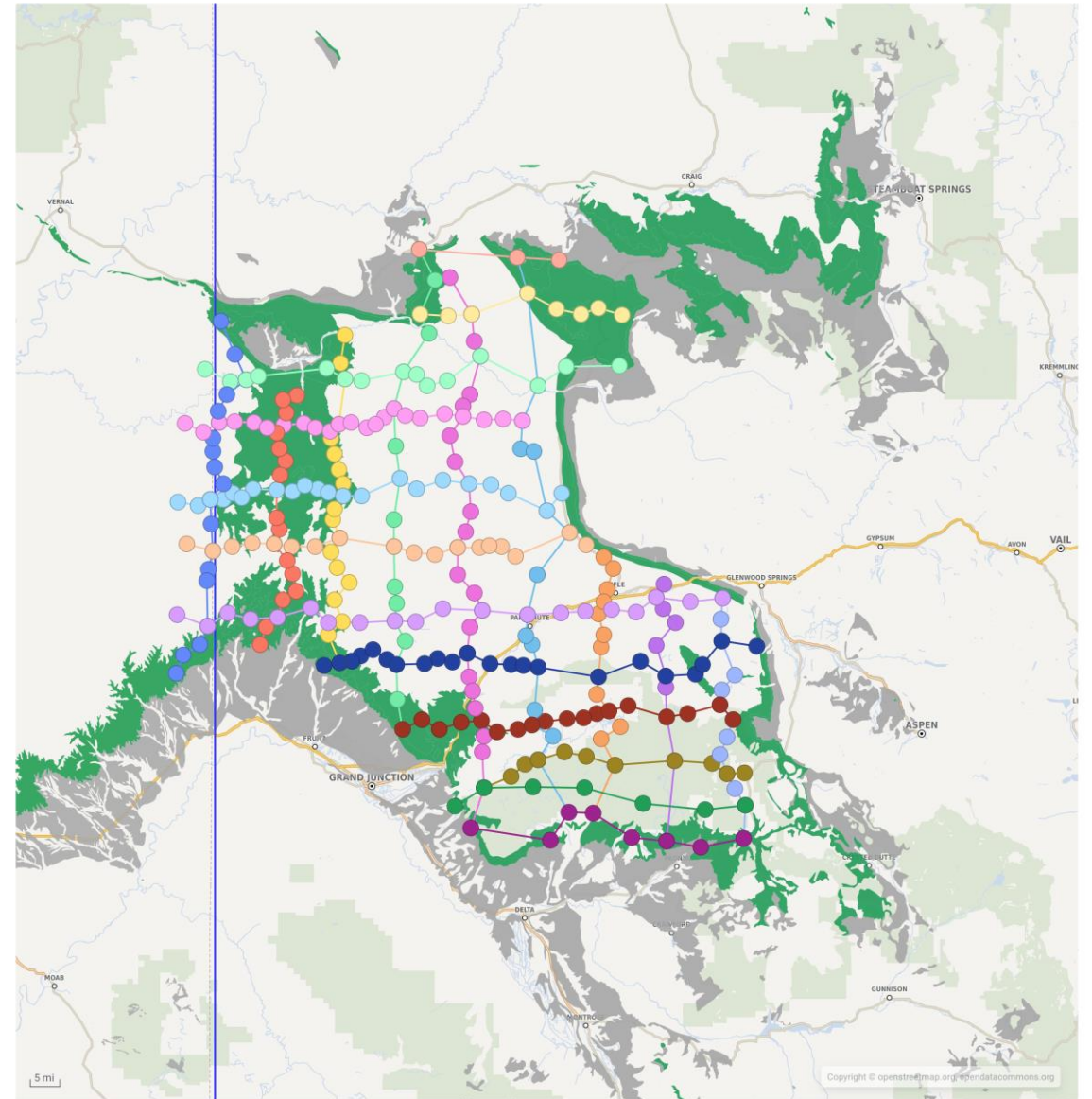
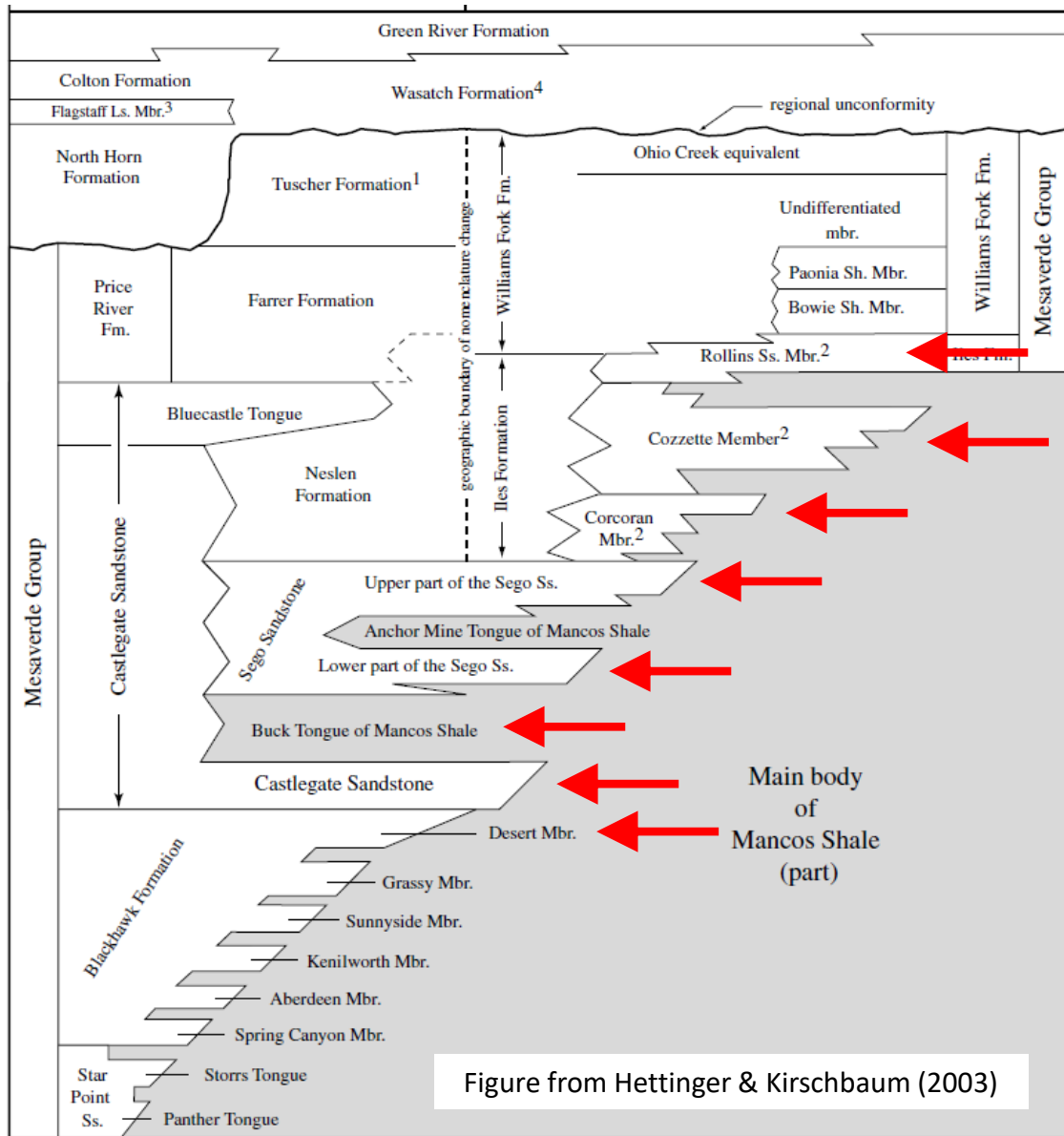
- Limited originally to initial area-of-interest (AOI)

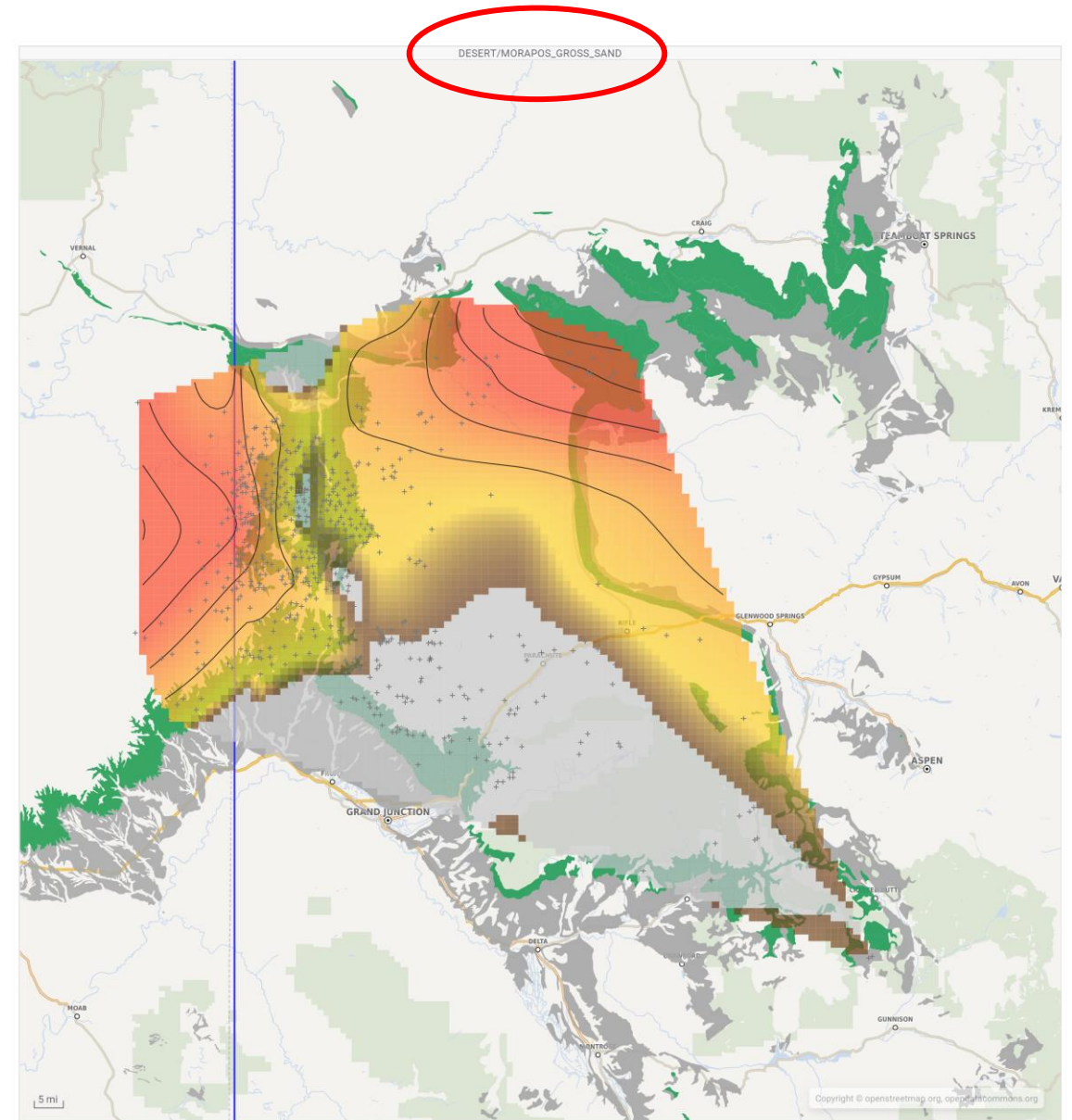
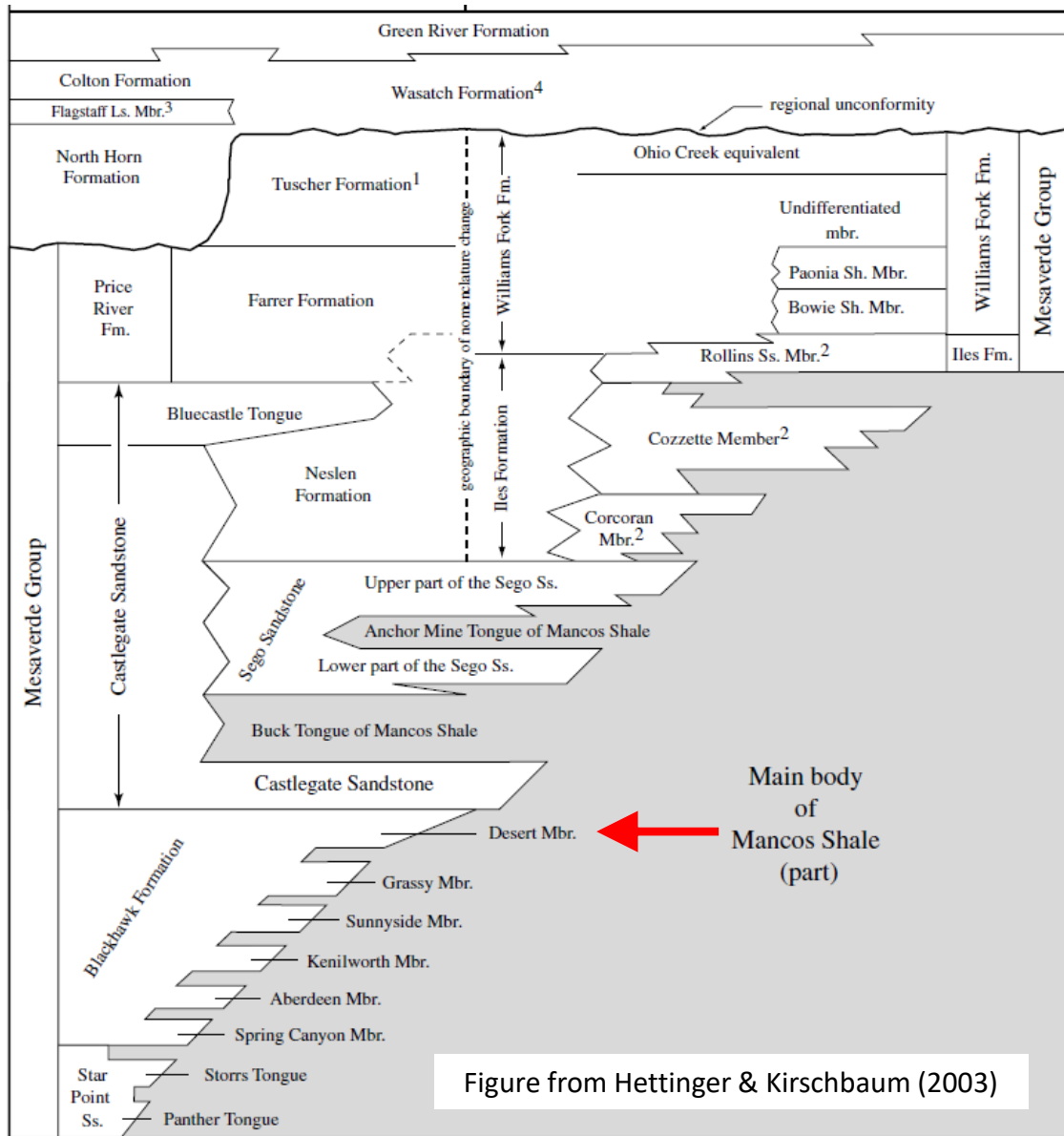


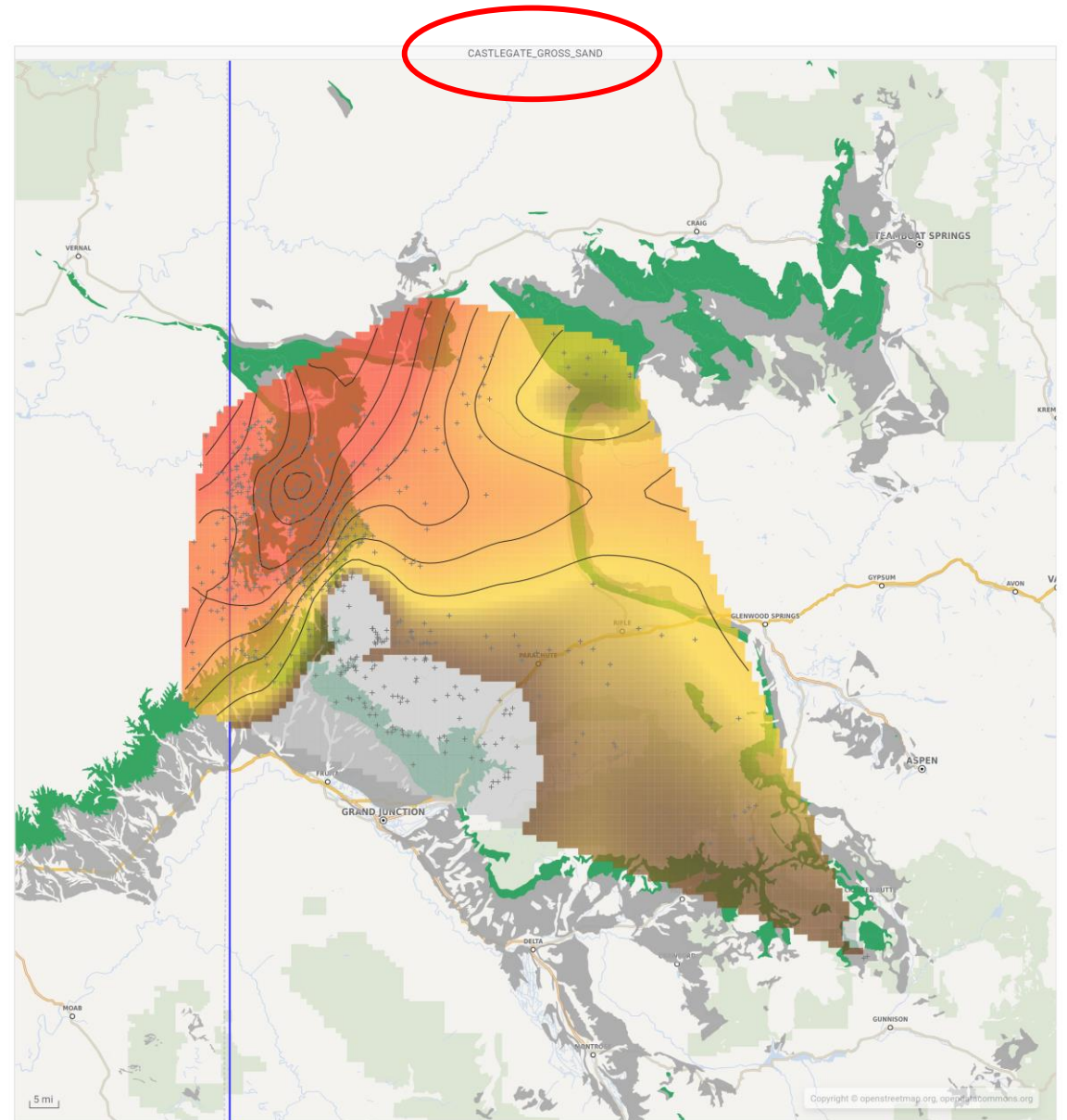
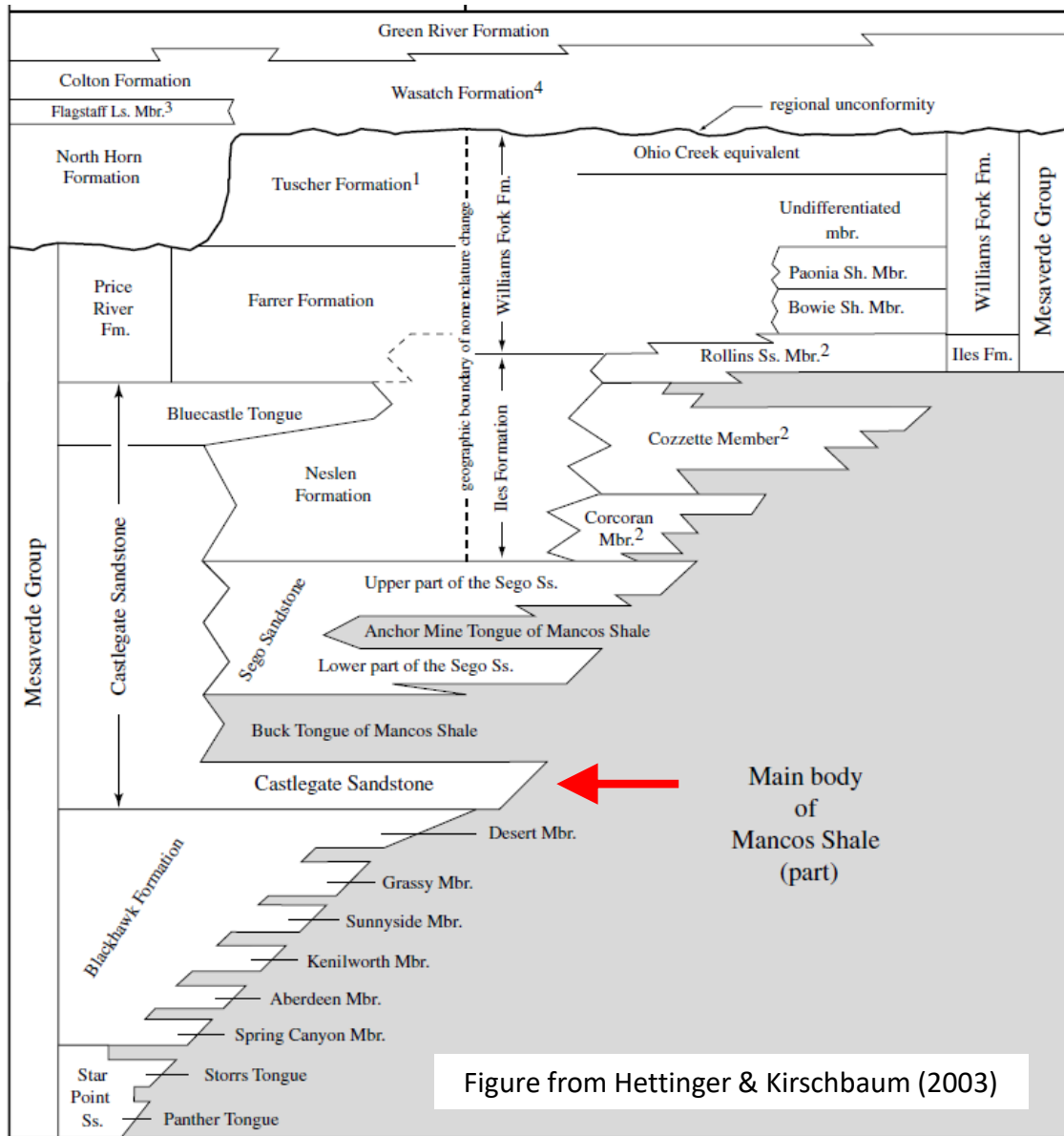
Areal Expansion

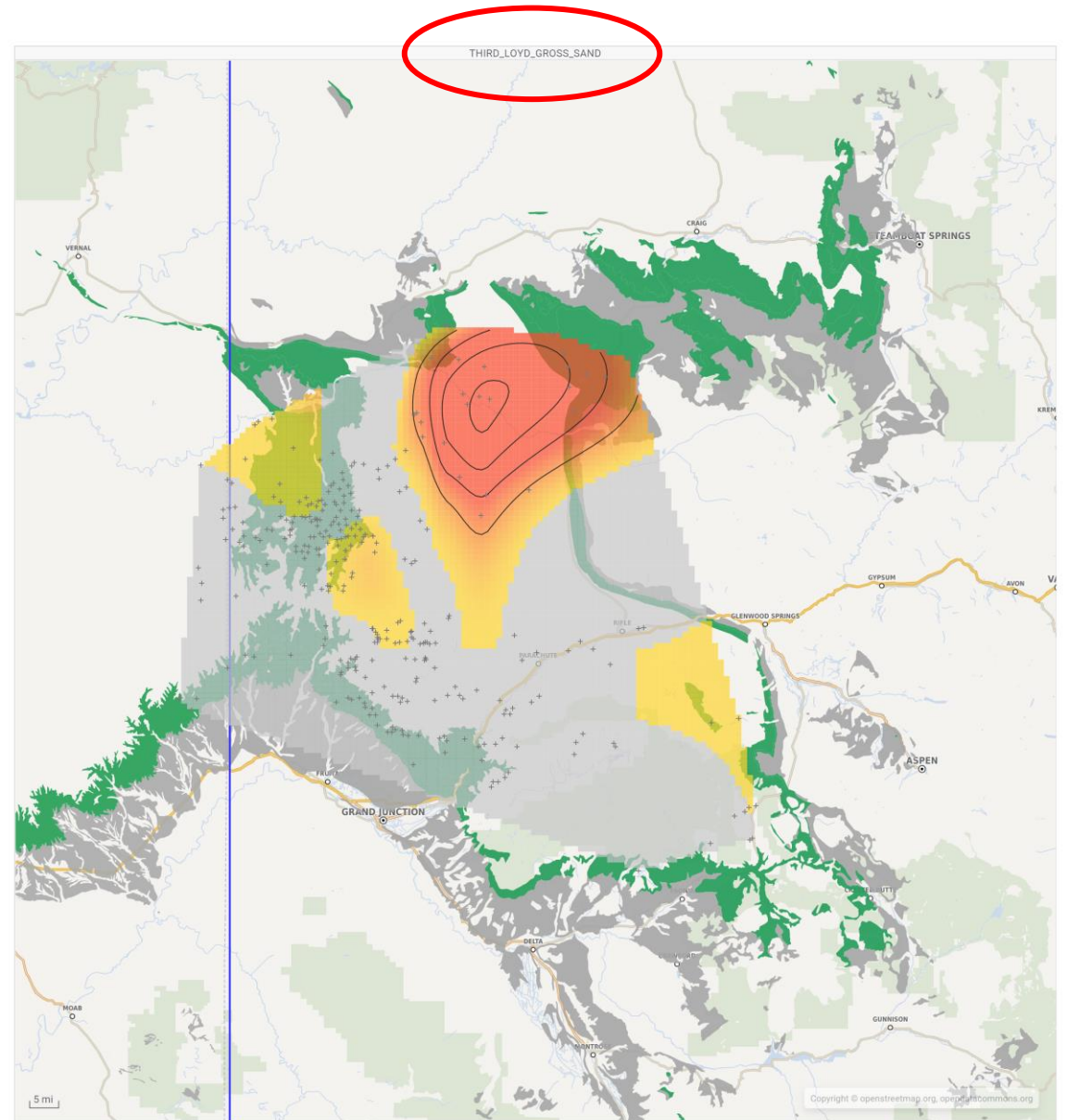
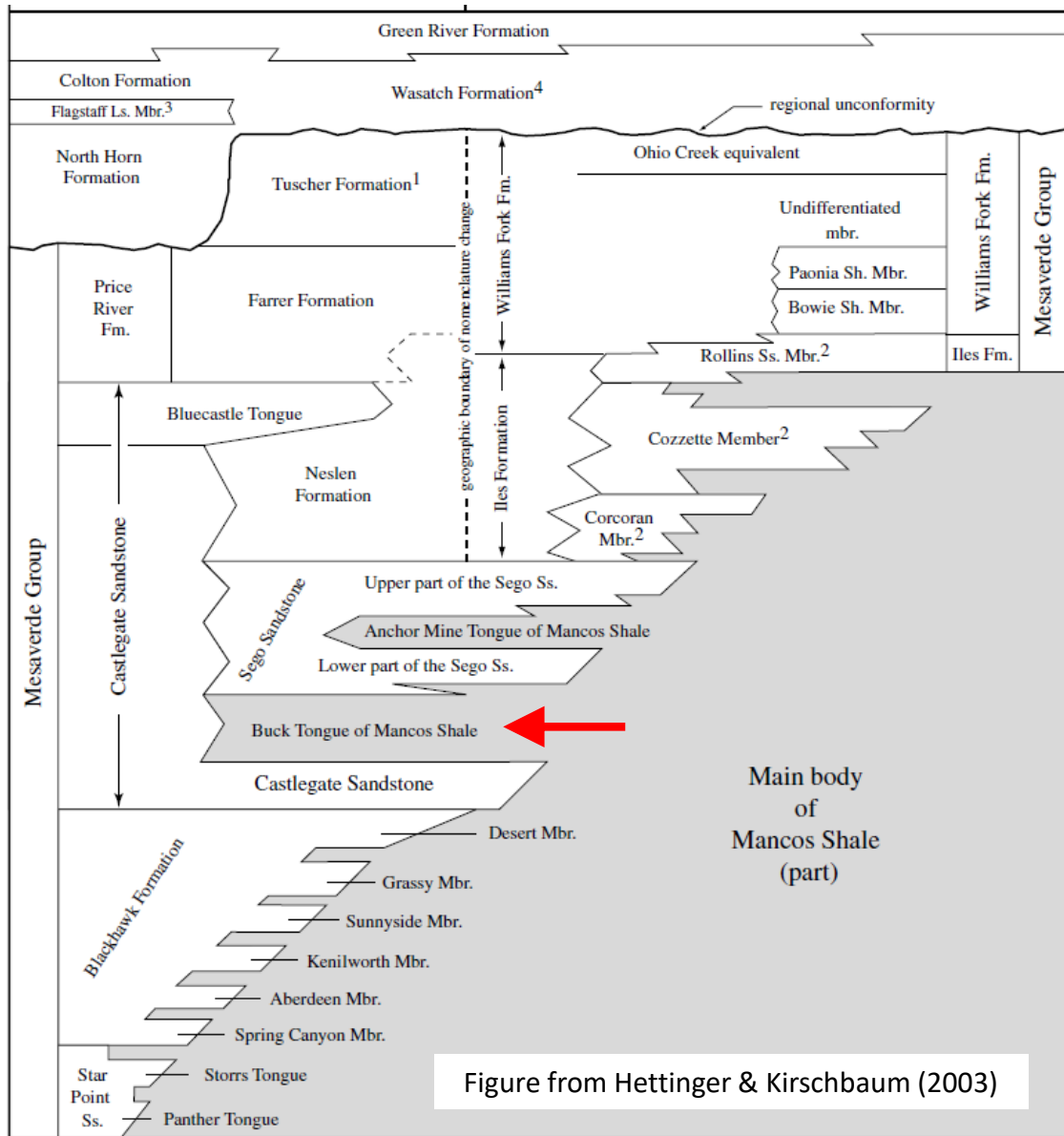
- Limited originally to initial area-of-interest (AOI)
- Expanded by well log availability and fossil control on basin margins

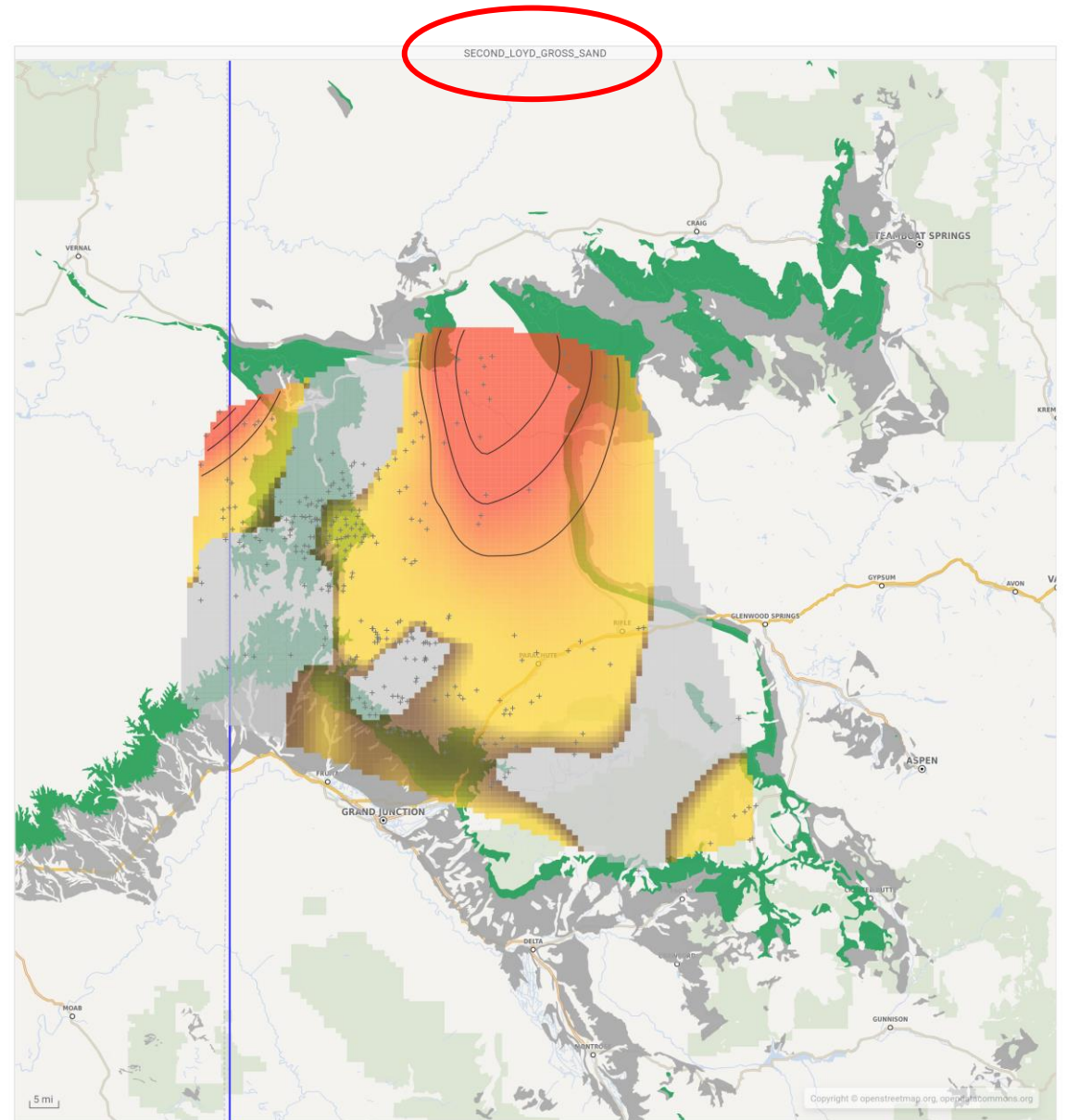
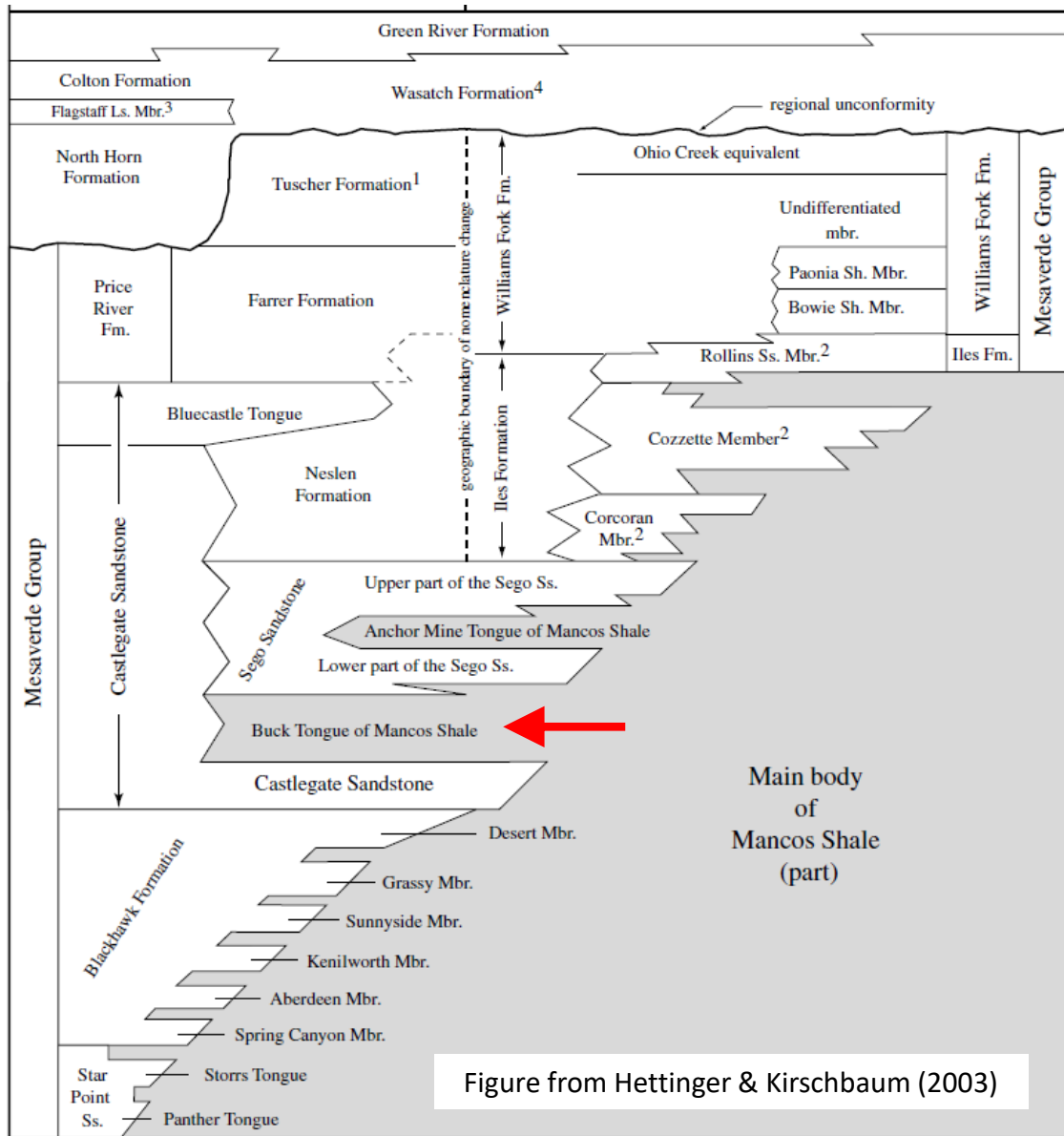
Results (Preview)

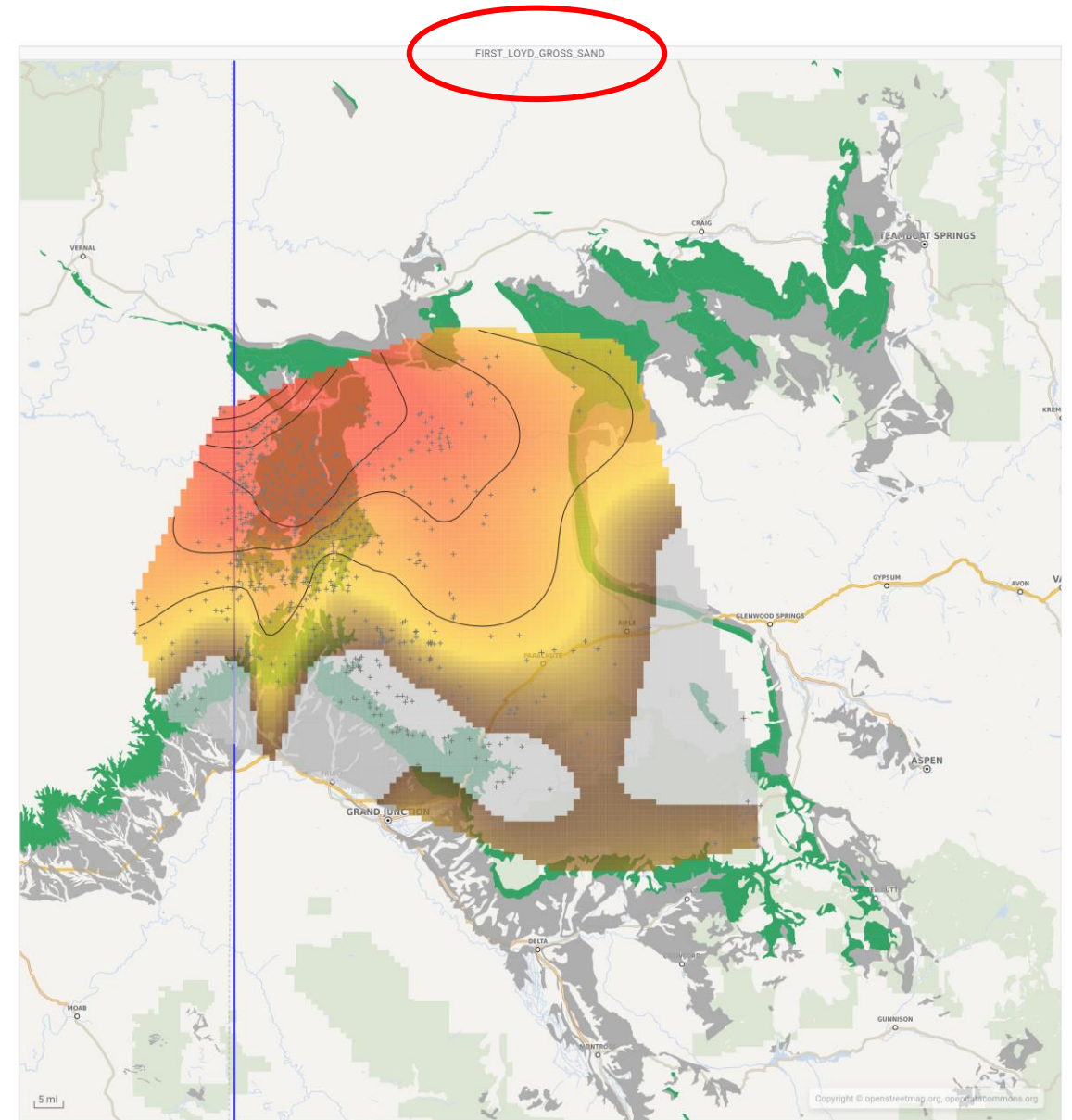
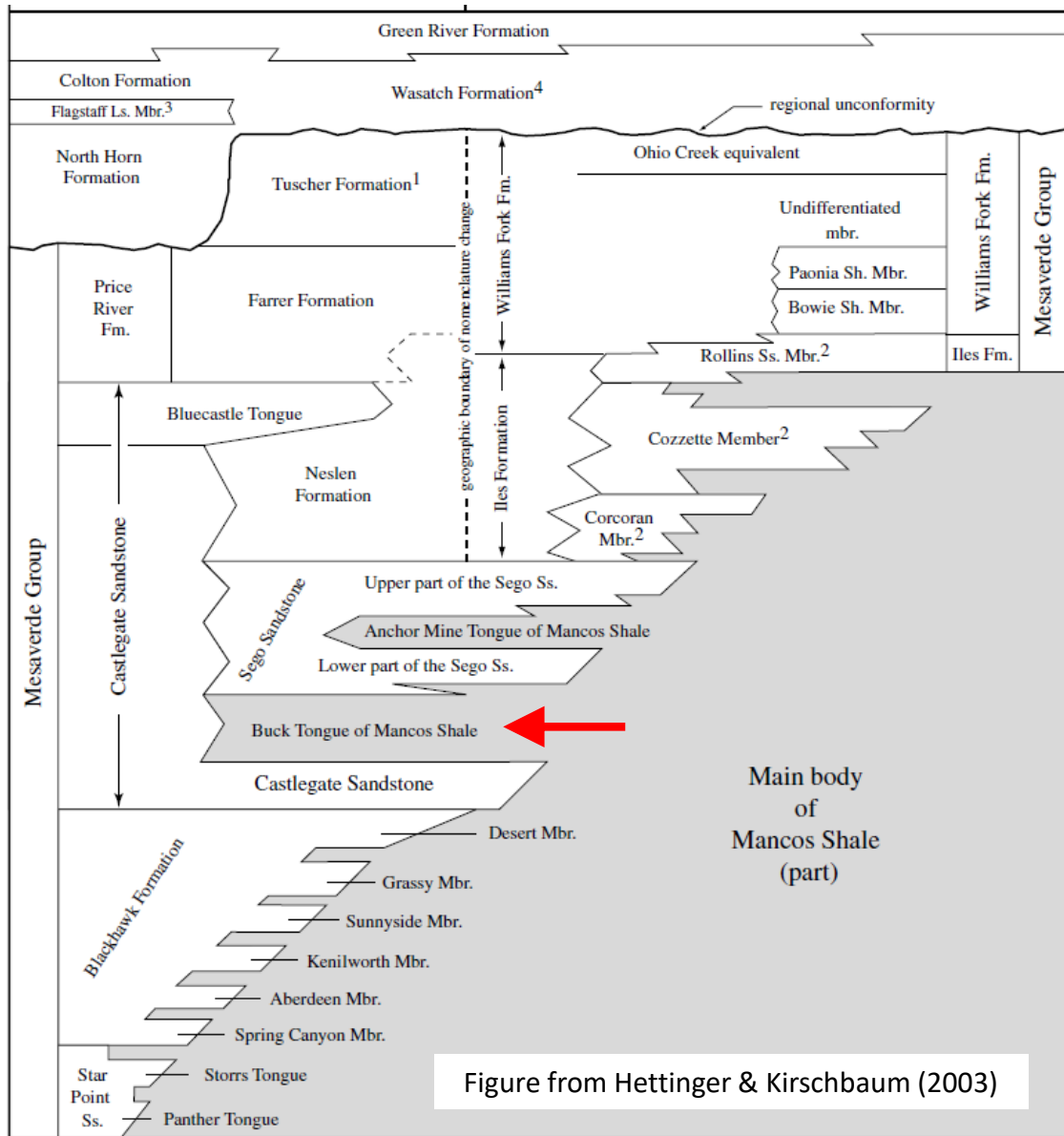


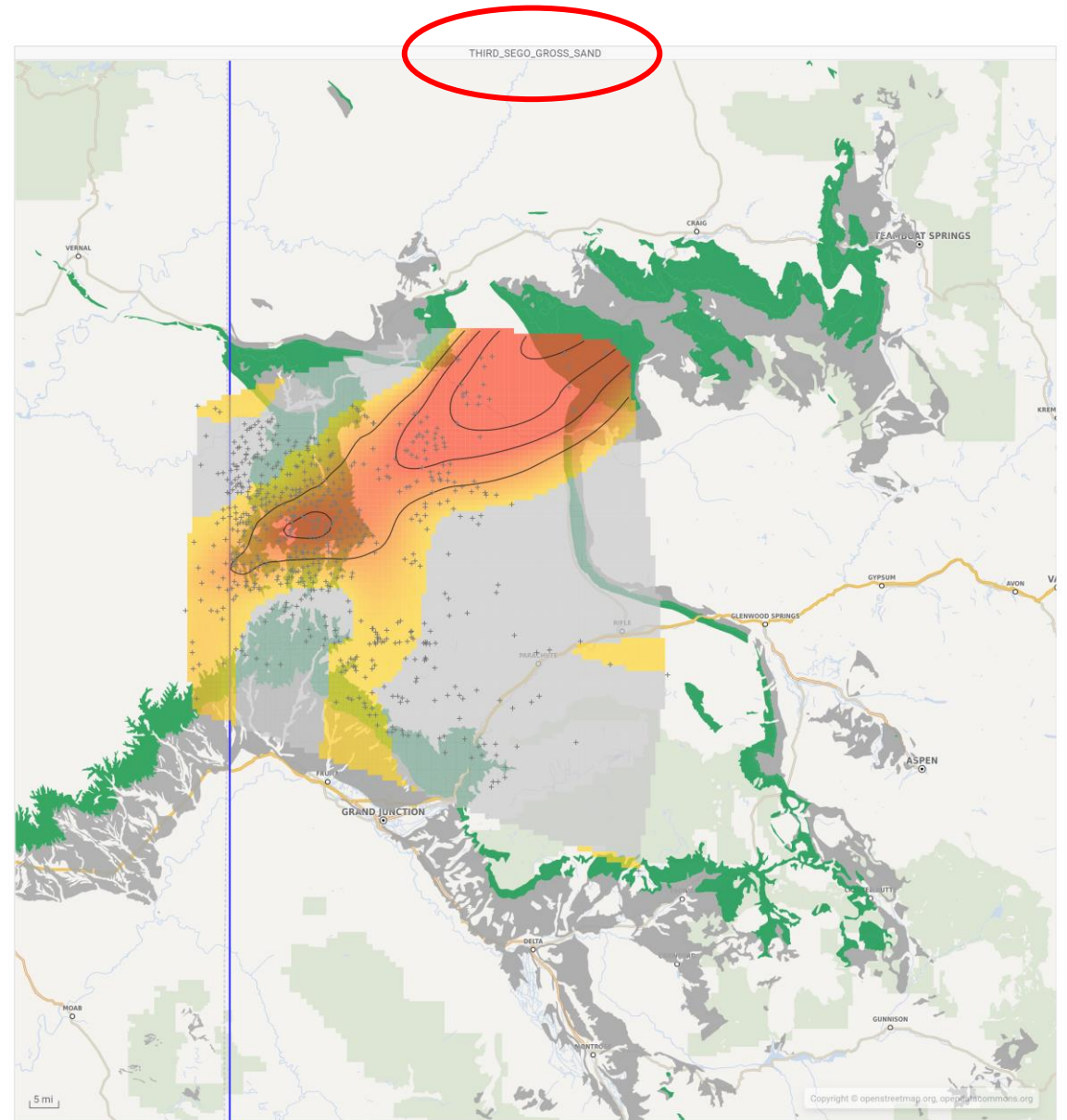
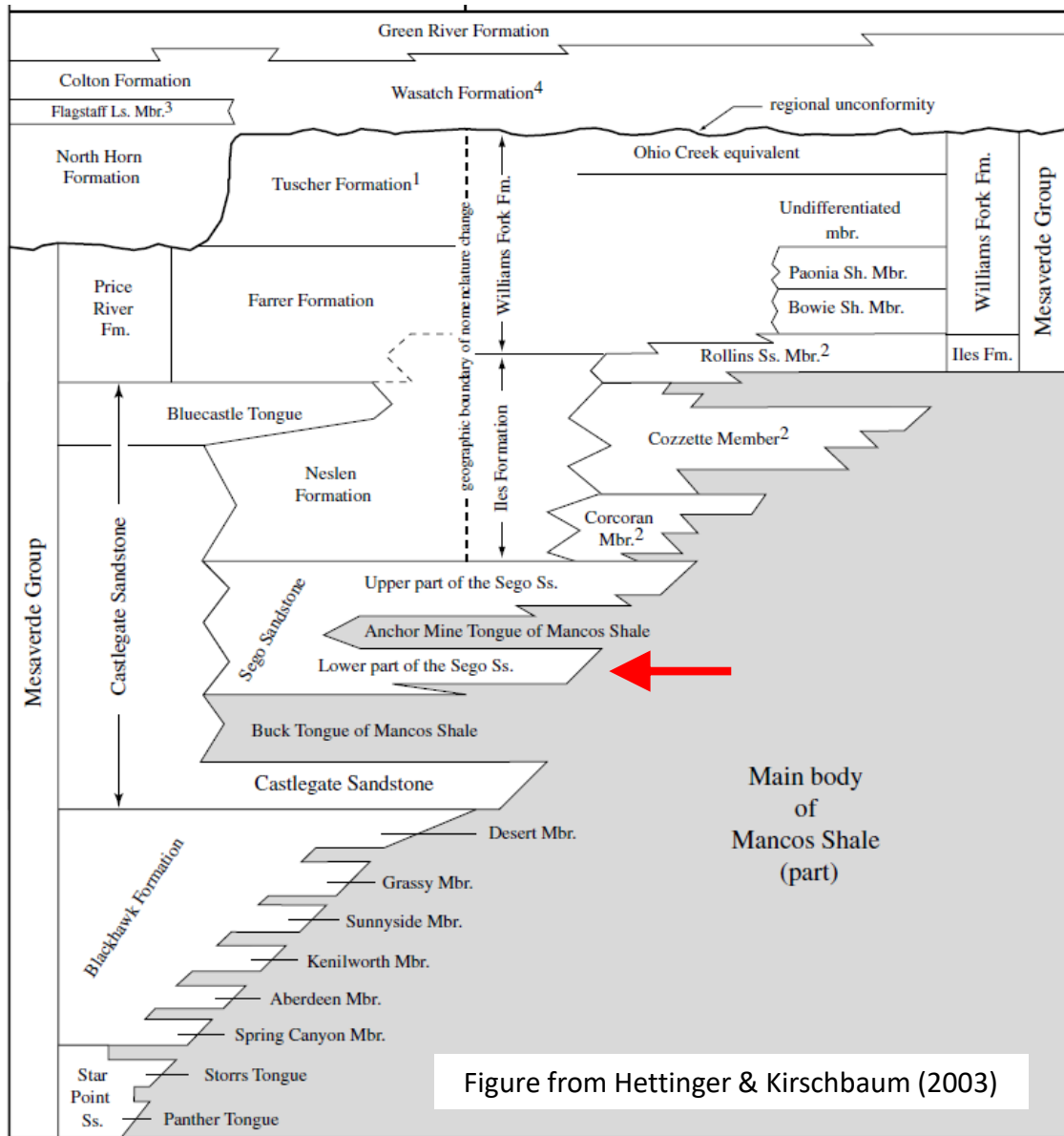


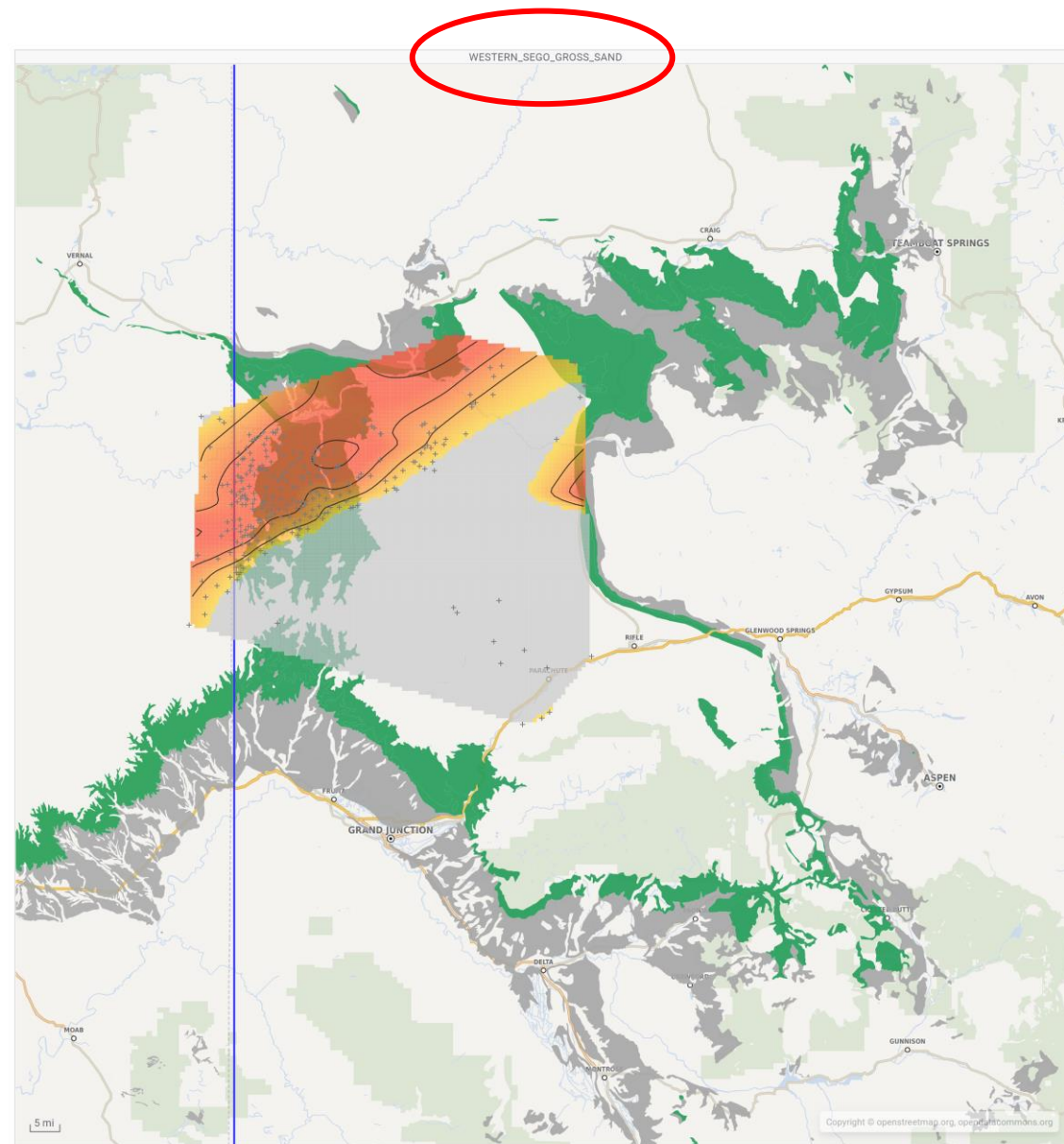
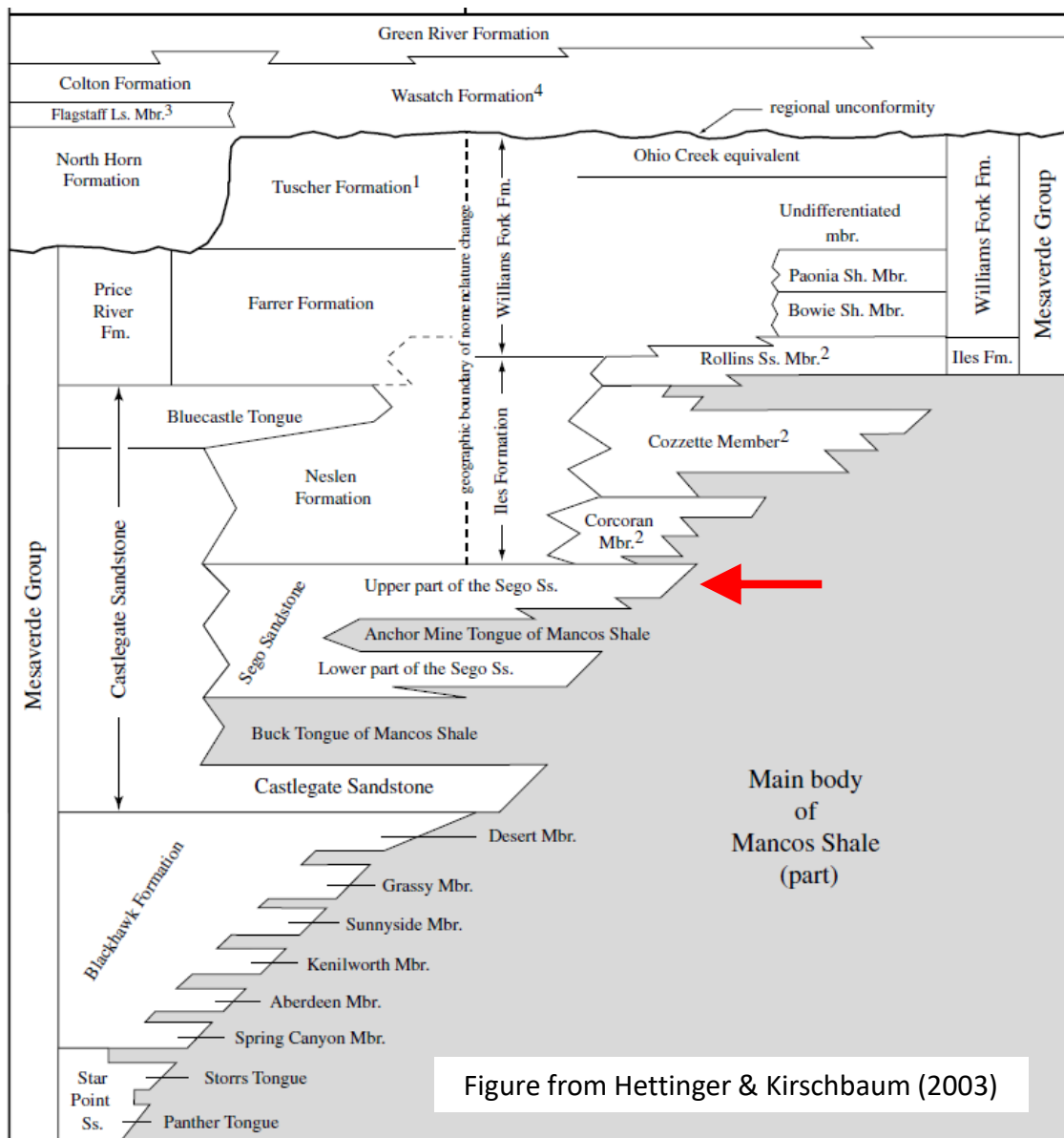


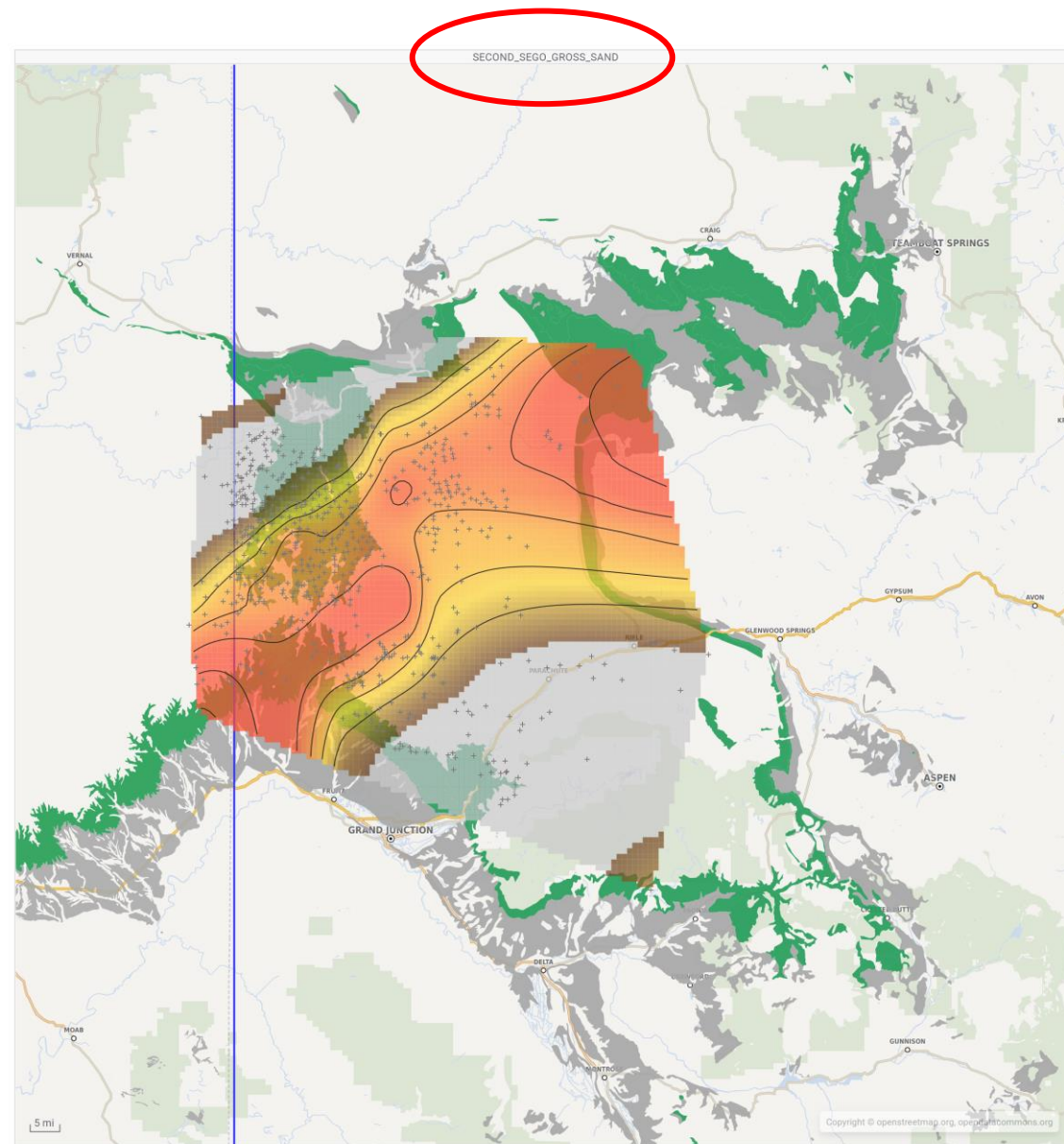
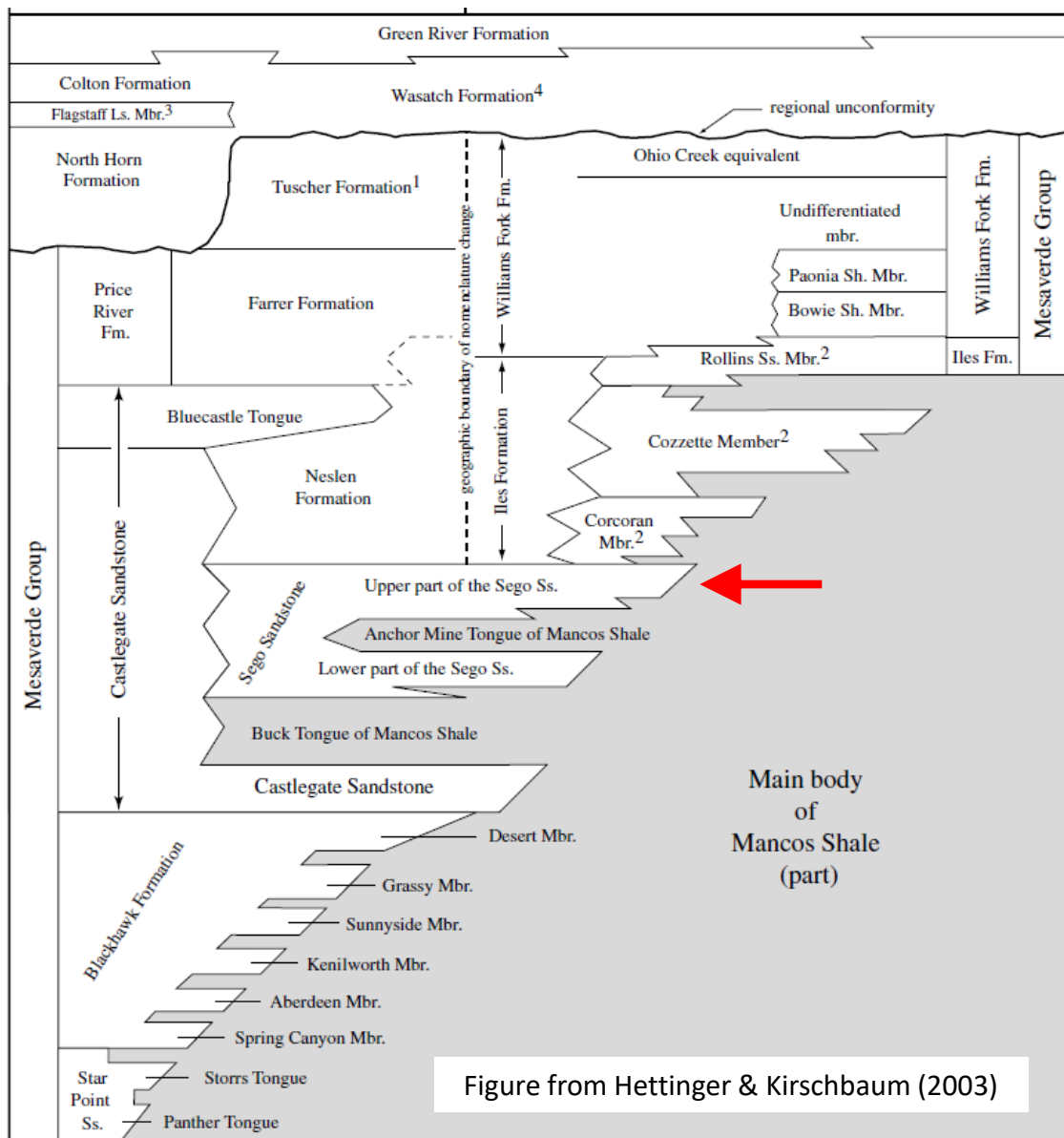


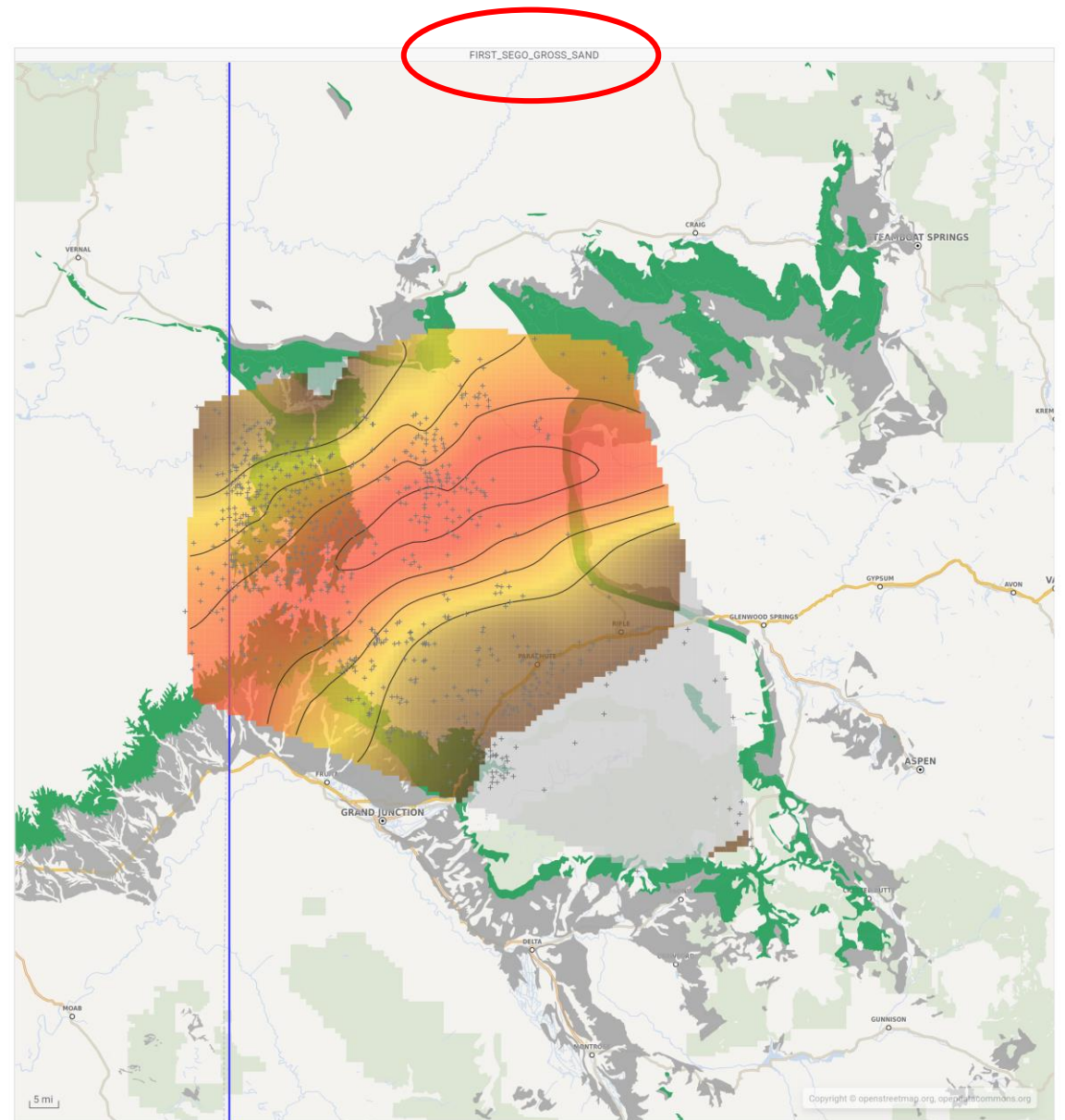
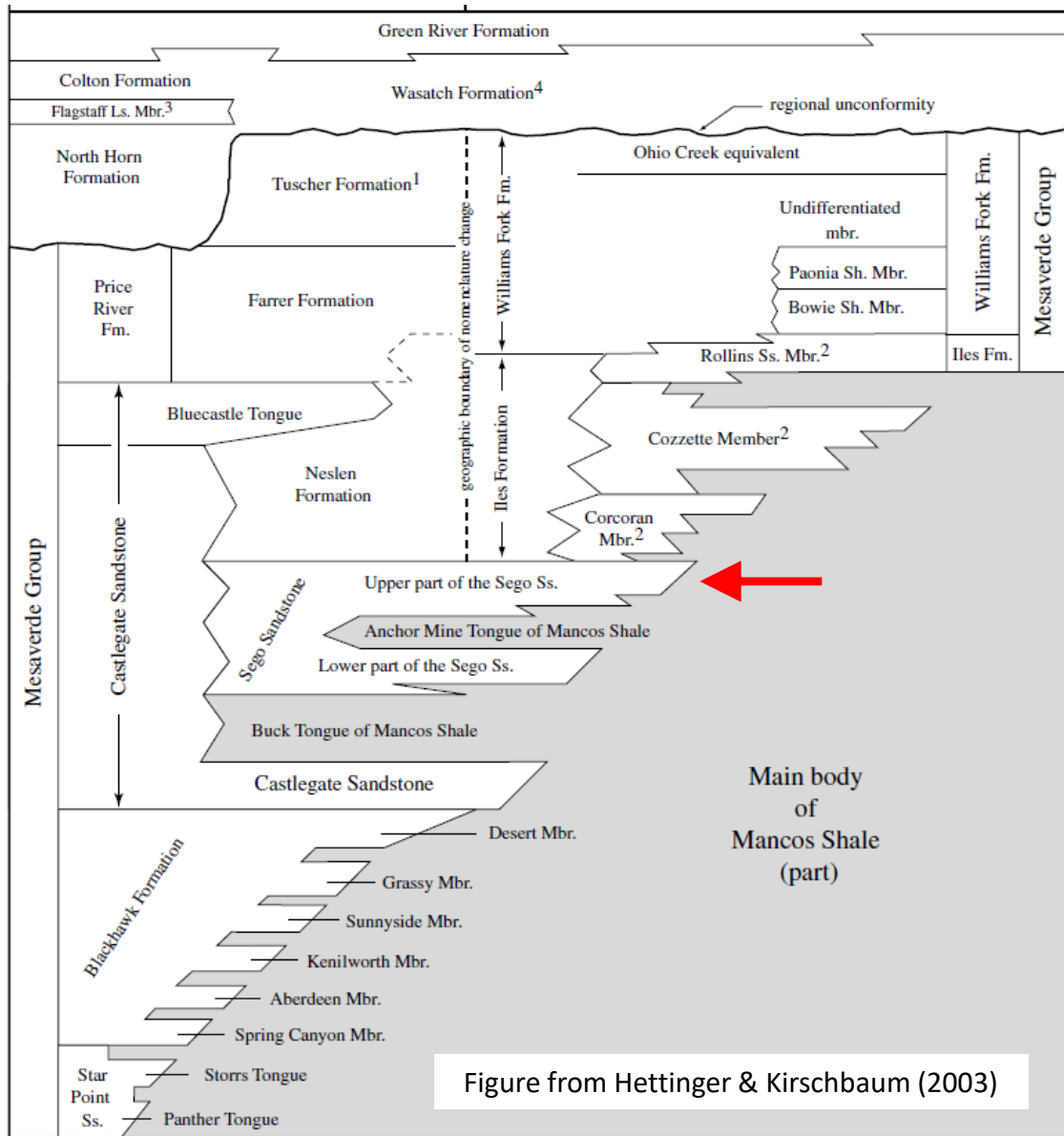


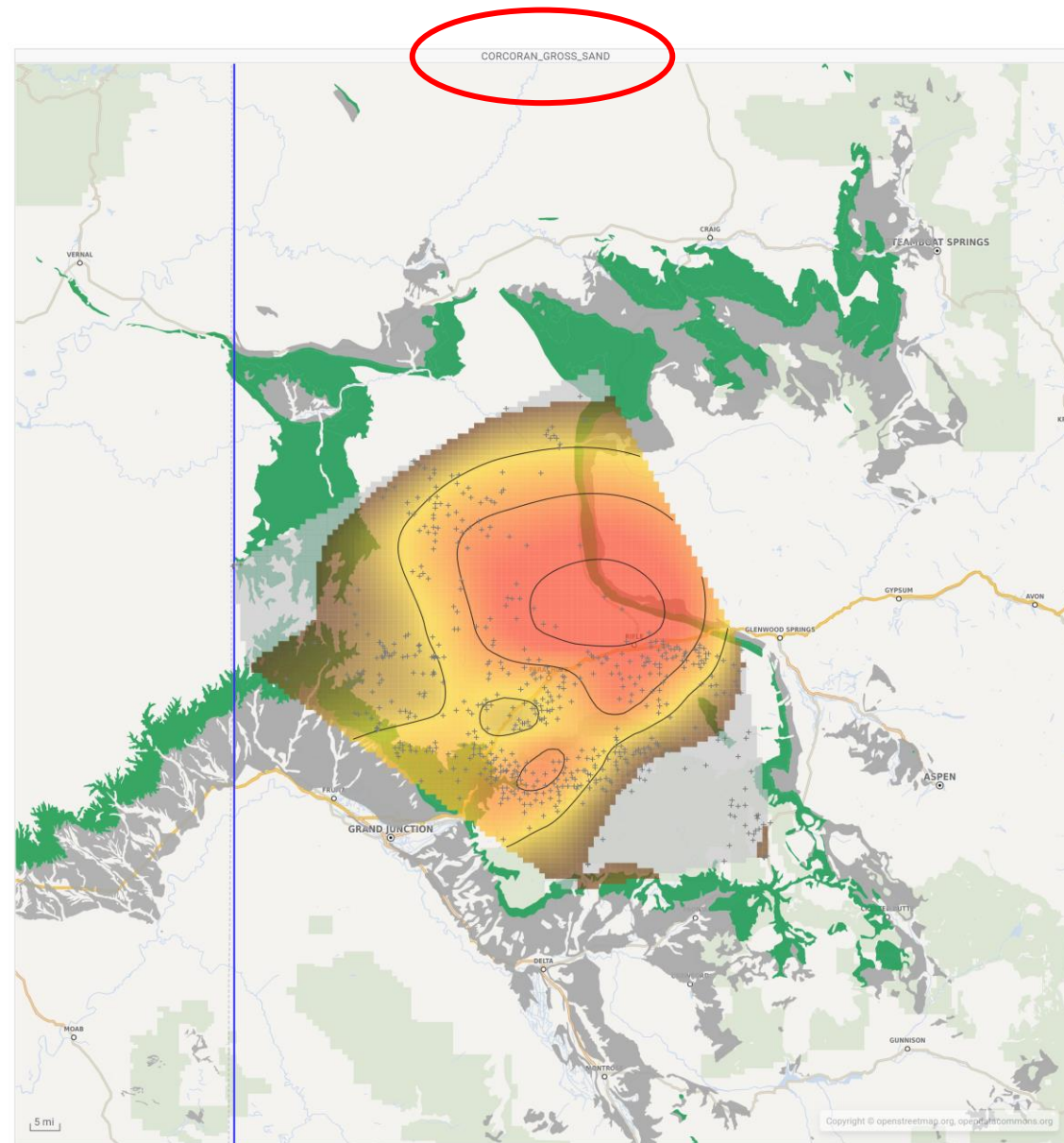
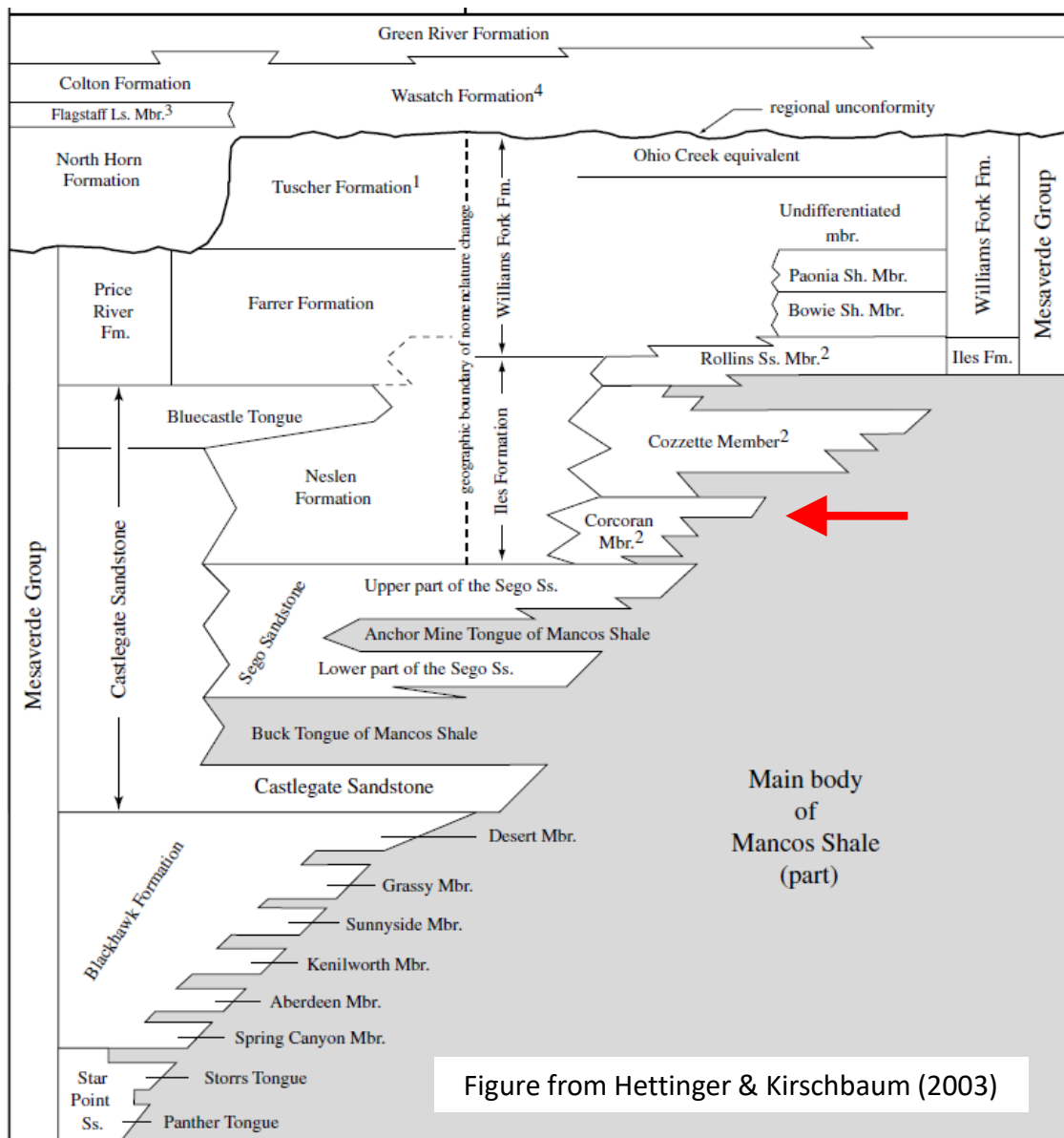












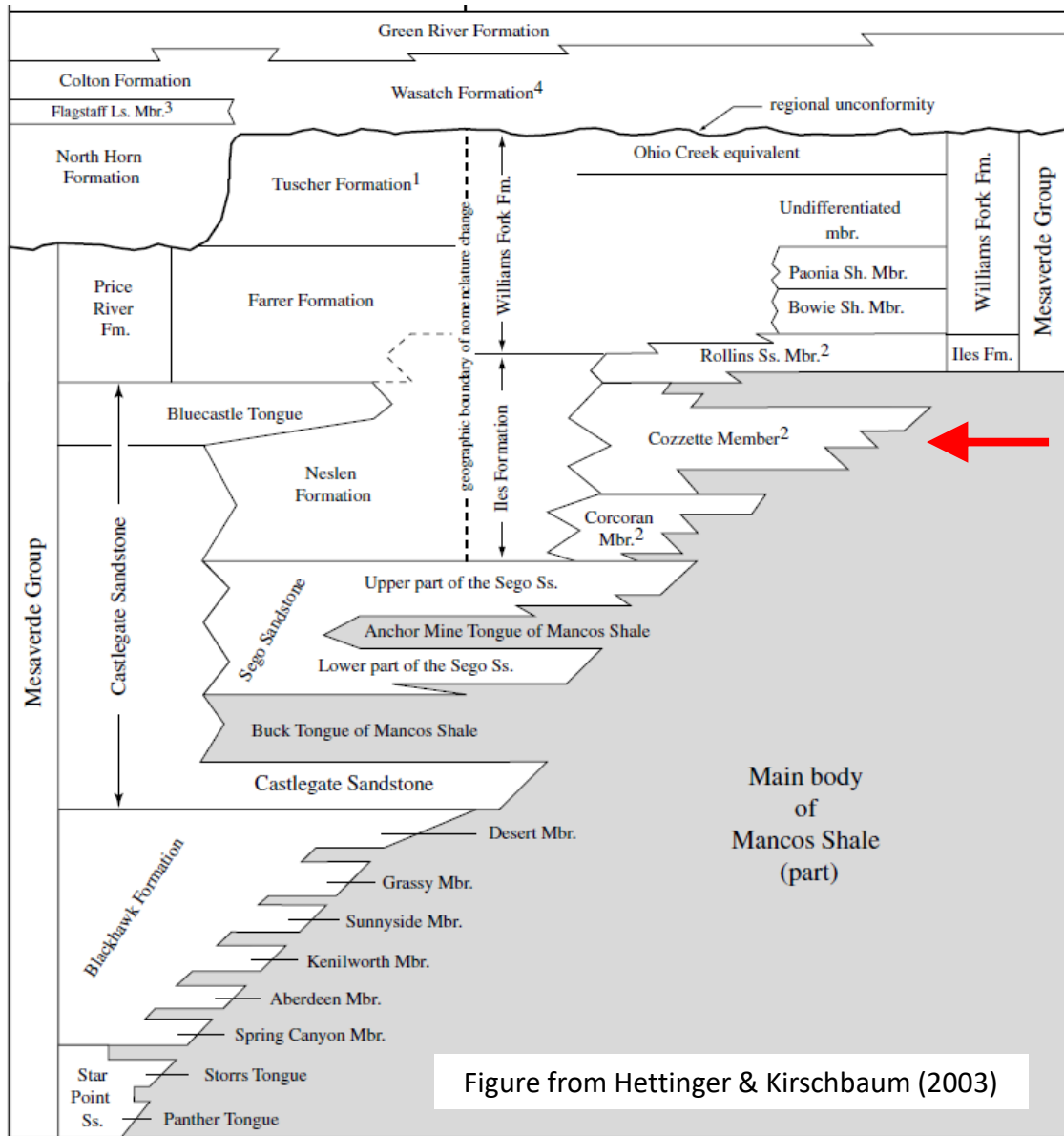
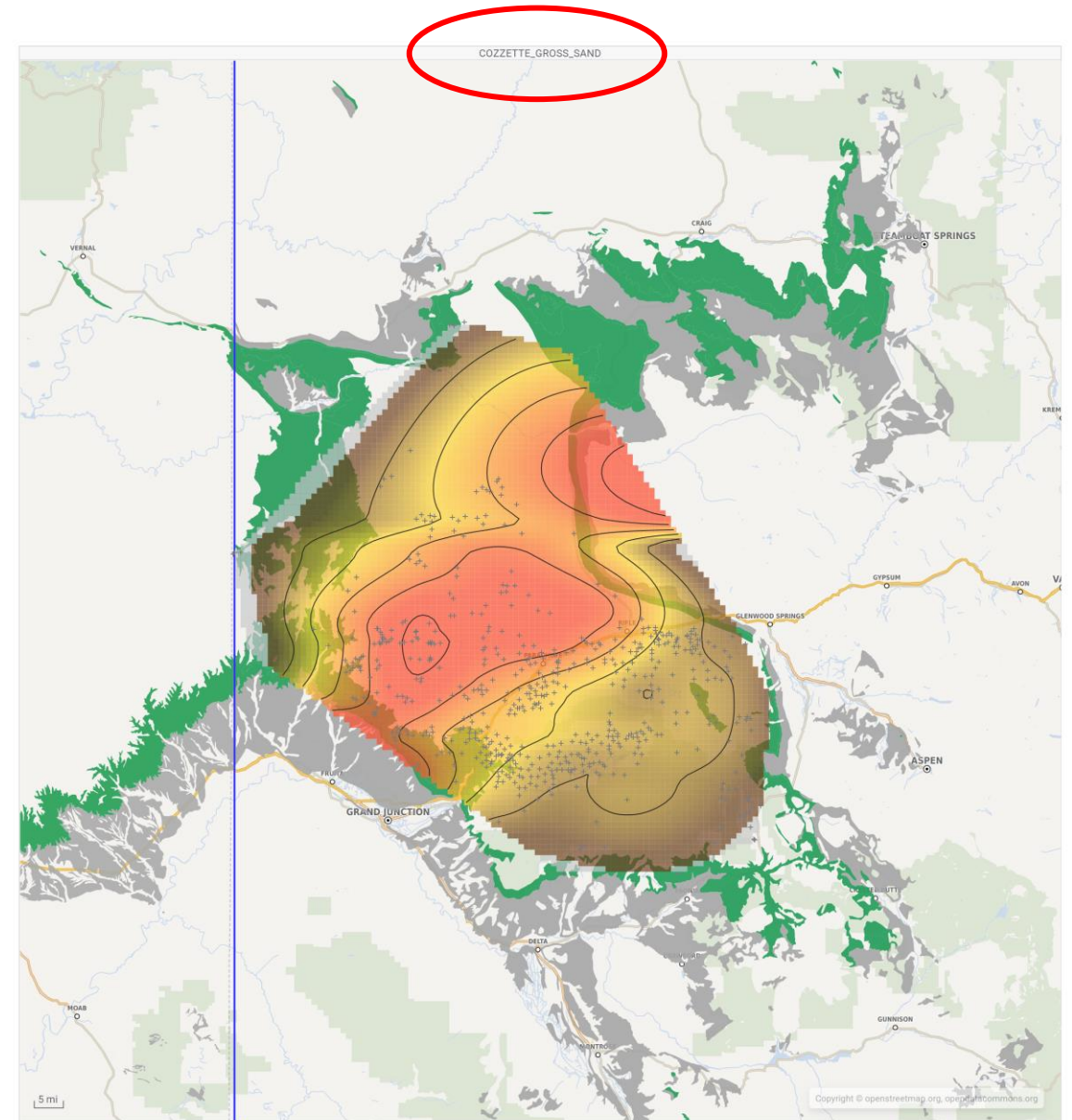


Figure from Hettinger & Kirschbaum (2003)



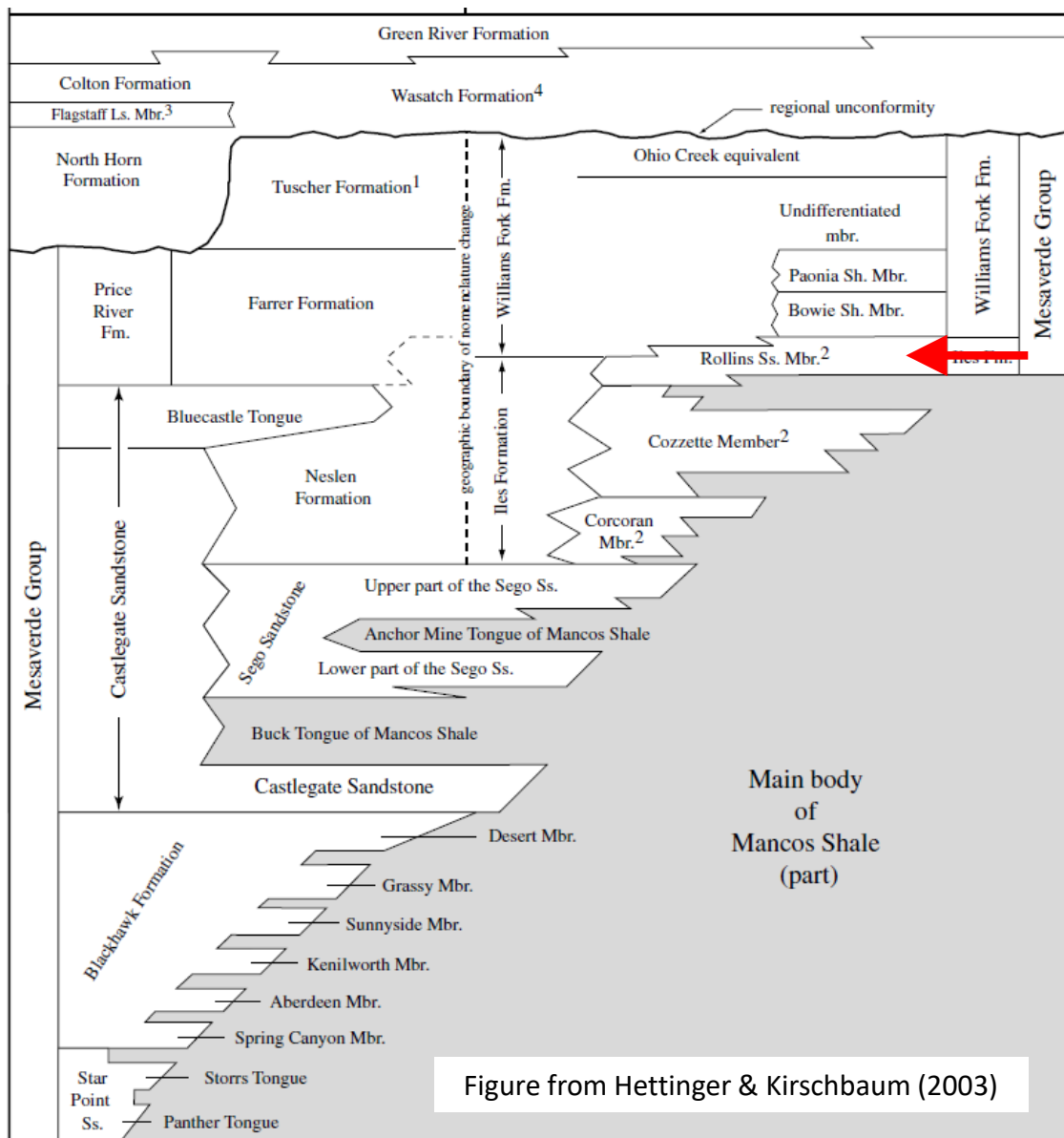
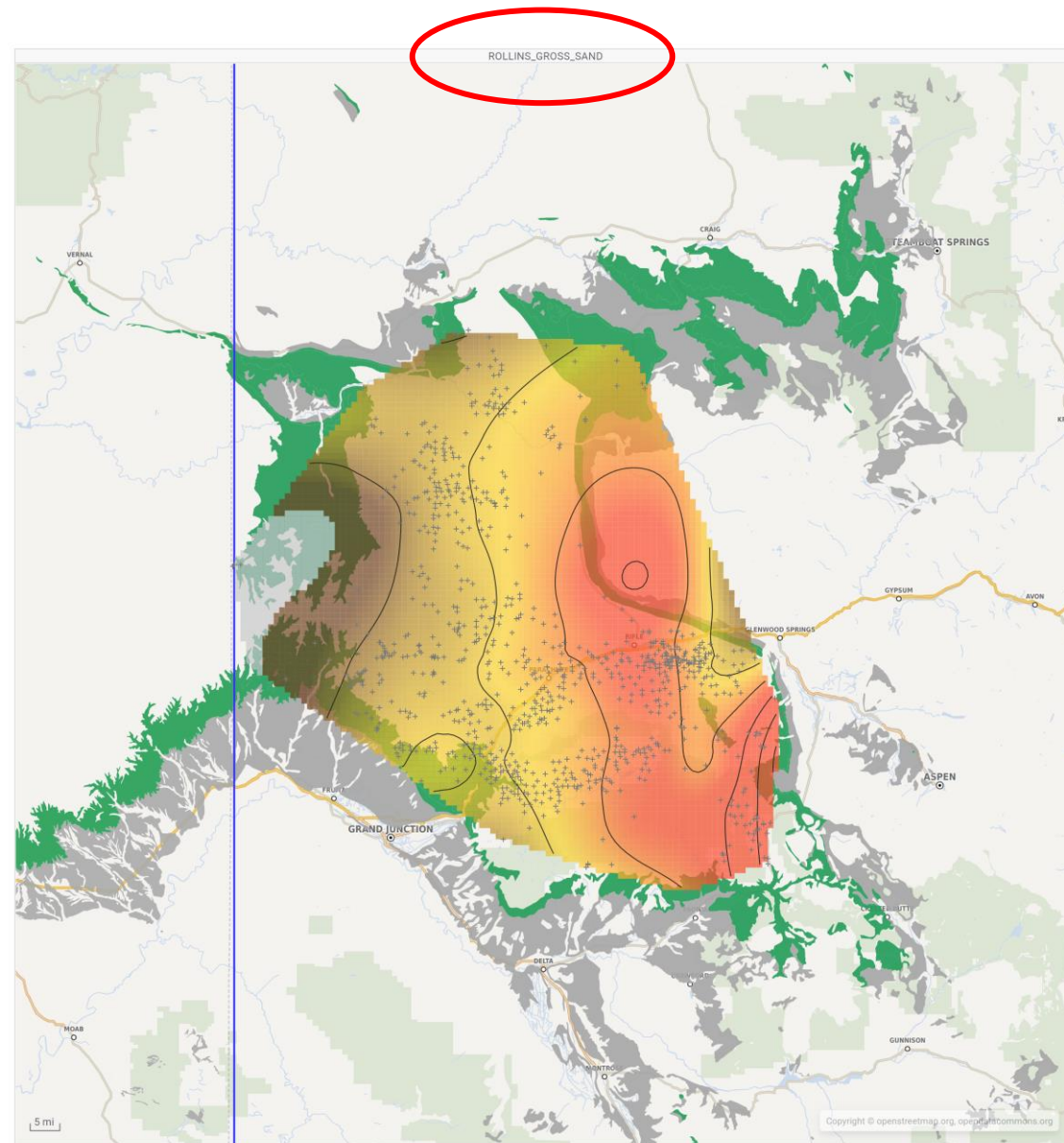


Figure from Hettinger & Kirschbaum (2003)



Conclusions

Conclusions

- Lots of work to be done
- Lots of “mature” basins ready to be organized
- Hopefully, we can add new value by reviewing old data

Acknowledgements

- Dr. Piret Plink-Bjorklund
 - Graduate advisor @ Colorado School of Mines
- Research Partnership to Secure Energy for America (RPSEA)
 - Primary funding source for reserach

SABATA

— ENERGY —

C O N S U L T A N T S

References (1/14)

- ANNA, L.O., 2012, West-East lithostratigraphic cross section of Cretaceous rocks from central Utah to western Kansas: U.S. Geological Survey, Open-File Report 2012-1074, 2 sheets.
- ASTIN, T.R., 1986, Septarian crack formation in carbonate concretions from shales and mudstones: Clay Minerals, v. 21, no. 4, p. 617–631.
- BARNUM, B.E., AND GARRIGUES, R.S., 1980, Geologic map and coal sections of the Cactus Reservoir quadrangle, Rio Blanco and Moffat counties, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map, no. 1179, scale 1:24,000.
- BARNUM, B.E., AND HAIL, W.J., Jr., 1996, Geologic map of Gillam Draw quadrangle, Rio Blanco County, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map, no. 2314, scale 1:24,000.
- BARNUM, B.E., SCOTT, R.W., AND PANTEA, M.P., 1997, Geologic map of the Texas Mountain quadrangle, Rio Blanco County, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map, no. 2321, scale 1:24,000.
- BRYANT, B., 1969, Geologic map of the Maroon Bells quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-788, scale 1:24,000, 1 sheet.
- BRYANT, B., 1972, Geologic map of the Highland Peak quadrangle, Pitkin County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-932, scale 1:24,000, 1 sheet.
- BRYANT, B., SHROBA, R.R., HARDING, A.E., AND MURRAY, K.E., 2002, Geologic map of the Storm King Mountain quadrangle, Garfield County, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2389, scale 1:24,000, 1 sheet, 24 p. text.
- CARRARA, P.E., 1997, Preliminary map of the Palisade quadrangle, Mesa County, Colorado: U.S. Geological Survey, Open-File Report OF-97-462, scale 1:24,000, 2 sheets, 18 p. text.

References (2/14)

- CARRARA, P.E., 2000, Geologic map of the Palisade quadrangle, Mesa County, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2326, scale 1:24,000, 1 sheet, 14 p. text.
- CARRARA, P.E., 2001, Geologic map of the Clifton quadrangle, Mesa County, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2359, scale 1:24,000, 1 sheet.
- CASHION, W.B., 1973, Geologic and structure map of the Grand Junction quadrangle, Colorado and Utah: U.S. Geological Survey, Geologic Quadrangle Map, no. 812, scale 1:250,000.
- COBBOLD, P.R., AND RODRIGUES, N., 2007, Seepage forces, important factors in the formation of horizontal hydraulic fractures and bedding-parallel fibrous veins ('beef' and 'cone-in-cone'): *Geofluids*, v. 7, no. 3, p. 313–322.
- COBBAN, W.A., MEREWETHER, E.A., FOUCH, T.D., AND OBRADOVICH, J.D., 1994, Some Cretaceous shorelines in the Western Interior of the United States in Caputo, M.V., Peterson, J.A., and Franczyk, K., eds., *Mesozoic Systems of the Rocky Mountain Region, USA: The Rocky Mountain Section of SEPM (Society for Sedimentary Geology)*, Denver, Colorado, p. 393–414.
- COBBAN, W.A., WALASZCZYK, I., OBRADOVICH, J.D., AND MCKINNEY, K.C., 2006, A USGS zonal table for the Upper Cretaceous Middle Cenomanian–Maastrichtian of the Western Interior of the United States based on ammonites, inoceramids, and radiometric ages: U.S. Geological Survey, Open-File Report 2006-1250, 45 p., 1 sheet.
- COBBAN, W.A., HOOK, S.C., AND MCKINNEY, K.C., 2008, Upper Cretaceous molluscan record along a transect from Virden, New Mexico to Del Rio, Texas: *New Mexico Geology*, v. 30, no. 3, p. 75–92.
- COLE, R.D., YOUNG, R.G., AND WILLIS, G.C., 1997, The Prairie Canyon Member, a new unit of the Upper Cretaceous Mancos Shale, west-central Colorado and east-central Utah: *Utah Geological Survey Miscellaneous Publication 97-4*, 23 p.
- COOGAN, J.C., STORK, A., AND FILLMORE, R.P., 2005, Geologic map of the Almont quadrangle, Gunnison County, Colorado: Colorado Geological Survey, Open-File Report OF-05-05, scale 1:24,000, 2 sheets, 27 p. text.

References (3/14)

- CULLINS, H.L., 1968, Geologic map of the Banty Point quadrangle, Rio Blanco County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map, no. 703, scale 1:24.000.
- CULLINS, H.L., 1969, Geologic map of the Mellen Hill quadrangle, Rio Blanco and Moffat counties, Colorado: U.S. Geological Survey, Geologic Quadrangle Map, no. 835, scale 1:24.000.
- CULLINS, H.L., 1971, Geologic map of the Rangely quadrangle, Rio Blanco County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map, no. 903, scale 1:24.000.
- DUBIEL, R.F., 2003, Geology, depositional models, and oil and gas assessment of the Green River total petroleum system, Uinta-Piceance province, eastern Utah and western Colorado: U.S. Geological Survey, Digital Data Series DDS-69-B, 41 p., 1 sheet.
- DYNI, J.R., 1968, Geologic map of the Elk Springs quadrangle, Moffat County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map, no. 702, scale 1:62.500.
- DYNI, J.R., AND CULLINS, H.L., 1965, Meeker and Loyd Sandstone Members of the Mancos Shale, Moffat and Rio Blanco counties, Colorado: U.S. Geological Survey, Bulletin 1194-J, 7 p.
- ELLIS, M.S., AND FREEMAN, V.L., 1984, Geologic map and cross-sections of the Carbondale 30' x 60' quadrangle, west-central Colorado: U.S. Geological Survey, Coal Investigations Map C-97-A, scale 1:100,000, 1 sheet.
- ELLIS, M.S., AND GABALDO, V., 1989, Geologic map and cross sections of parts of the Grand Junction and Delta 30' x 60' quadrangles, west-central Colorado: U.S. Geological Survey, Coal Investigations Map C-124, scale 1:100,000, 1 sheet.
- FINLEY, R.J., AMBROSE, W.A., BERLINGER, M.J., GUTIERREZ, G.N.T., AND VER PLOEG, A.J., 1983, Geologic analysis of primary and secondary tight gas sand objectives: Gas Research Institute Report GRI-84/0026, 334 p.
- FISHER, D.J., ERDMAN, C.E., AND REESIDE, J.B., JR., 1960, Cretaceous and Tertiary formation of the Book Cliffs, Carbon, Emery, and Grand counties, Utah, and Garfield and Mesa counties, Colorado: U.S. Geological Survey, Professional Paper 332, 80 p., 12 sheets.

References (4/14)

- FORRESTER, J.B., 1918, A short comment on Bulletin 371 of the U.S. Geological Survey: Utah Academy of Sciences Transactions, v. 1, p. 24-31.
- FRANCYK, K.J., 1989, Depositional controls on the Late Campanian Sego Sandstone and implications for associated coal-forming environments in the Uinta and Piceance basins: U.S. Geological Survey, Bulletin 1787-F, 17 p., 2 sheets.
- FREEMAN, V.L., 1972a, Geologic map of the Ruedi quadrangle, Pitkin and Eagle counties, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-1004, scale 1:24,000, 1 sheet.
- FREEMAN, V.L., 1972b, Geologic map of the Woody Creek quadrangle, Pitkin and Eagle counties, Colorado: U.S. Geological Survey, Geologic Quadrangle Map, no. 967, scale 1:24,000.
- GARRIGUES, R.S., AND BARNUM, B.E., 1980, Geologic map and coal sections of the Rangely NE quadrangle, Rio Blanco and Moffat counties, Colorado: U.S. Geological Survey, Open-File Report, no. 80-274, scale 1:24,000.
- GASKILL, D.L., AND GODWIN, L.H., 1966a, Geologic map of the Marble quadrangle, Gunnison and Pitkin counties, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-512, scale 1:24,000, 1 sheet.
- GASKILL, D.L., AND GODWIN, L.H., 1966b, Geologic map of the Marcellina Mountain quadrangle, Gunnison County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-511, scale 1:24,000, 1 sheet.
- GASKILL, D.L., GODWIN, L.H., AND MUTSCHLER, F.E., 1967, Geologic map of the Oh-Be-Joyful quadrangle, Gunnison County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-578, scale 1:24,000, 1 sheet.
- GASKILL, D.L., COLMAN, S.M., DELONG, J.E., AND ROBINSON, C.H., 1986, Geologic map of the Crested Butte quadrangle, Gunnison County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map, GQ-1580, scale 1:24,000, 1 sheet.

References (5/14)

- GASKILL, D.L., DELONG, J.E., AND COCHRAN, D.M., 1987, Geologic map of the Mt. Axtell quadrangle, Gunnison County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-1604, scale 1:24,000, 1 sheet, 7 p. text.
- GASKILL, D.L., MUTSCHLER, F.E., KRAMER, J.H., THOMAS, J.A., AND ZACHARY, S.G., 1991, Geologic map of the Gothic quadrangle, Gunnison County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-1689, scale 1:24,000, 1 sheet.
- GILL, J.R., AND COBBAN, W.A., 1966, The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming: U.S. Geological Survey, Professional Paper 393-A, 69 p.
- GILL, J.R., AND COBBAN, W.A., 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: U.S. Geological Survey, Professional Paper 776, 37 p.
- GILL, J.R., AND HAIL, W.J., JR., 1975, Stratigraphic sections across Upper Cretaceous Mancos Shale–Mesaverde Group boundary, eastern Utah and western Colorado: U.S. Geological Survey, Oil and Gas Investigations Chart OC-68, 1 sheet.
- GILL, J.R., MEREWETHER, E.A., AND COBBAN, W.A., 1970, Stratigraphy and nomenclature of some Upper Cretaceous and Lower Tertiary rocks in south-central Wyoming: U.S. Geological Survey, Professional Paper, no. 667, 53 p.
- GODWIN, L.H., 1968, Geologic map of the Chair Mountain quadrangle, Gunnison and Pitkin counties, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-704, scale 1:24,000, 1 sheet.
- GUALTIERI, J.L., 1988, Geologic map of the Westwater 30' x 60' quadrangle, Gunnison and Pitkin counties, Colorado: U.S. Geological Survey, Miscellaneous Investigations Series Map, no. 1765, scale 1:100,000.
- HALE, L.A., 1959, Intertonguing Upper Cretaceous sediments of northeastern Utah-northwestern Colorado in Haun, J.D., and Weimer, R.J., eds., Symposium on Cretaceous rocks of Colorado and Adjacent Areas---Eleventh Field Conference, Washakie, Sand Wash, and Piceance Basins: Denver, Colorado, Rocky Mountain Association of Geologists, p. 55--66, 4 sheets.

References (6/14)

- HAIL, W.J., JR., 1974, Geologic map of the Rough Gulch quadrangle, Rio Blanco and Moffat counties, Colorado: U.S. Geological Survey, Geologic Quadrangle Map, no. 1195, scale 1:24,000.
- HAIL, W.J., JR., AND BARNUM, B.E., 1993, Geologic map of the Divide Creek quadrangle, Rio Blanco and Moffat counties, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map, no. 2232, scale 1:24,000.
- HAMPSON, G.J., PROCTER, E.J., AND KELLY, C., 2008, Controls on isolated shallow-marine sandstone deposition and shelf construction: Late Cretaceous Western Interior Seaway, northern Utah and Colorado, in Hampson, G.J., Steel, R.J., Burgess, P.M., and Dalrymple, R.W., eds., Recent Advances in Models of Siliciclastic Shallow-Marine Stratigraphy: Tulsa, Oklahoma, SEPM Special Publication 90, p. 355--389.
- HAMPSON, G.J., 2010, Sediment dispersal and quantitative stratigraphic architecture across an ancient shelf: *Sedimentology*, v. 57, no. 1, p. 96–141, doi: 10.1111/j.1365-3091.2009.01093.x.
- HANCOCK, E.T., 1925, Geology and coal resources of the Axial and Monument Butte quadrangles, Moffat County, Colorado: U.S. Geological Survey, Bulletin 757, 134 p., 2 sheets.
- HARDIE, J.K., AND ZOOK, J.M., 1997, Geologic map and coal measures of the Axial quadrangle, Moffat and Rio Blanco counties, Colorado: Colorado Geological Survey, Open-File Report, no. 97-05, scale 1:24,000.
- HARDIE, J.K., AND ZOOK, J.M., 2014, Geologic map of the Axial quadrangle, Moffat and Rio Blanco counties, Colorado: Colorado Geological Survey, Open-File Report, no. 14-08, scale 1:24,000.
- HETTINGER, R.K., AND KIRSCHBAUM, M.A., 2002, Stratigraphy of the Upper Cretaceous Mancos Shale (upper part) and Mesaverde Group in the southern part of the Uinta and Piceance basins, Utah and Colorado: U.S. Geological Survey, Geologic Investigations Series, no. 2764, 21 p., 2 sheets.
- HETTINGER, R.K., AND KIRSCHBAUM, M.A., 2003, Stratigraphy of the Upper Cretaceous Mancos Shale (upper part) and Mesaverde Group in the southern part of the Uinta and Piceance basins, Utah and Colorado: U.S. Geological Survey, Digital Data Series, no. 69-B, 21 p., 2 sheets.

References (7/14)

- HODGE, J., WHITE, J.L., AND NELSON, M., 2016, Geologic map of the Roubideau quadrangle, Delta and Montrose counties, Colorado: Colorado Geological Survey, Open-File Report OF-16-06, scale 1:24,000, 2 sheets.
- IZETT, G.A., COBBAN, W.A., AND GILL, J.R., 1971, The Pierre Shale near Kremmling, Colorado, and its correlation to the east and west: U.S. Geological Survey, Professional Paper 684-A, 19 p., 1 sheet.
- IZETT, G.A., HONEY, J.G., AND BROWNFIELD, M.E., 1985, Geologic map of the Citadel Plateau quadrangle, Moffat County, Colorado: U.S. Geological Survey, Miscellaneous Investigations Series Map, no. 1532, scale 1:48,000.
- JOHNSON, R.C., 1986, Structure contour map of the top of the Castlegate Sandstone, eastern part of the Uinta Basin and the western part of the Piceance Creek basin, Utah and Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-1826, scale 1:253,440, 1 sheet.
- JOHNSON, R.C., 1987, Geologic history and hydrocarbon potential of Late Cretaceous-age, low-permeability reservoirs, Piceance basin, western Colorado: U.S. Department of Energy Report DOE/MC/20422-2337, 97 p.
- JOHNSON, R.C., 1989, Geologic history and hydrocarbon potential of Late Cretaceous-age, low-permeability reservoirs, Piceance basin, western Colorado: U.S. Geological Survey, Bulletin 1787-E, 51 p., 2 sheets.
- JOHNSON, R.C., 2003a, Depositional framework of the Upper Cretaceous Mancos Shale and the lower part of the Upper Cretaceous Mesaverde Group, western Colorado and eastern Utah: U.S. Geological Survey, Digital Data Series, DDS-69-B, 24 p., 1 sheet.
- JOHNSON, R.C., 2003b, Northwest to southeast cross section of Cretaceous and Lower Tertiary rocks across the eastern part of the Uinta basin, Utah: U.S. Geological Survey, Digital Data Series, DDS-69-B, 6 p., 1 sheet.
- KAUFFMAN, E.G., 1977, Geological and biological overview: Western Interior Cretaceous basin: The Mountain Geologist, v. 14, no. 3-4, p. 75-99.

References (8/14)

- KAUFFMAN, E.G., SAGEMAN, B.B., KIRKLAND, J.I., ELDER, W.P., HARRIES, P.J., AND VILLAMIL, T., 1993, Molluscan biostratigraphy of the Cretaceous Western Interior Basin, North America, in Caldwell, W.G.E., and Kauffman, E.G., eds., *Evolution of the Western Interior Basin: St. John's, Newfoundland, Canada*, Geological Association of Canada, p. 397–434.
- KAUFFMAN, E.G., ARTHUR, M.A., HOWE, B., AND SCHOLLE, P.A., 1996, Widespread venting of methane-rich fluids in Late Cretaceous (Campanian) submarine springs (Tepee Buttes), Western Interior seaway, U.S.A.: *Geology*, v. 24, no. 9, p. 799–802.
- KIRKHAM, R.M., STREUFERT, R.K., HEMBORG, H.T., AND STELLING, P.L., 1996, Geologic map of the Cattle Creek quadrangle, Garfield County, Colorado: Colorado Geological Survey, Open-File Report OF-96-01, scale 1:24,000, 1 sheet.
- KIRKHAM, R.M., WIDMANN, B.L., AND STREUFERT, R.K., 1998, Geologic map of the Leon quadrangle, Eagle and Garfield counties, Colorado: Colorado Geological Survey, Open-File Report OF-98-03, scale 1:24,000, 1 sheet, 20 p. text.
- KIRKHAM, R.M., WIDMANN, B.L., AND STREUFERT, R.K., 2008, Geologic map of the Leon quadrangle, Eagle and Garfield counties, Colorado: Colorado Geological Survey, Map Series MS-40, scale 1:24,000, 1 sheet, 26 p. text.
- KIRKHAM, R.M., STREUFERT, R.K., CAPPA, J.A., SHAW, C.A., ALLEN, J.L., AND SCHROEDER, T.J., II, 2009, Geologic map of the Glenwood Springs quadrangle, Garfield County, Colorado: Colorado Geological Survey, Map Series MS-38, 32 p., scale 1:24,000, 1 sheet.
- KIRKHAM, R.M., STREUFERT, R.K., HEMBORG, T., AND STELLING, P.L., 2014, Geologic map of the Cattle Creek quadrangle, Garfield County, Colorado: Colorado Geological Survey, Open-File Report OF-14-14, scale 1:24,000, 2 sheets.
- LARSON, N.L., JORGENSEN, S.D., FARRAR, R.A., AND LARSON, P.L., 1997, *Ammonites and the other cephalopods of the Pierre Seaway: An identification guide*: Tucson, Arizona, Geoscience Press, Inc., 148 p.
- LIVACCARI, R., AND HODGE, J., 2009, Geologic map of the Fruita quadrangle, Mesa County, Colorado: Colorado Geological Survey, Open-File Report OF-09-04, 68 p., scale 1:24,000, 2 sheets.

References (9/14)

- MCLAURIN, B.T., AND STEEL, R.J., 2000, Fourth-order nonmarine to marine sequences, middle Castlegate Formation, Book Cliffs, Utah: *Geology*, v. 28, no. 4, p. 359–362, doi: 10.1130/0091-7613(2000)28%3C359:FNTMSM%3E2.0.CO;2.
- MCKAY, E.J., 1974, Geologic map of the Lone Mountain quadrangle, Moffat County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-1144, scale 1:62,500, 1 sheet.
- MIAL, A.D., AND ARUSH, M., 2001, The Castlegate Sandstone of the Book Cliffs, Utah: Sequence stratigraphy, paleogeography, and tectonic controls: *Journal of Sedimentary Research*, v. 71, no. 4, p. 537–548, doi: 10.1306/103000710537.
- MOLENAAR, C.M., AND WILSON, B.W., 1993, Stratigraphic cross section of Cretaceous rocks along the north flank of the Uinta basin, northeastern Utah, to Rangely, northwestern Colorado: U.S. Geological Survey, Miscellaneous Investigations Series Map I-1797-D, 1 sheet.
- MORGAN, M.L., NOE, D.C., WHITE, J.L., AND TOWNLEY, S.M., 2008, Geologic map of the Delta quadrangle, Delta and Montrose counties, Colorado: Colorado Geological Survey, Open-File Report OF-08-02, scale 1:24,000, 2 sheets, 59 p. text.
- MUNGER, R.D., 1965, Subsurface exploration mapping, southern Uinta basin, Castlegate and Dakota-Cedar Mountain formations: *The Mountain Geologist*, v. 2, no. 3, p. 141{166.
- MUTSCHLER, F.E., 1970, Geologic map of the Snowmass Mountain quadrangle, Pitkin and Gunnison counties, Colorado: Colorado Geological Survey, Geologic Quadrangle Map GQ-853, scale 1:24,000, 1 sheet.
- NAISBITT, J., 1982, *Megatrends*: New York, Warner Books, 333 p.
- NOE, D.C., 2015, Geologic map of the Paonia quadrangle, Delta County, Colorado: Colorado Geological Survey, Open-File Report, no. 15-07, scale 1:24,000.
- NOE, D.C., AND KLINK, A.T., 2015, Geologic map of the Crawford quadrangle, Delta and Montrose counties, Colorado: Colorado Geological Survey, Open-File Report, no. 15-06, scale 1:24,000.

References (10/14)

- NOE, D.C., AND RODGERS, E.L., 2014, Geologic map of the Hotchkiss quadrangle, Delta County, Colorado: Colorado Geological Survey, Open-File Report, no. 14-15, scale 1:24,000.
- NOE, D.C., AND ZAWASKI, M.J., 2013, Orchard City quadrangle geologic map, Delta County, Colorado: Colorado Geological Survey, Open-File Report, no. 13-05, scale 1:24,000.
- NOE, D.C., MORGAN, M.L., AND TOWNLEY, S.M., 2014, Geologic map of the Olathe NW quadrangle, Delta and Montrose counties, Colorado: Colorado Geological Survey, Open-File Report OF-13-07, scale 1:24,000, 2 sheets, 43 p. text.
- NOE, D.C., LOGAN, Z.D., MCCALL, K.J., AND WARDEN, G.W., 2015a, Geologic map of the Lazear quadrangle, Delta County, Colorado: Colorado Geological Survey, Open-File Report OF-15-08, scale 1:24,000, 2 sheets, 11 p. text.
- NOE, D.C., WHITE, J.L., AND NELSON, M., 2015b, Geologic map of the North Delta quadrangle, Delta County, Colorado: Colorado Geological Survey, Open-File Report, no. 15-09, scale 1:24,000.
- O'SULLIVAN, R.B., 1985, Preliminary geologic map of the Rio Blanco quadrangle, Rio Blanco and Garfield counties, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-1816, scale 1:24,000, 1 sheet.
- PATTERSON, P.E., KRONMUELLER, K., AND DAVIES, T.D., 2003, Sequence stratigraphy of the Mesaverde Group and Ohio Creek Conglomerate, northern Piceance basin, Colorado, in Peterson, K.M., Olson, T.M., and Anderson, D.S., eds., Piceance Basin 2003 Guidebook: Rocky Mountain Association of Geologists, Denver, Colorado, p. 115–128.
- PERRY, W.J., SHROBA, R.R., SCOTT, R.B., AND MALDONADO, F., 2003, Geologic map of the Horse Mountain quadrangle, Garfield County, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2415, scale 1:24,000, 1 sheet, 18 p. text.
- REHEIS, M.C., 1980a, Geologic map and coal sections of the Sawmill Mountain quadrangle, Rio Blanco County, Colorado: U.S. Geological Survey, Open-File Report, no. 80-252, scale 1:24,000.
- REHEIS, M.C., 1980b, Geologic map and coal sections of the Thornburgh quadrangle, Moffat and Rio Blanco counties, Colorado: U.S. Geological Survey, Open-File Report, no. 80-251, scale 1:24,000.

References (11/14)

- REHEIS, M.C., 1981, Geologic map and coal resources of the Easton Gulch quadrangle, Moffat County, Colorado: U.S. Geological Survey, Coal Investigations Map, no. 87, scale 1:24,000
- REHEIS, M.C., 1984a, Geologic map and coal sections of the Sawmill Mountain quadrangle, Rio Blanco County, Colorado: U.S. Geological Survey, Coal Investigations Map, no. 99, scale 1:24,000.
- REHEIS, M.C., 1984b, Geologic map and coal sections of the Thornburgh quadrangle, Moffat and Rio Blanco counties, Colorado: U.S. Geological Survey, Coal Investigations Map, no. 100, scale 1:24,000.
- ROBERTS, L.N.R., AND KIRSCHBAUM, M.A., 1995, Paleogeography and the Late Cretaceous of the Western Interior of middle North America—Coal distribution and sediment accumulation: U.S. Geological Survey, Professional Paper 1561, 115 p., 1 sheet.
- ROGERS, N.T., 2012, Subsurface stratigraphy of the Upper Cretaceous lower Mancos Formation and related units, Piceance basin, northwestern Colorado [M.Sc. thesis]: Boulder, Colorado, University of Colorado, 250 p.
- ROWLEY, P.D., AND HANSEN, W.R., 1979, Geologic map of the Plug Hat Rock quadrangle, Moffat County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-1514, scale 1:24,000, 1 sheet.
- ROWLEY, P.D., DYNI, J.R., HANSEN, W.R., AND PIPIRINGOS, G.N., 1979, Geologic map of the Indian Water Canyon quadrangle, Moffat County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-1516, scale 1:24,000, 1 sheet.
- ROWLEY, P.D., HANSEN, W.R., TWETO, O., AND CARRARA, P.E., 1985, Geologic map of the Vernal 1 degree x 2 degrees quadrangle, Colorado, Utah, and Wyoming: U.S. Geological Survey, Miscellaneous Investigations Series Map I-1526, scale 1:250,000, 1 sheet.
- TWETO, O., 1976, Geologic map of the Craig 1 degree x 2 degrees quadrangle, northwestern Colorado: U.S. Geological Survey, Miscellaneous Investigations Series Map I-972, scale 1:250,000, 1 sheet.

References (12/14)

- TWETO, O., STEVEN, T.A., HAIL, W.J., JR., AND MOENCH, R.H., 1976, Preliminary geologic map of the Montrose 1 degree x 2 degrees quadrangle, northwestern Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-761, scale 1:250,000, 1 sheet.
- TWETO, O., MOENCH, R.H., AND REED, J.C., 1978, Geologic map of the Leadville 1 degree x 2 degrees quadrangle, northwestern Colorado: U.S. Geological Survey, Miscellaneous Investigations Series Map I-999, scale 1:250,000, 1 sheet.
- SACERDOTI, R., 2008, A sedimentological and sequence stratigraphic analysis of the Upper Mancos sandstone body succession in northwestern Colorado [MS Thesis]: Colorado School of Mines, Golden, Colorado, 78 p.
- SCHWENDEMAN, K.M., 2011, Sequence stratigraphy of the Upper Cretaceous Castlegate condensed section through Iles Formation, Piceance basin, northwestern Colorado [M.Sc. thesis]: Boulder, Colorado, University of Colorado, 201 p.
- SCOTT, R.B., AND SHROBA, R.R., 1997, Revised preliminary geologic map of the New Castle quadrangle, Garfield County, Colorado: U.S. Geological Survey, Open-File Report OF-97-737, scale 1:24,000, 1 sheet, 28 p. text.
- SCOTT, R.B., SHROBA, R.R., AND EGGER, A., 2001, Geologic map of the Rifle Falls quadrangle, Garfield County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2341, scale 1:24,000, 1 sheet, 17 p. text.
- SCOTT, R.B., CARRARA, P.E., HOOD, W.C., AND MURRAY, K.E., 2002, Geologic map of the Grand Junction quadrangle, Mesa County, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2363, scale 1:24,000, 1 sheet.
- SHROBA, R.R., AND SCOTT, R.B., 2001, Geology map of the Silt quadrangle, Garfield County, Colorado: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2331, scale 1:24,000, 1 sheet, 31 p. text.
- SPRINKEL, D.A., 2007, Interim geologic map of the Vernal 30' x 60' quadrangle, Uintah and Duchesne counties, Utah, and Moffat and Rio Blanco counties, Colorado: Utah Geological Survey, Open-File Report, no. 506DM, scale 1:100,000.

References (13/14)

- STREUFERT, R.K., 1999, Geologic map of the Mount Sopris quadrangle, Garfield and Pitkin counties, Colorado: Colorado Geological Survey, Open-File Report OF-99-7, scale 1:24,000, 1 sheet.
- STREUFERT, R.K., 2008, Geologic map of the Mount Sopris quadrangle, Garfield and Pitkin counties, Colorado: Colorado Geological Survey, Map Series MS-41, scale 1:24,000, 1 sheet, 21 p. text.
- STREUFERT, R.K., WIDMANN, B.L., AND KIRKHAM, R.M., 1998, Geologic map of the Basalt quadrangle, Eagle, Garfield, and Pitkin counties, Colorado: Colorado Geological Survey, Open-File Report OF-98-1, scale 1:24,000, 1 sheet, 18 p. text.
- STREUFERT, R.K., MORGAN, M.L., EAKINS, W., AND HEMBORG, H.T., 1999, Geology and mineral resources of Gunnison County, Colorado: Colorado Geological Survey, Resource Series RS-37, scale 1:150,000, 1 sheet, 76 p. text.
- STREUFERT, R.K., WIDMANN, B.L., AND KIRKHAM, R.M., 2008, Geologic map of the Basalt quadrangle, Eagle, Garfield and Pitkin counties, Colorado: Colorado Geological Survey, Map Series MS-39, scale 1:24,000, 1 sheet, 22 p. text.
- U.S. GEOLOGICAL SURVEY, 2018, Castlegate: https://ngmdb.usgs.gov/Geolex/Units/Castlegate_6997.html (accessed July 2018).
- VAN LOENEN, R.E., AND BRYANT, W.A., 2000, Geologic map of the Skull Creek quadrangle, Moffat County, Colorado: U.S. Geological Survey, Geologic Investigations Series Map I-2647, scale 1:24,000, 1 sheet.
- VAN LOENEN, R.E., SELNER, G., AND BRYANT, W.A., 1999, Geologic map of the Lazy Y quadrangle, Moffat County, Colorado: U.S. Geological Survey, Geologic Investigations Series Map, no. 2646, scale 1:24,000.
- VAN WAGONER, J.C., MITCHUM, R.M., CAMPION, K.M., AND RAHMANIAN, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: Concepts for high-resolution correlation of time and facies: AAPG Methods in Exploration Series, No. 7, 55 p.
- VAN WAGONER, J.C., 1991, Road log, day four: Nonmarine sequence stratigraphy and facies architecture of the downdip Castlegate Sandstone in the Book Cliffs of western Colorado and eastern Utah in Van Wagoner, J.C., Jones, C.R., Taylor, D.R., Nummedal, D., Jennette, D.C., and Riley, G.W., eds., AAPG Special Publication 25: Sequence Stratigraphy Applications to Shelf Sandstone Reservoirs: Tulsa, Oklahoma, American Association of Petroleum Geologists, p. 3-1–3-17.

References (14/14)

- VAN WAGONER, J.C., 1995, Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A., in Van Wagoner, J.C., and Bertram, G.T., eds., AAPG Memoir 64: Sequence Stratigraphy of Foreland Basin Deposits: Tulsa, Oklahoma, American Association of Petroleum Geologists, p. 137-223.
- WALTON, P.T., 1944, Geology of the Cretaceous of the Uinta basin, Utah: GSA Bulletin, v. 55, no. 1, p. 91-130.
- WHITE, J.L., 2014, Geologic map of the Corcoran Point quadrangle, Mesa County, Colorado: Colorado Geological Survey, Open-File Report, no. 14-05, scale 1:24,000.
- WHITE, J.L., AND HODGE, J., 2013, Meeker quadrangle geologic map, Rio Blanco County, Colorado: Colorado Geological Survey, Open-File Report, no. 13-03, scale 1:24,000.
- WHITE, J.L., AND WARDEN, G., 2013, Geologic map of the LO 7 Hill quadrangle, Rio Blanco County, Colorado: Colorado Geological Survey, Open-File Report, no. 13-02, scale 1:24,000.
- WHITE, J.L., ZAWASKI, J.L., AND HODGE, J., 2013, Geologic map of the Rattlesnake Mesa quadrangle, Rio Blanco County, Colorado: Colorado Geological Survey, Open-File Report, no. 13-06, scale 1:24,000.
- WHITE, J.L., MACLEAN, R., AND CARROLL, C.J., 2014, Geologic map of the Whitewater quadrangle, Mesa County, Colorado: Colorado Geological Survey, Open-File Report OF-14-09, scale 1:24,000, 2 sheets, 38 p. text.
- YOSHIDA, S., WILLIS, A., AND MIAL, A.D., 1996, Tectonic control of nested sequences in the Castlegate Sandstone (Upper Cretaceous), Book Cliffs, Utah: Journal of Sedimentary Research, v. 66, no. 4, p. 737–748, doi: 10.1306/D42683F6-2B26-11D7-8648000102C1865D.
- YOUNG, R.G., 1955, Sedimentary facies and intertonguing in the Upper Cretaceous of the Book Cliffs, Utah Colorado: GSA Bulletin, v. 66, no. 2, p. 177--202.