Geologic mapping as a tool for predicting groundwater contamination: Assessing arsenic risk in east-central Wisconsin

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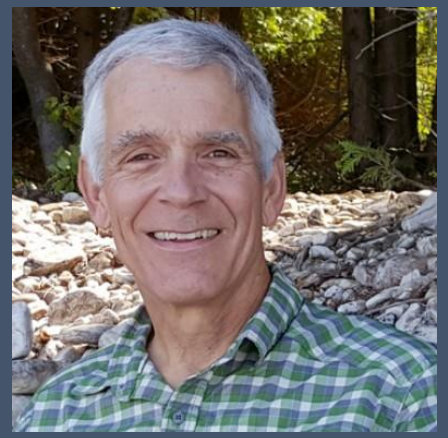
Acknowledgements

- Synthesizing ideas and work from many people

Sarah Bremmer– Grant County geologic mapping

Billy Fitzpatrick – Geochemistry



Ken Bradbury – Hydraulic conductivity estimates

Bill Batten – Fond du Lac county map

Steve Mauel – GIS and regional geology

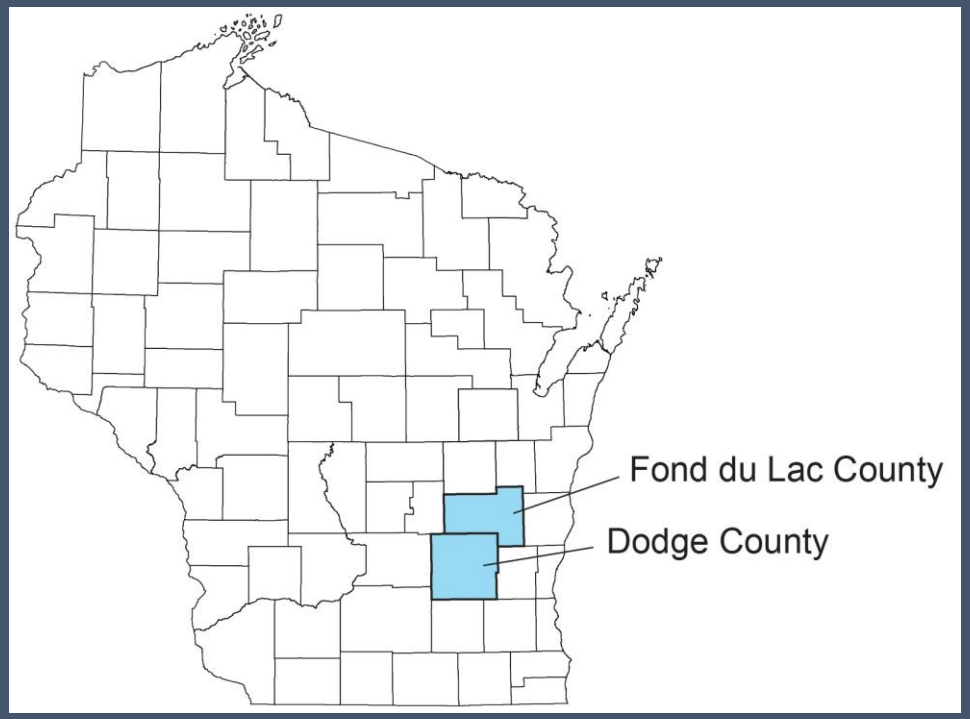
Esther Stewart – Dodge County geologic map

Photos from https://wgnhs.wisc.edu/about/people/

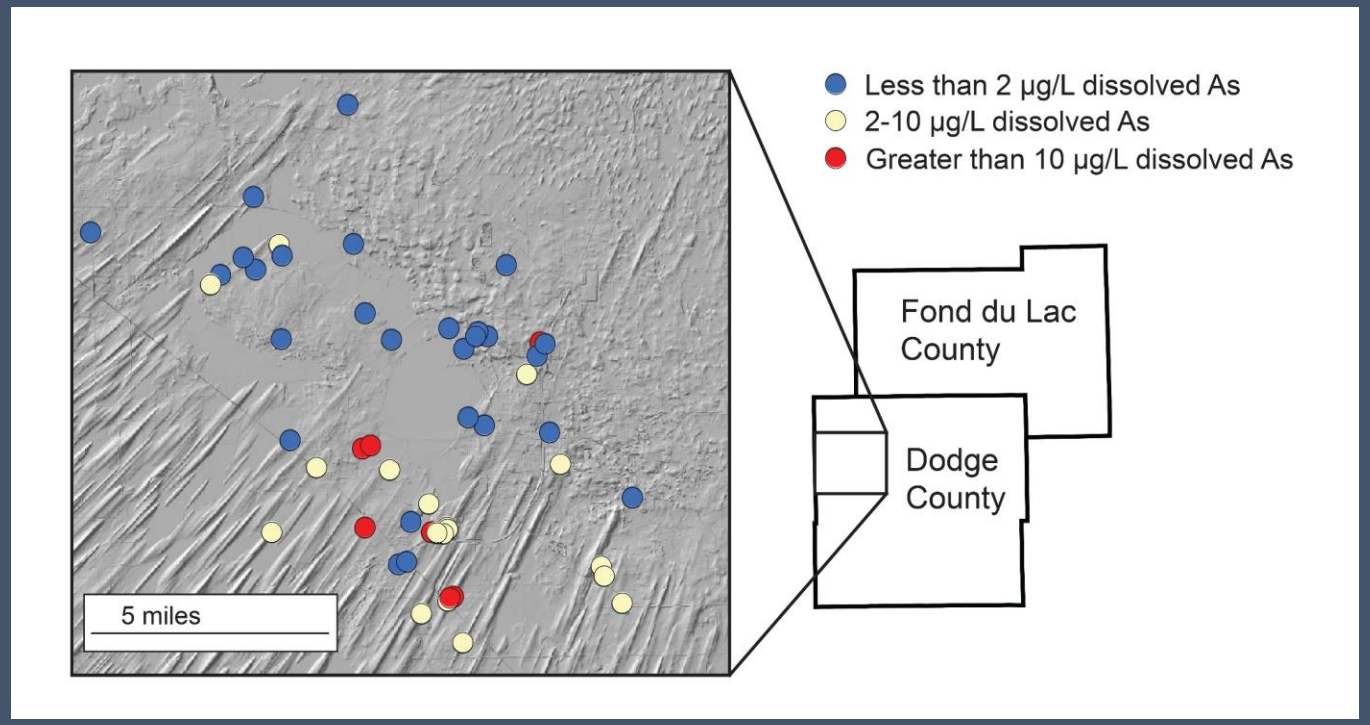
Purpose

- Dissolved arsenic in groundwater wells is a longstanding problem in eastern Wisconsin
  - 48.5% of wells reported by the WDNR in Fond du Lac and Dodge counties detected As over 2 ug/L
- Can we use geologic mapping to better understand and predict areas of elevated risk?

Focus area



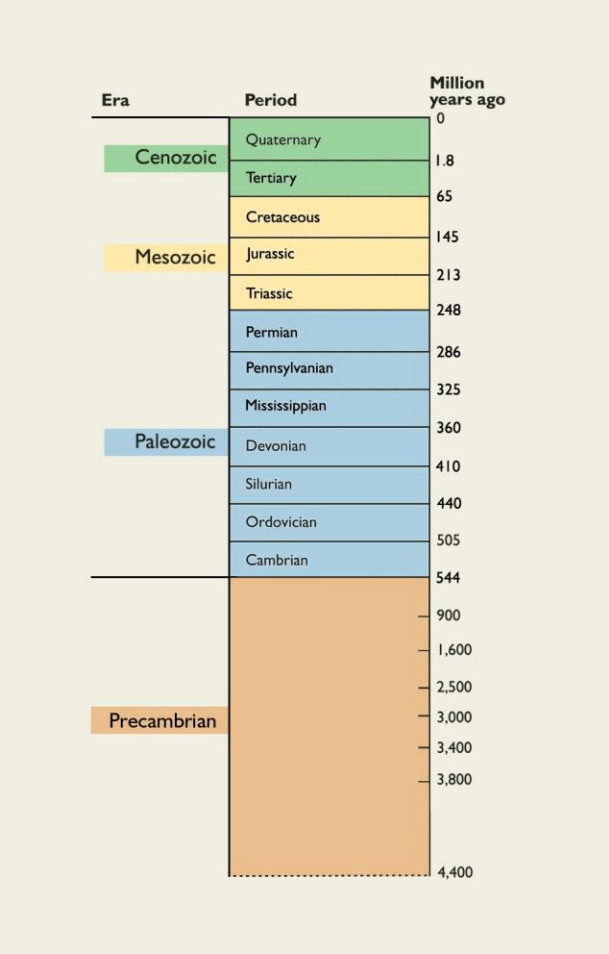
Dissolved arsenic in groundwater wells

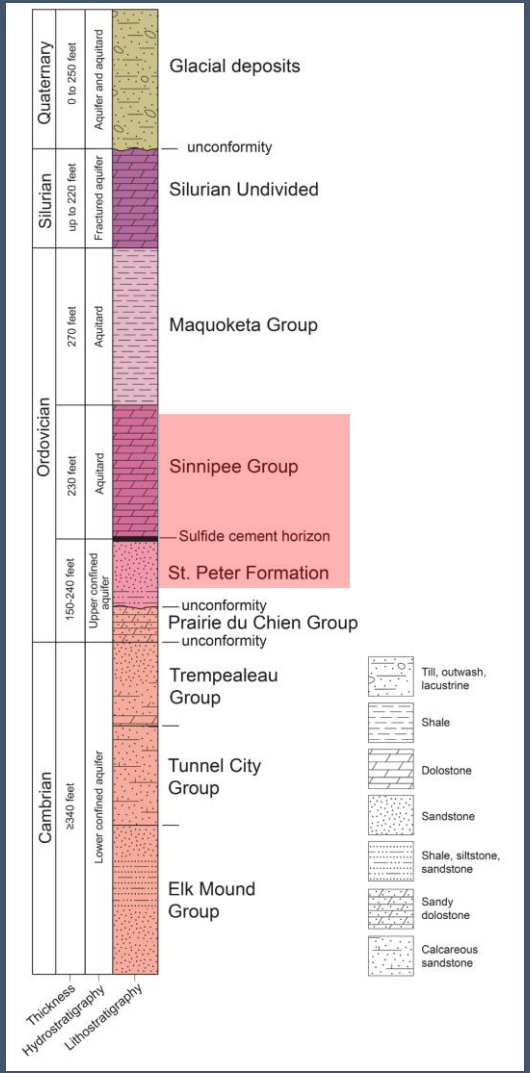


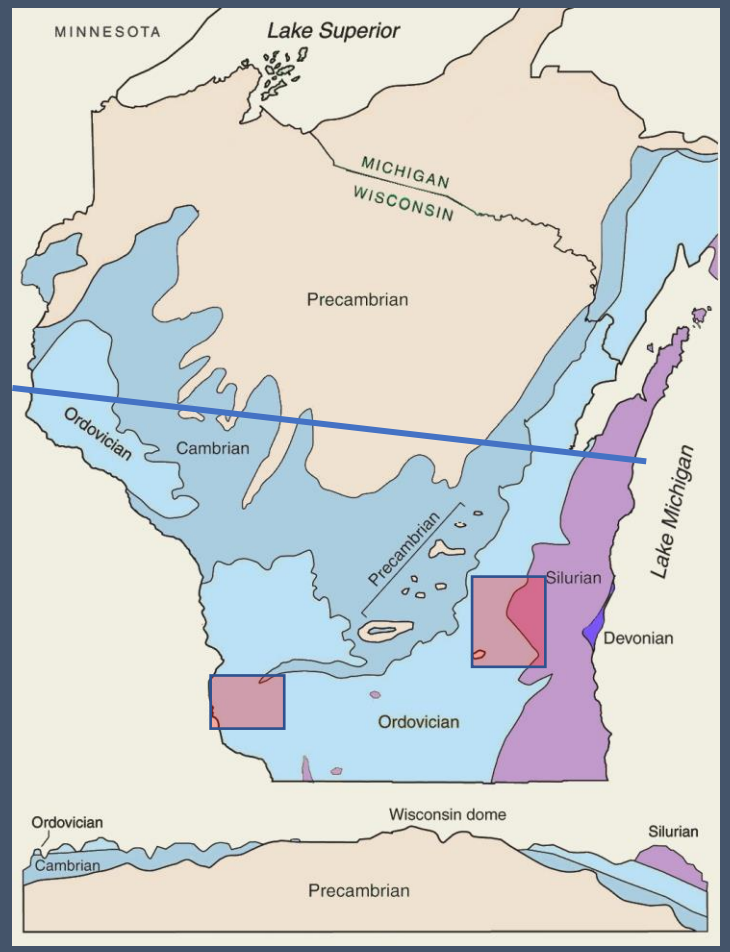
Overview

- **Mapping Paleozoic rocks of Wisconsin**
- How do folds and faults alter bedrock units?
- Stratigraphic and well construction controls on arsenic in wells
- What matters to communities?
  - GRAC project investigating a link between groundwater contamination and folding
- Summary – What we've learned

Location and Age of Paleozoic rocks in Wisconsin







Mountain Press
2004

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Mapping approach today

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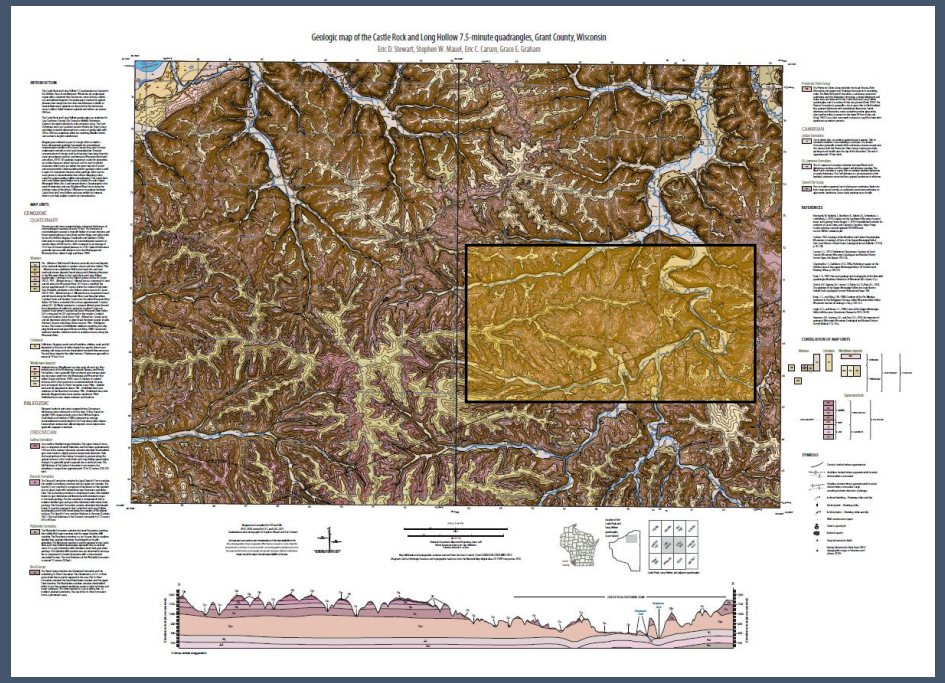
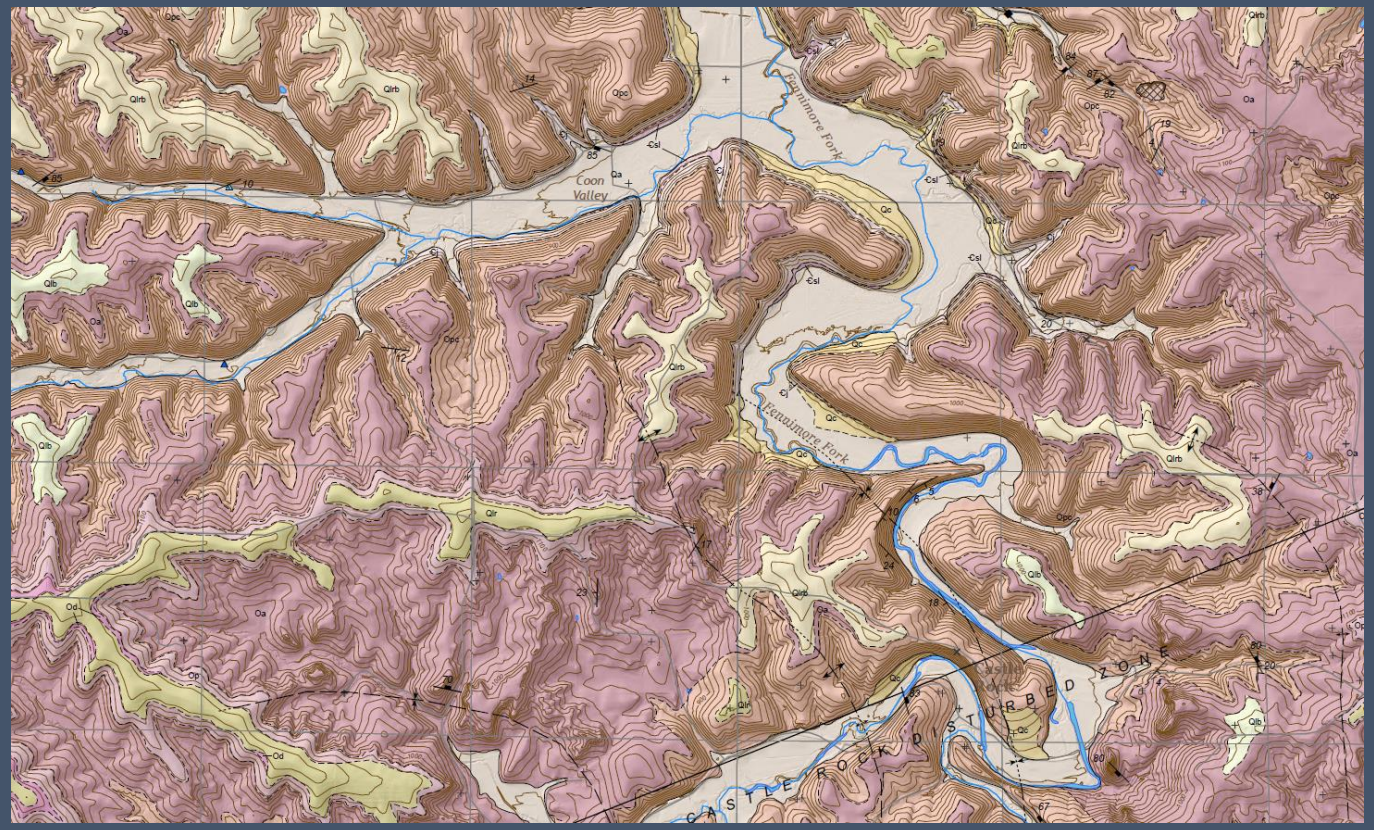
- Depends on the location and scale
  - In Driftless area at 1:24,000 scale, field work

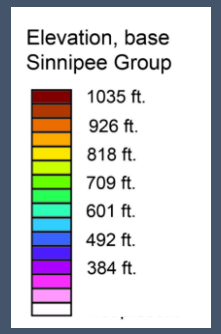


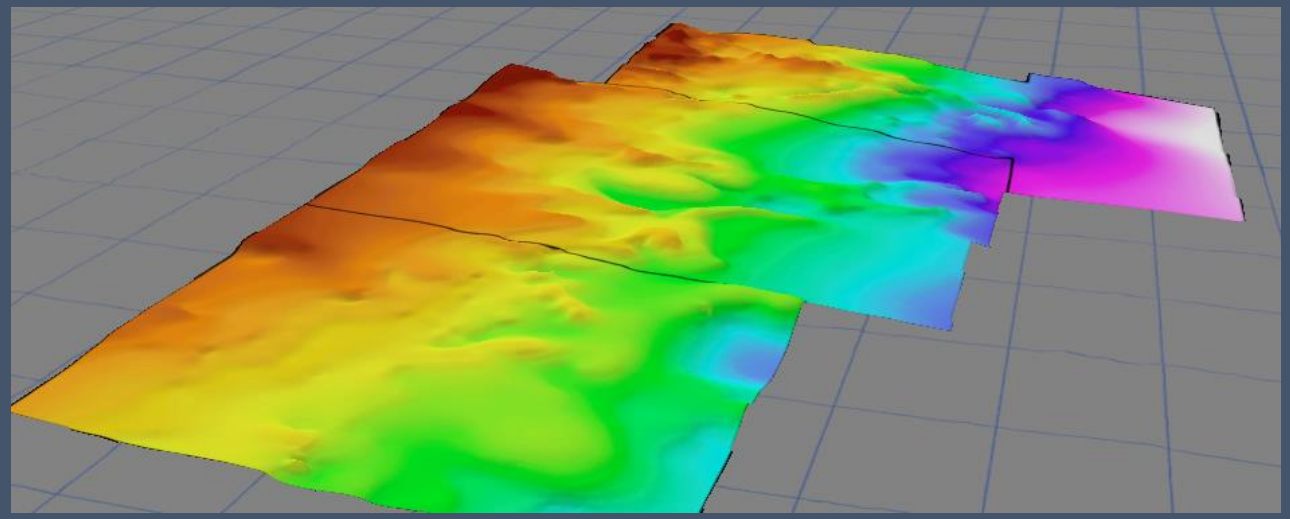
Stewart and others (in revision)



Approach today

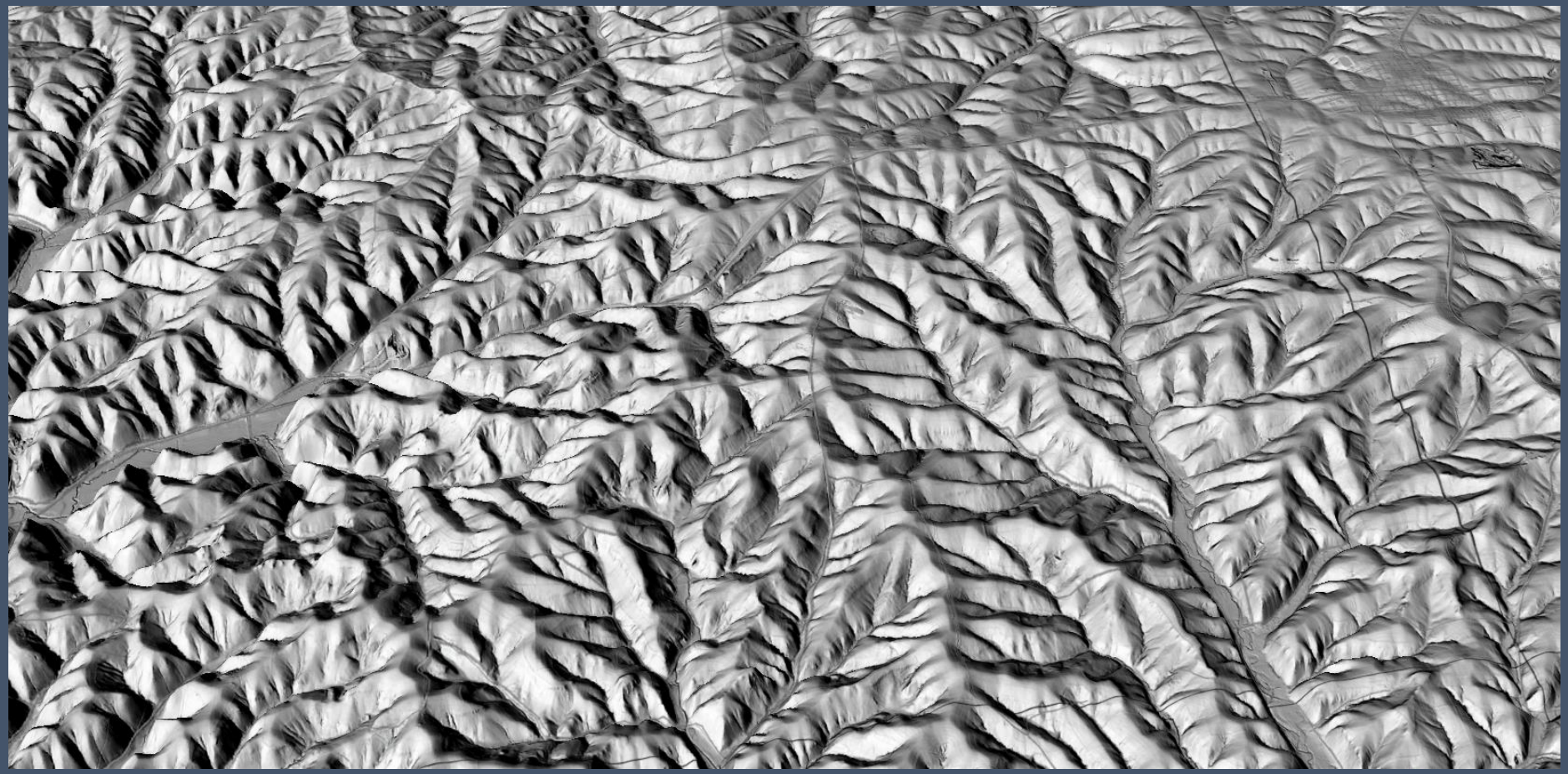
- At 1:100,000 and in glaciated parts of the state, we create 3D surfaces of unit contacts, and intercept them with a bedrock surface





Map is made by intersecting contact surfaces with a bedrock surface

- Create 3D surfaces of unit contacts, and intercept them with a bedrock surface



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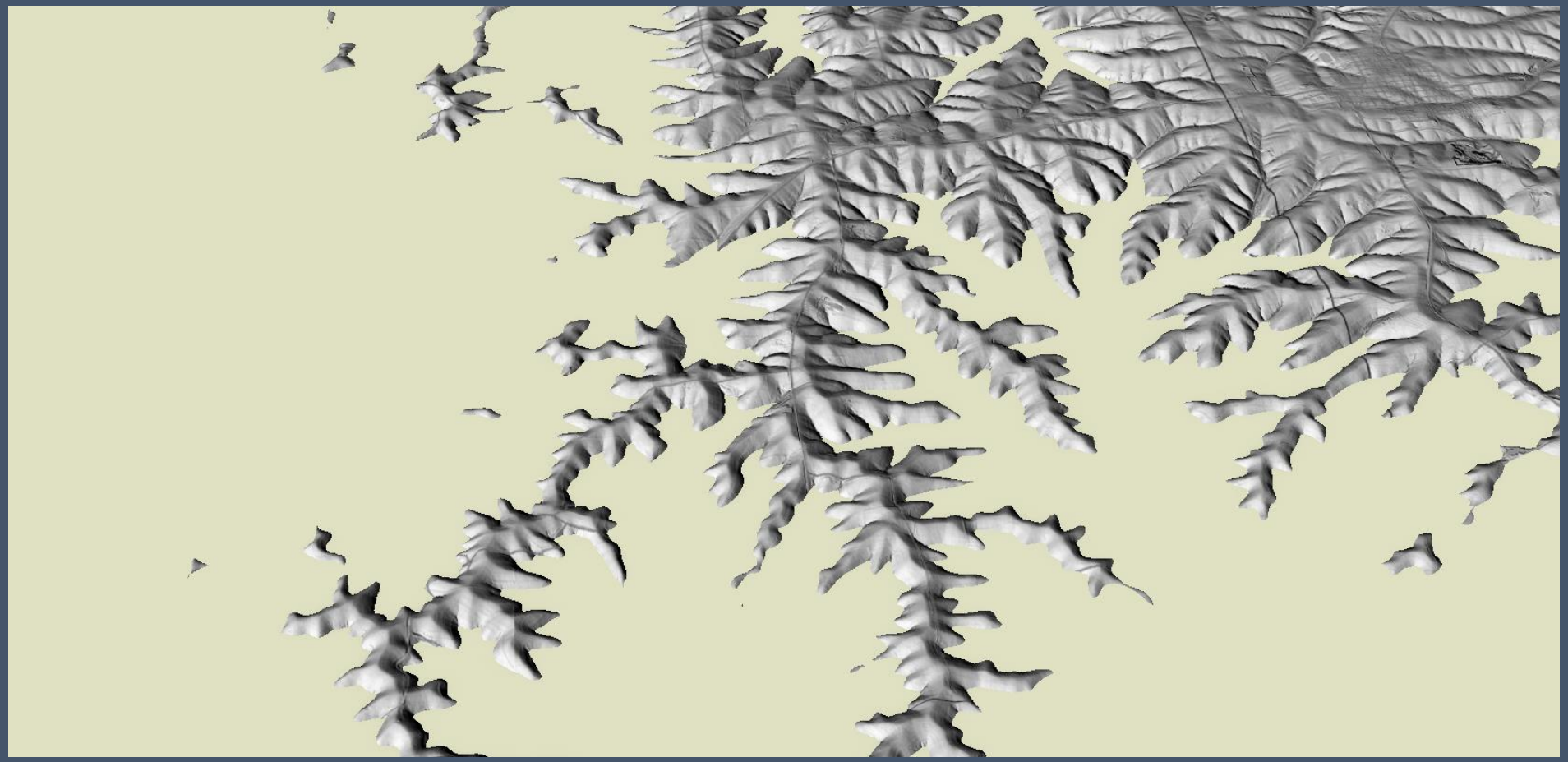

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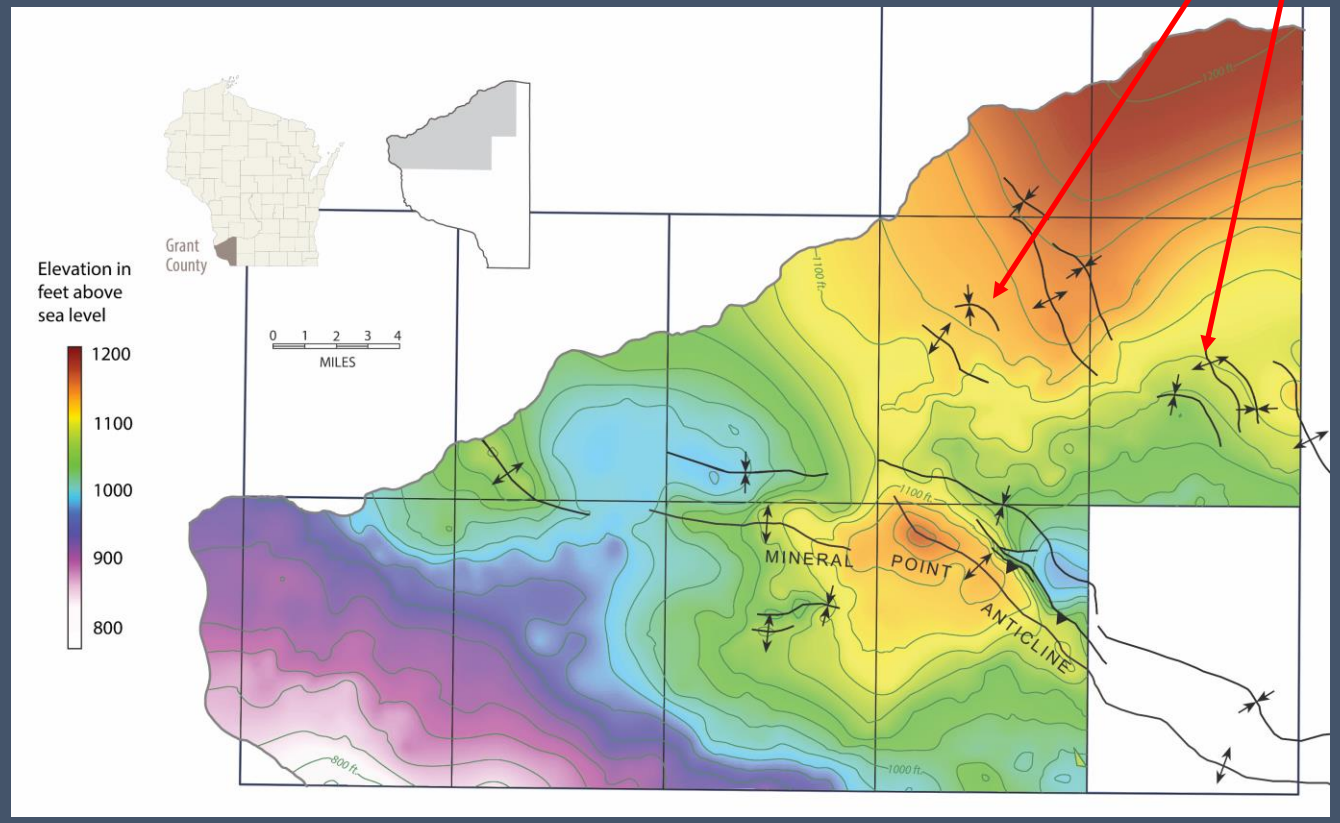
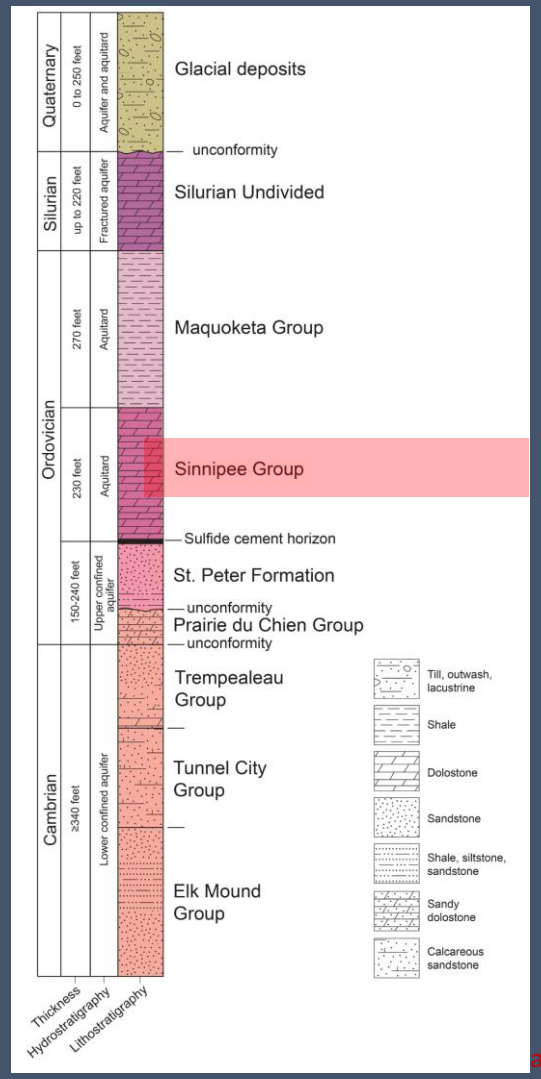
What are they?

Fold axes based on folding of underlying base Prairie du Chien surface

Map of the base of the Ordovician Sinnipee Group





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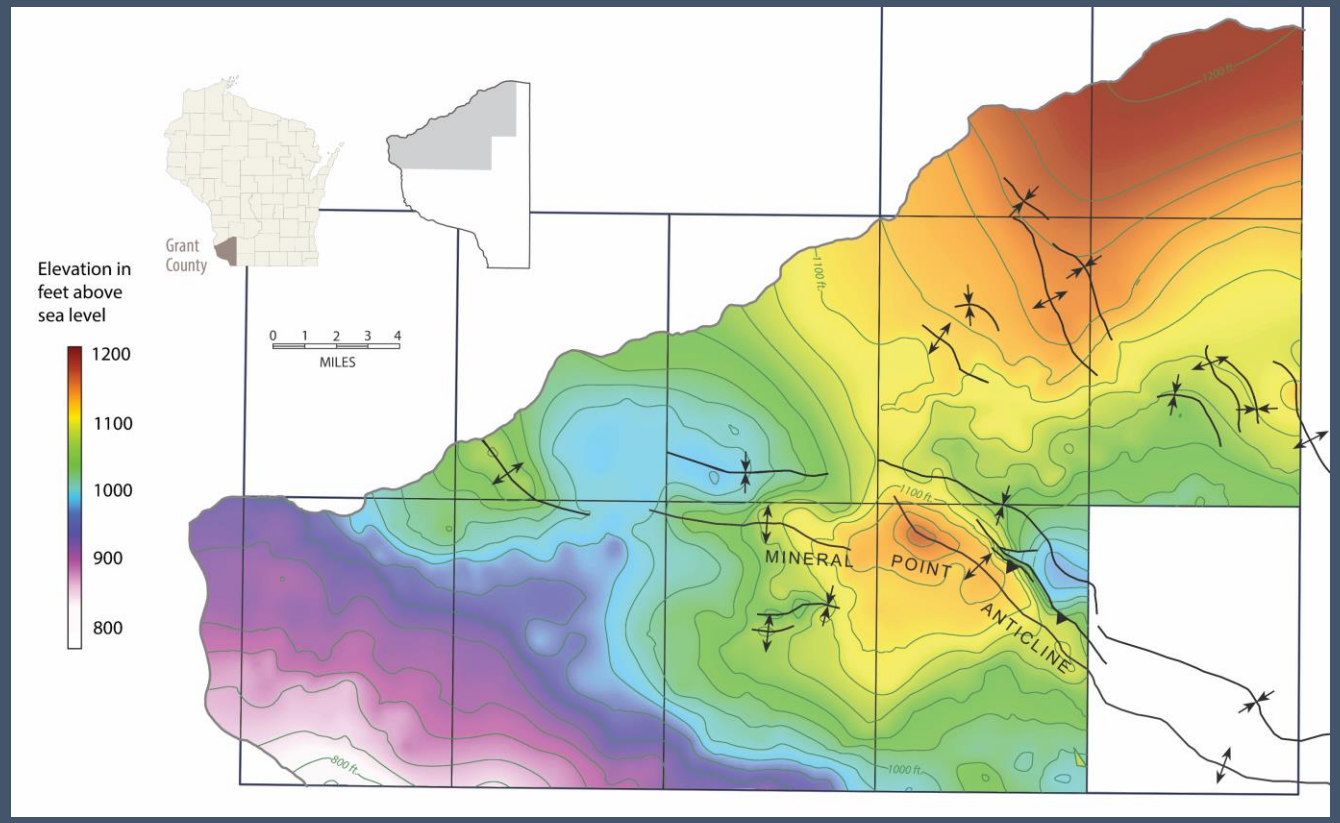
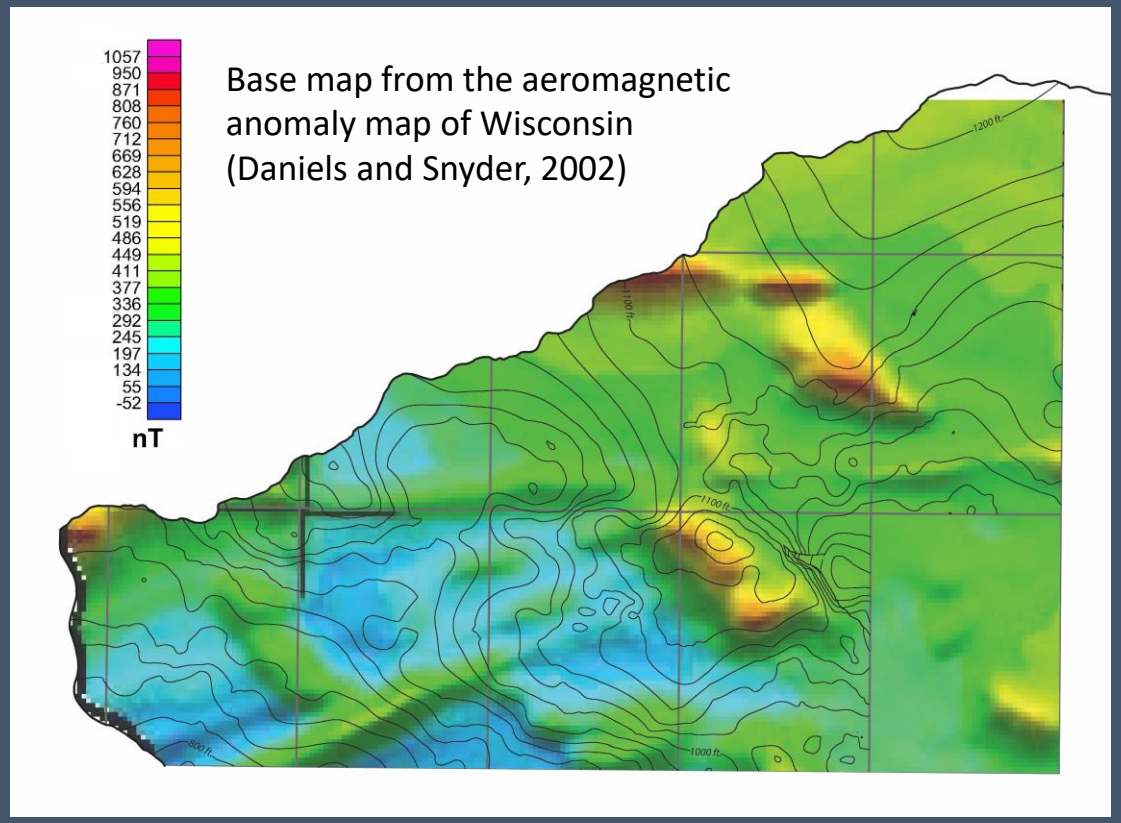
What are they?

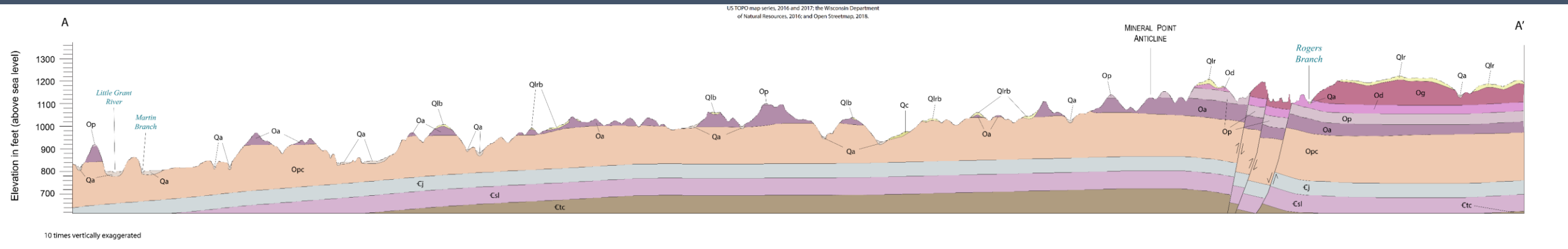
- In many cases, folds form when Precambrian basement was reactivated in the Paleozoic



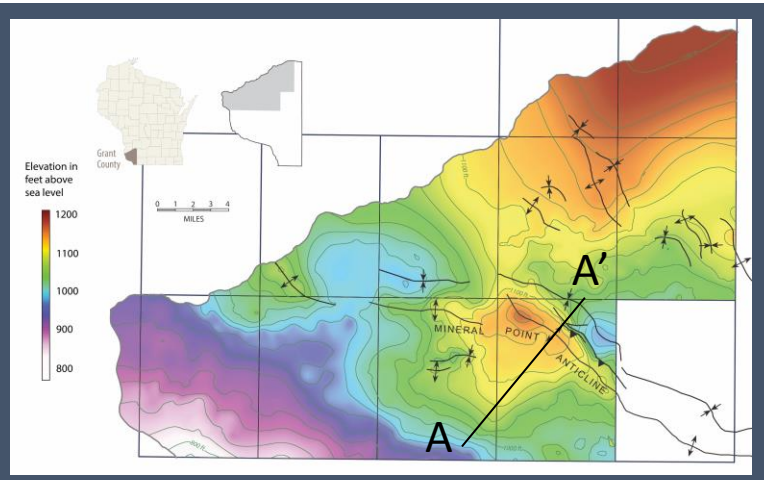


Paleozoic folds in Wisconsin are subtle

- Mineral Point anticline – near Fennimore, Grant County, SW Wisconsin



Cross section from Bremmer and others (in prep)



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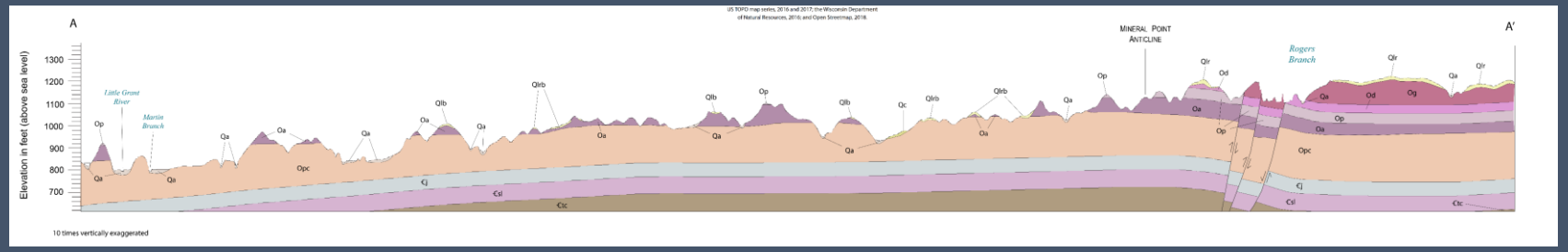
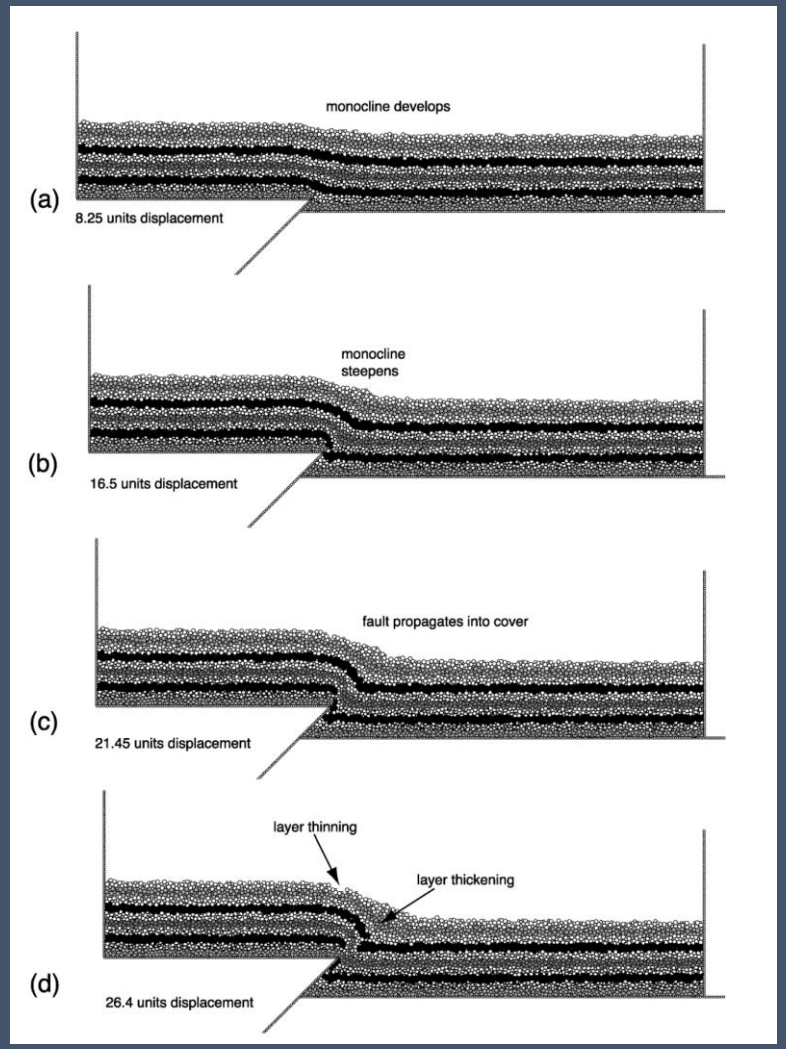
Small fault-propagation fold involving Precambrian basement



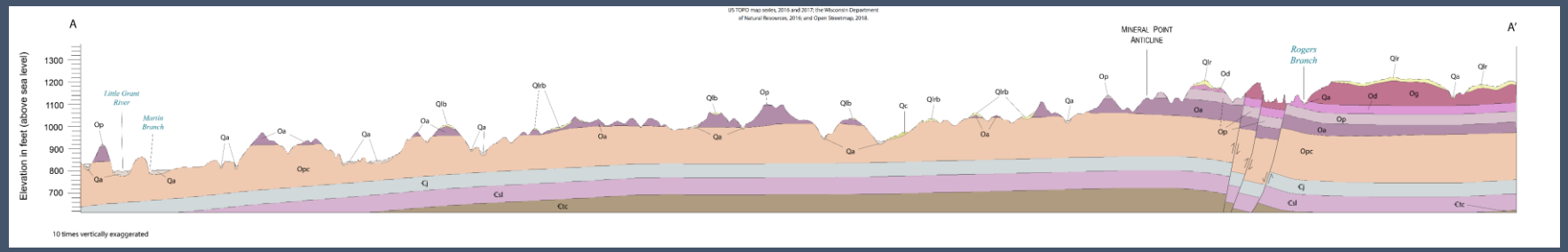
Cross section from Bremmer and others (in prep), vertical exaggeration 10 times

- Some Paleozoic folds may be cut by faults, in others, the faults may be buried

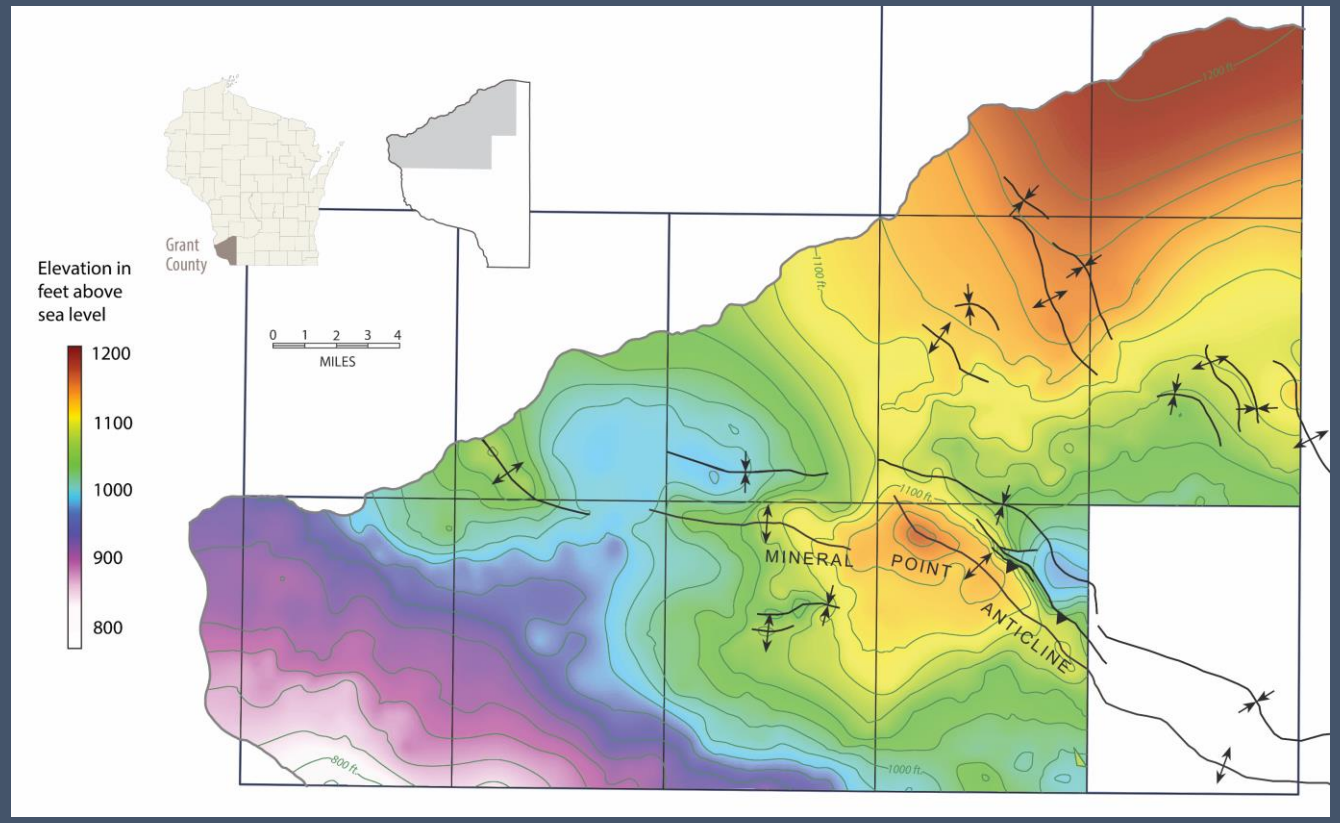


Finch and others (2003)

Small fault-propagation folds



Cross section from Bremmer and others (in prep)



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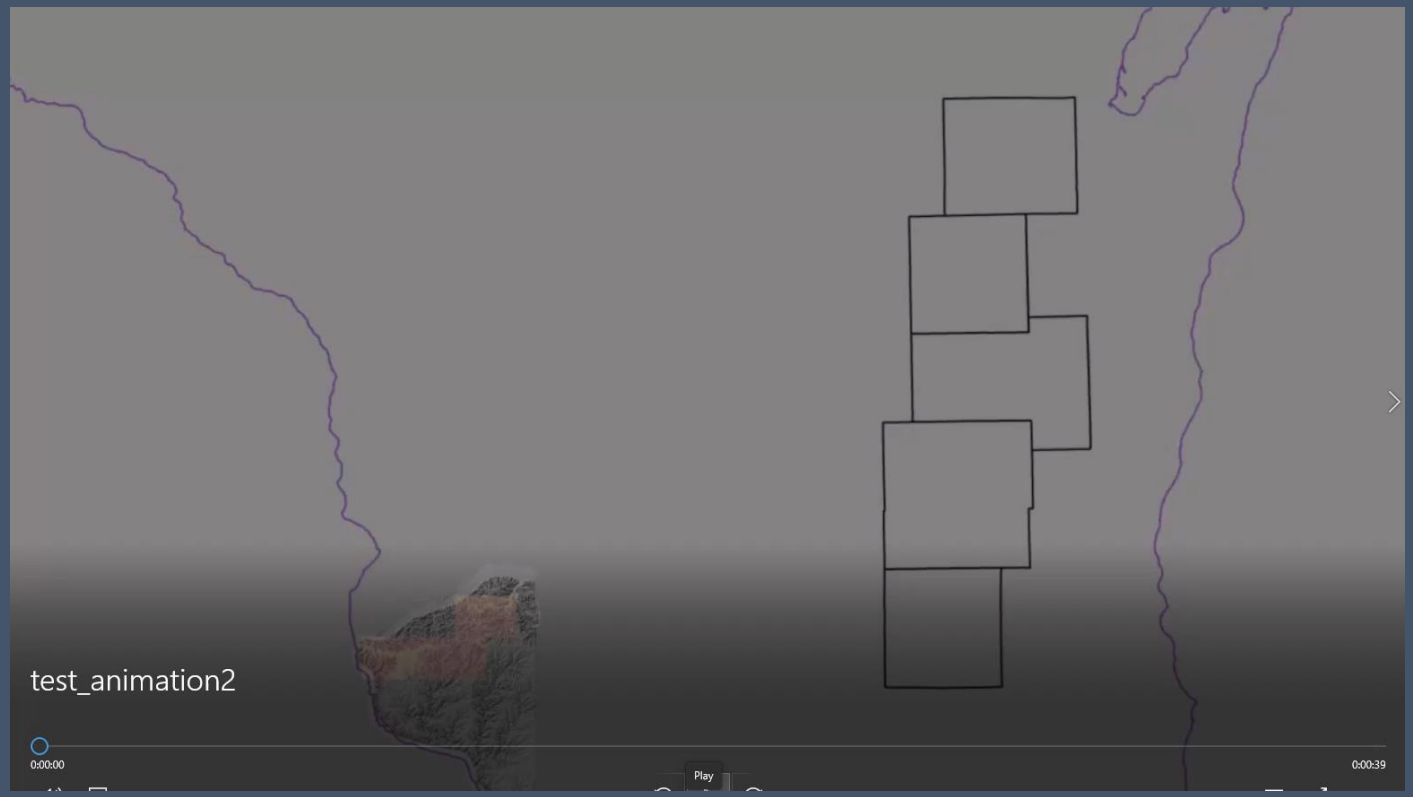
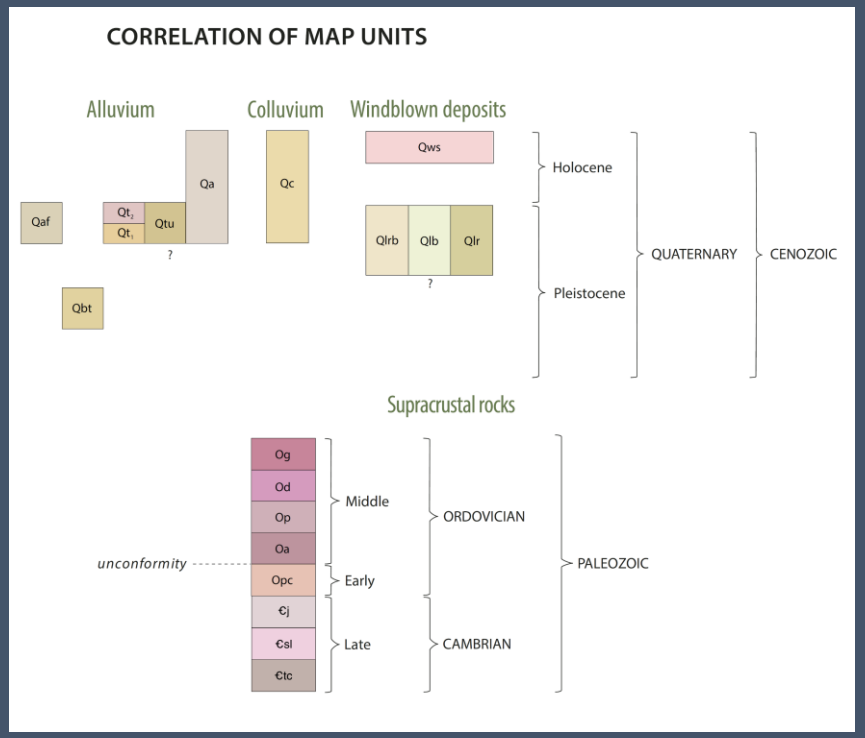
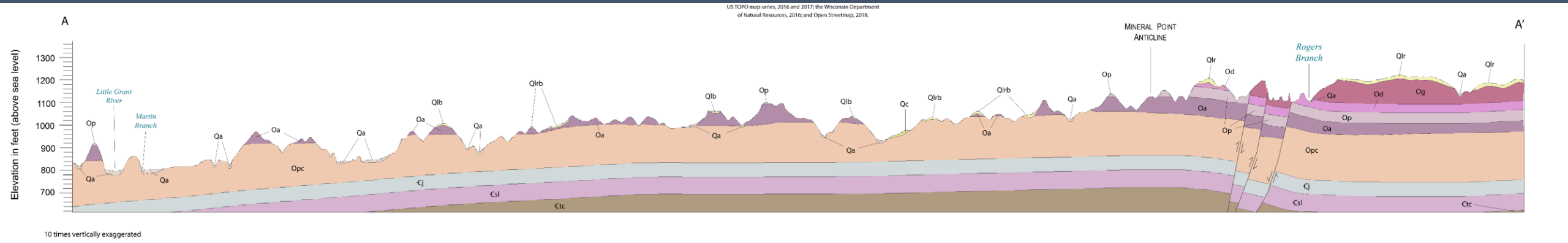
Paleozoic folds in Wisconsin are subtle







Overview

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- **How do folds and faults alter bedrock units**
- Stratigraphic and well construction controls on arsenic in wells
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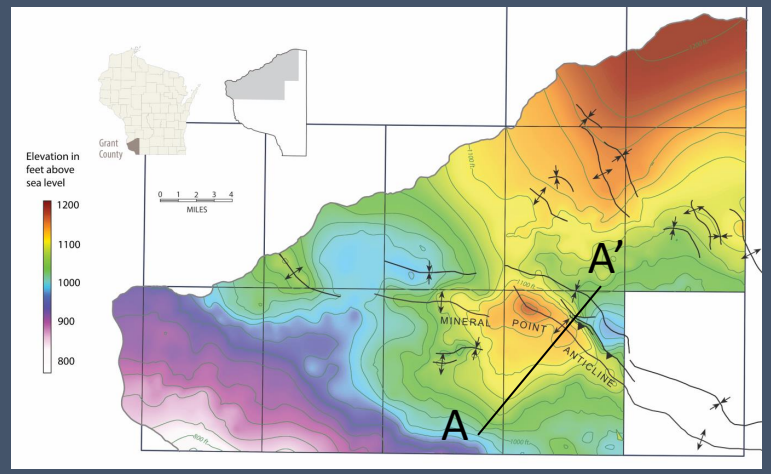
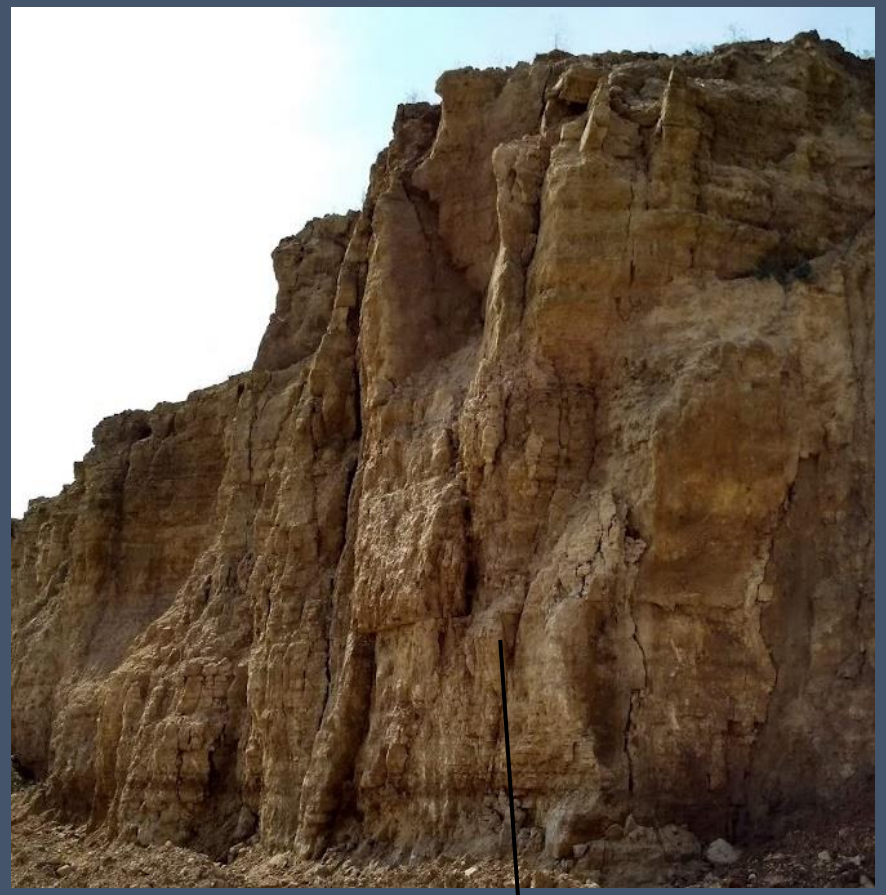
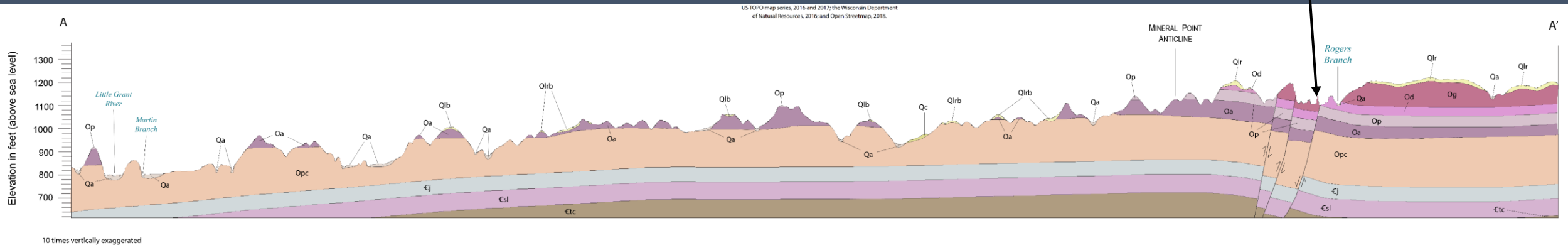
- Summary – What we've learned
  - Map scale and approach

Southwest Wisconsin: Increased fracturing observed near faults



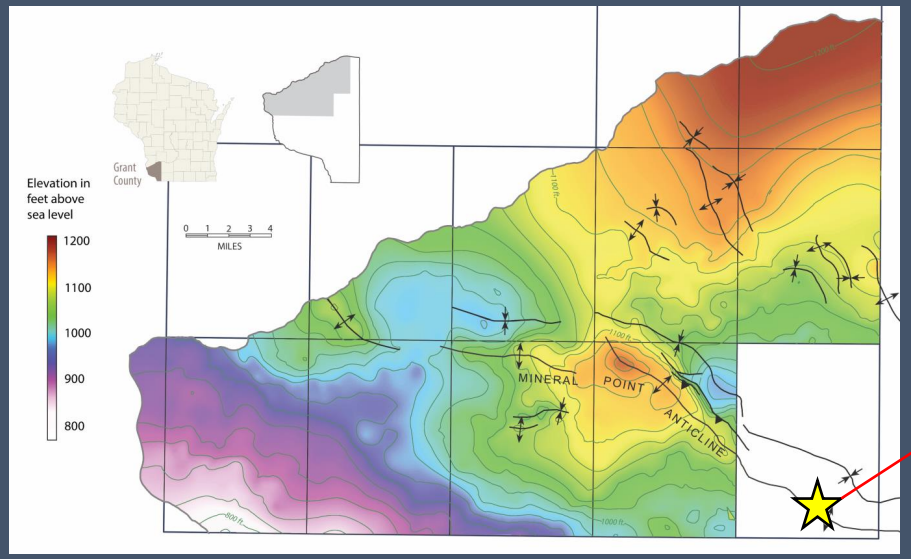
Heavily fractured Galena Formation, faulted zone along Mineral Point anticline

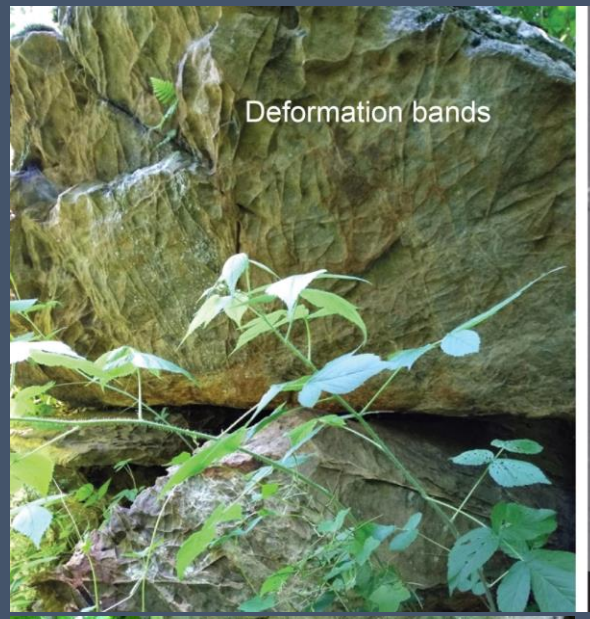


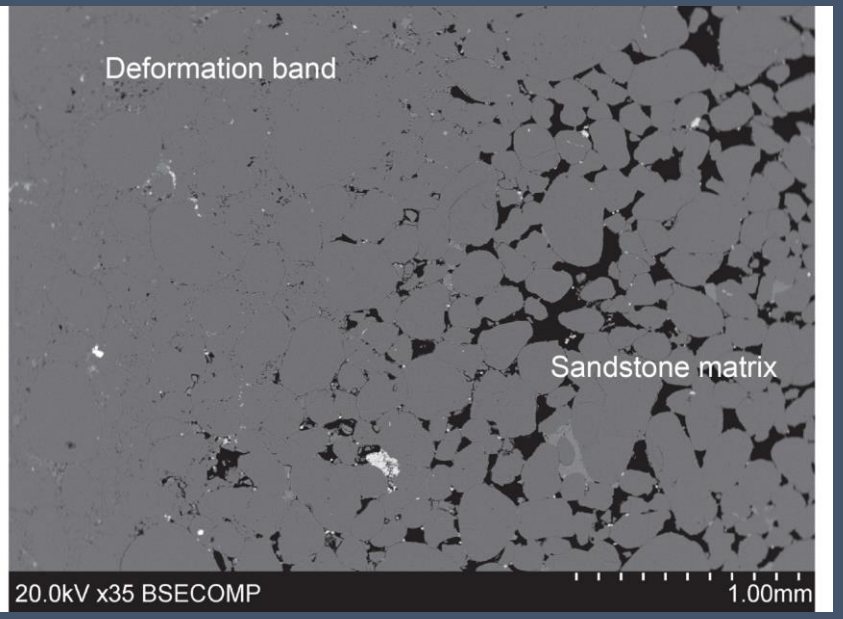


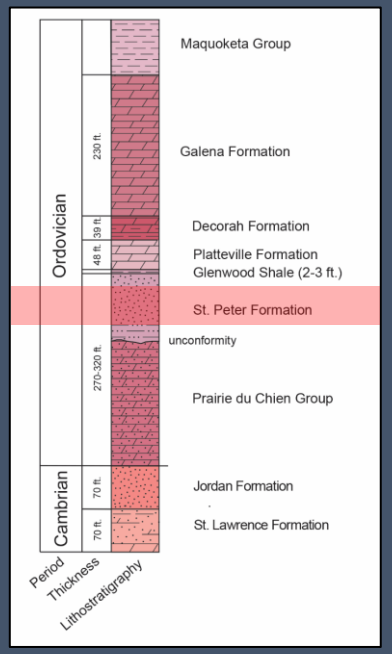
Deformation bands

Reduction in sandstone porosity in deformation bands may lead to reduction in horizontal hydraulic conductivity

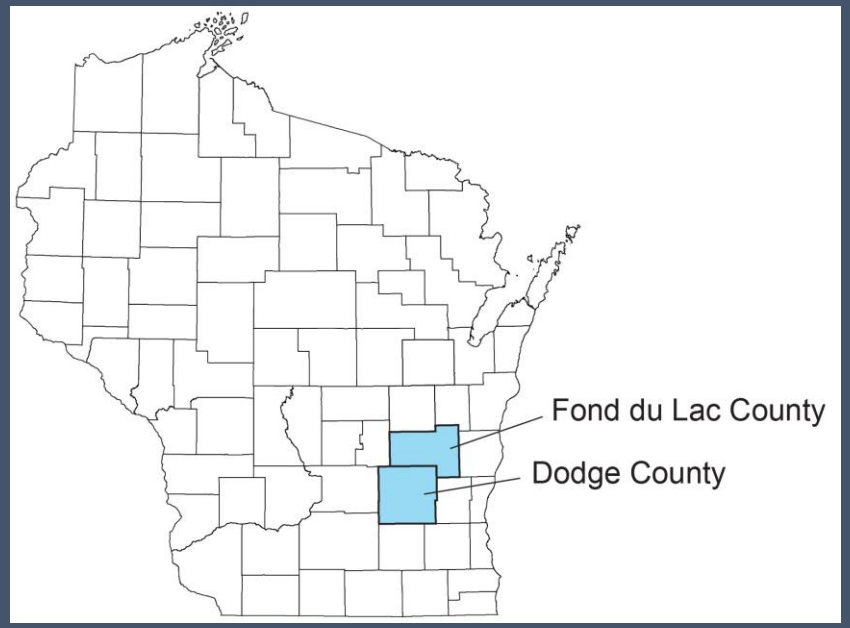


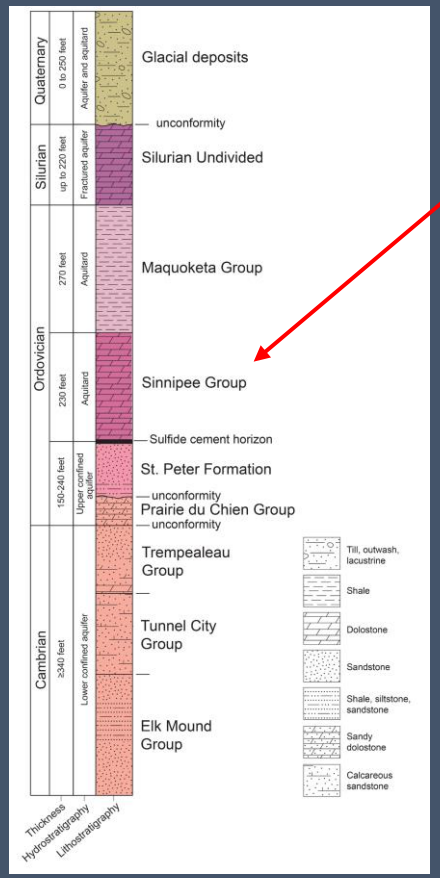


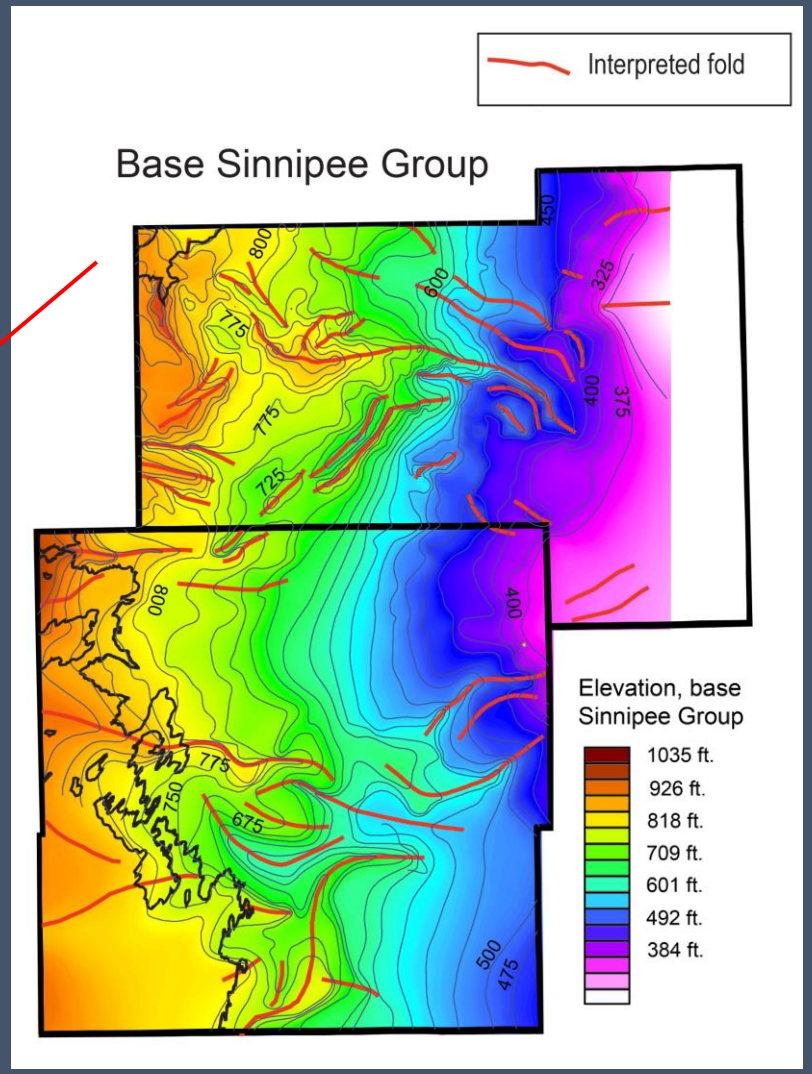




Fracturing in bedrock units in glaciated parts of the state



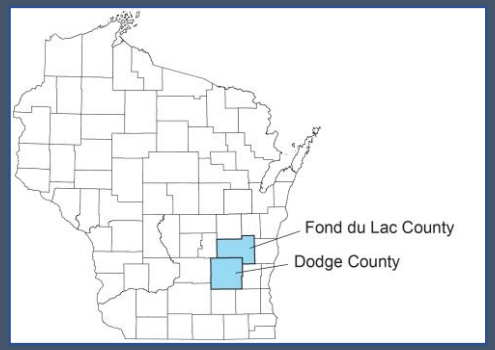


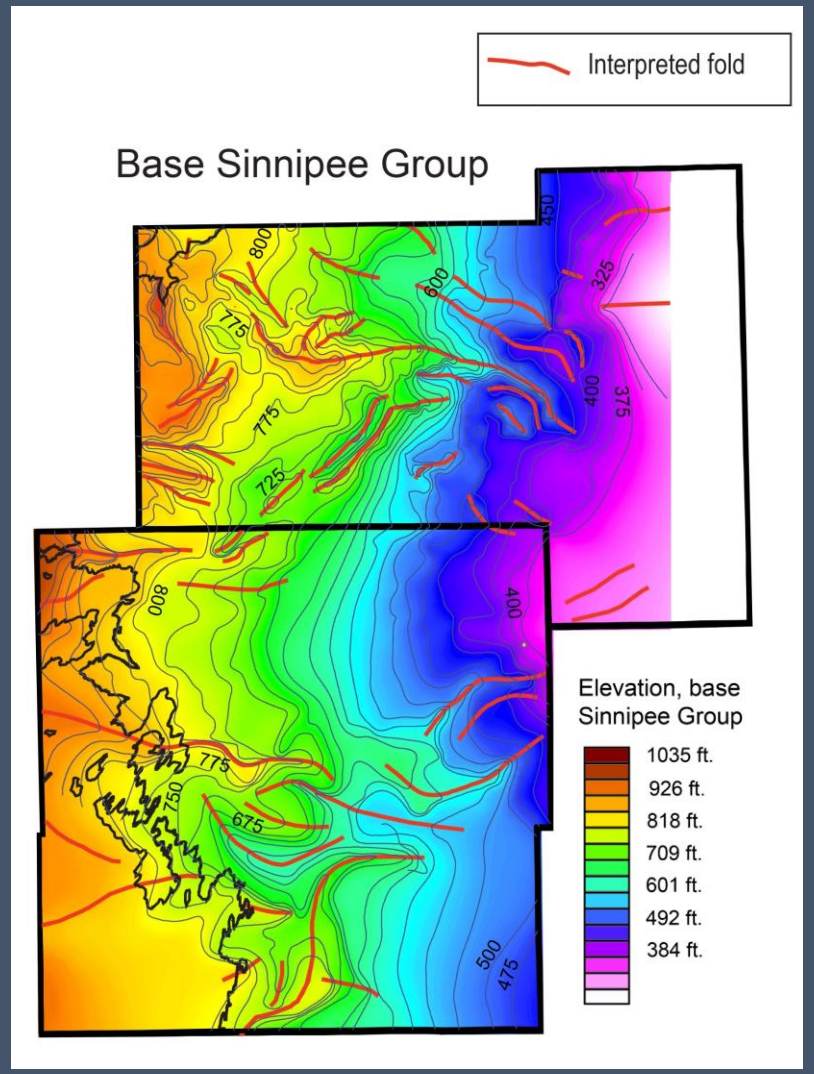


Structure contour map based on mapping by Batten (2018) and Stewart (2021)

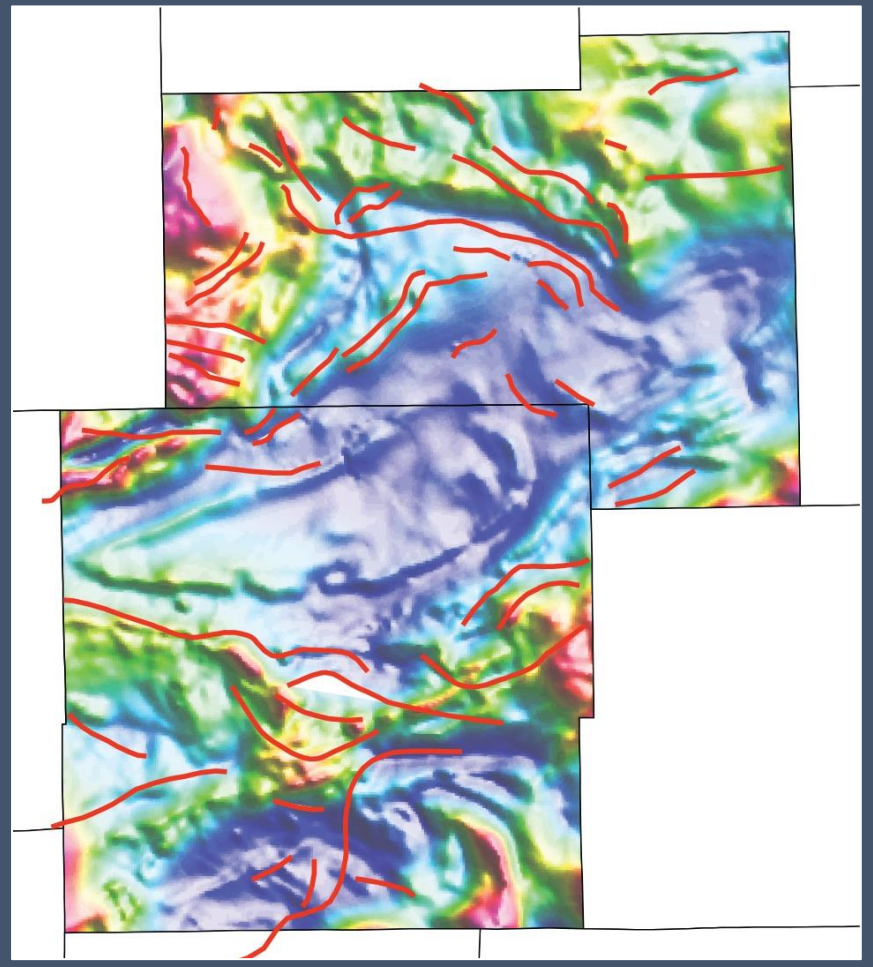
Regional geology

- Folds probably formed from reactivated Precambrian structures





Base map from aeromag compilation by E. Anderson, USGS, modified from Daniels and Snyder (2002)



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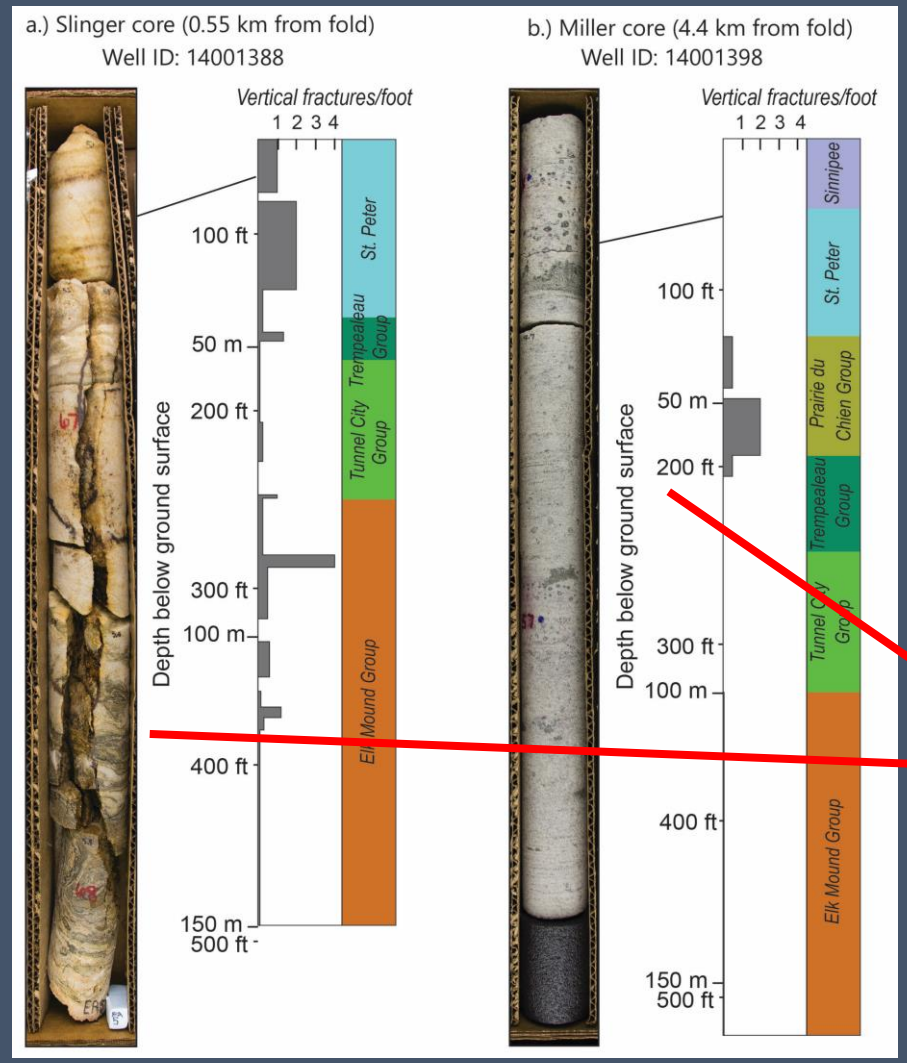
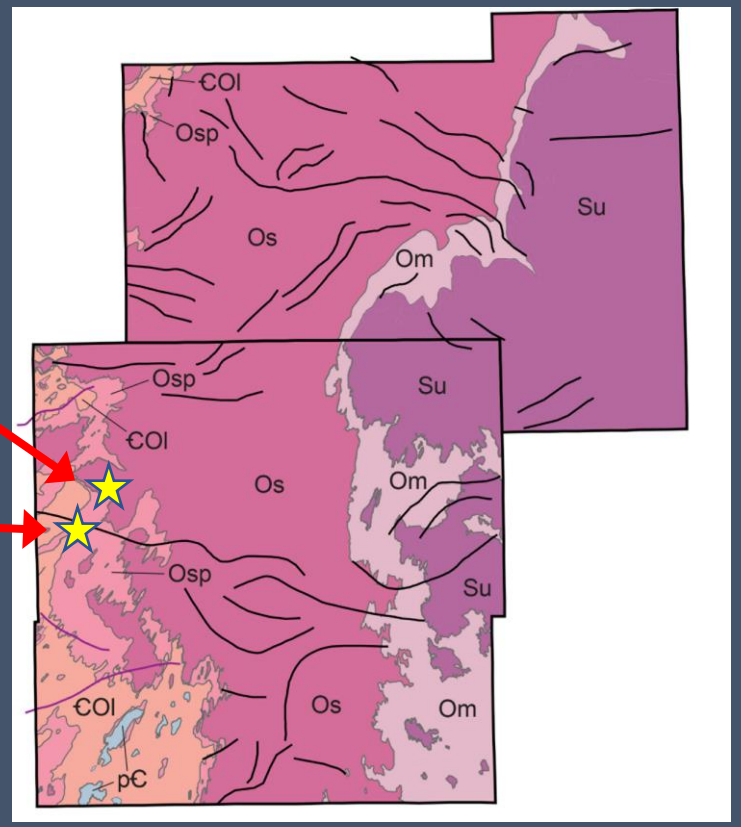
Fracturing in core in Dodge County

- More fractures/foot near folds than far away

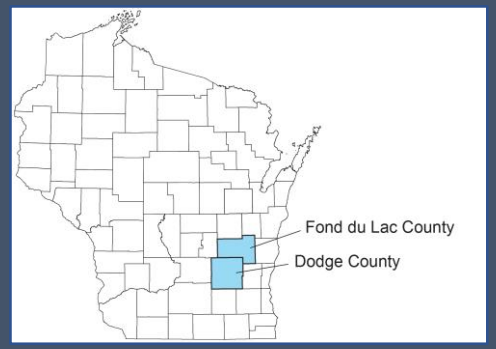


Stewart and others (2021)

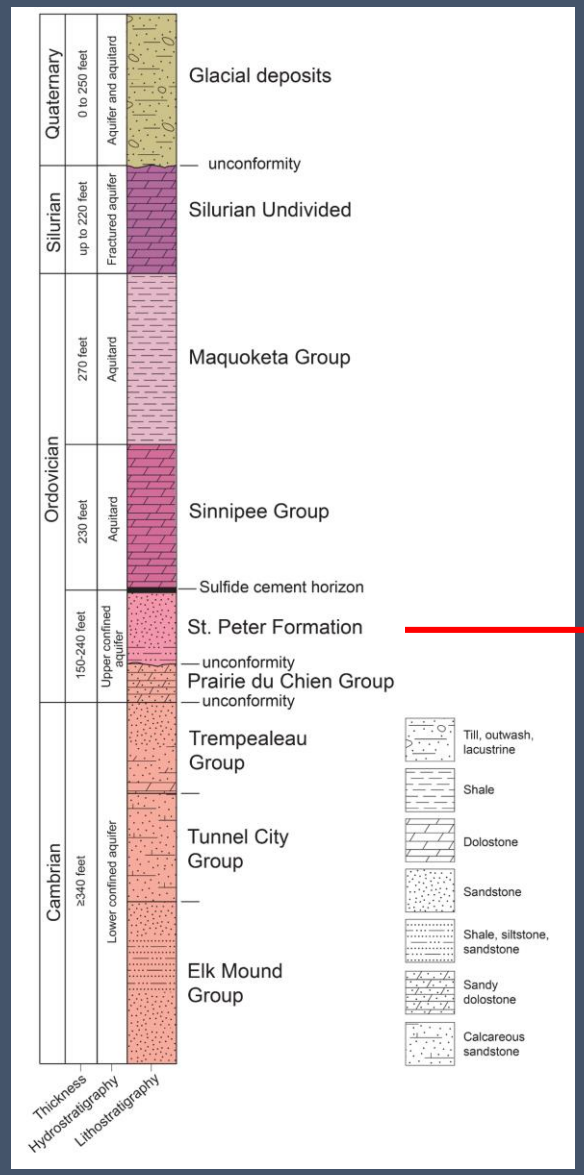
Map based on Batten (2018) and Stewart (2021)



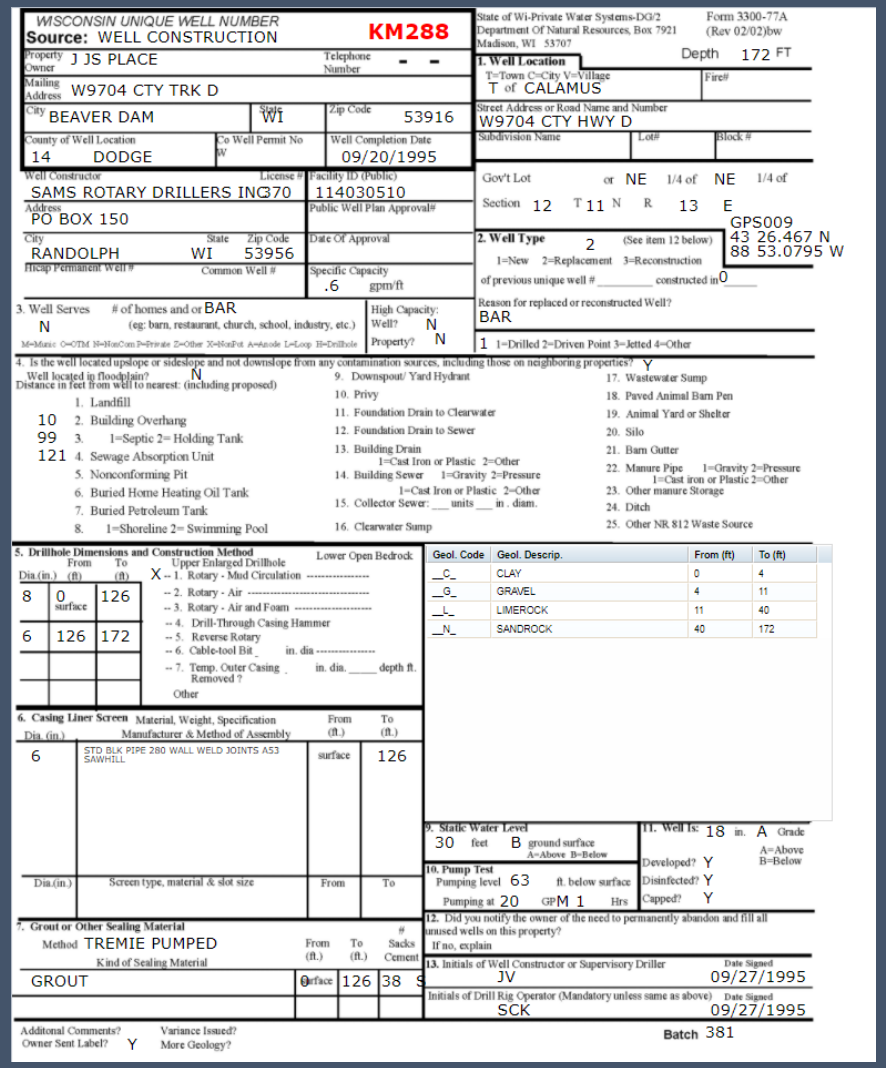
★ Core location



Testing the field and core observations with well data



- Estimated hydraulic conductivity (K) from specific capacity tests in wells (Bradbury and Rothschild, 1985)



WISCONSIN UNIQUE WELL NUMBER KM288
Source: WELL CONSTRUCTION

State of Wi-Private Water Systems-DG/2, Department Of Natural Resources, Box 7921, Madison, WI 53707 — Form 3300-77A (Rev 02/02)bw

Property Owner: J JS PLACE — Telephone Number: - -
Mailing Address: W9704 CTY TRK D
City: BEAVER DAM — State: WI — Zip Code: 53916
County of Well Location: 14 DODGE — Co Well Permit No: W — Well Completion Date: 09/20/1995

Depth 172 FT

1. Well Location
T=Town C=City V=Village: T of CALAMUS — Fire#
Street Address or Road Name and Number: W9704 CTY HWY D
Subdivision Name — Lot# — Block #
Gov't Lot or NE 1/4 of NE 1/4 of Section 12 T 11 N R 13 E
GPS009 43 26.467 N 88 53.0795 W

Well Constructor: SAMS ROTARY DRILLERS INC — License #: 370 — Facility ID (Public): 114030510
Address: PO BOX 150 — Public Well Plan Approval#
City: RANDOLPH — State: WI — Zip Code: 53956 — Date Of Approval
Fricap Permanent Well # — Common Well # — Specific Capacity: .6 gpm/ft

2. Well Type: 2 (See item 12 below) 1=New 2=Replacement 3=Reconstruction
of previous unique well # _____ constructed in 0
Reason for replaced or reconstructed Well? BAR
1 1=Drilled 2=Driven Point 3=Jetted 4=Other

3. Well Serves: N — # of homes and or BAR (eg: barn, restaurant, church, school, industry, etc.)
M=Manic O=OTM N=NonCom P=Private Z=Other X=NonFot A=Anode L=Loop H=Drillhole
High Capacity: Well? N — Property? N

4. Is the well located upslope or sideslope and not downslope from any contamination sources, including those on neighboring properties? Y
Well located in floodplain? N
Distance in feet from well to nearest: (including proposed)
10 1. Landfill
99 2. Building Overhang
121 3. 1=Septic 2= Holding Tank
4. Sewage Absorption Unit
5. Nonconforming Pit
6. Buried Home Heating Oil Tank
7. Buried Petroleum Tank
8. 1=Shoreline 2= Swimming Pool
9. Downspout/ Yard Hydrant
10. Privy
11. Foundation Drain to Clearwater
12. Foundation Drain to Sewer
13. Building Drain 1=Cast Iron or Plastic 2=Other
14. Building Sewer 1=Gravity 2=Pressure 1=Cast Iron or Plastic 2=Other
15. Collector Sewer: ___ units ___ in . diam.
16. Clearwater Sump
17. Wastewater Sump
18. Paved Animal Barn Pen
19. Animal Yard or Shelter
20. Silo
21. Barn Gutter
22. Manure Pipe 1=Gravity 2=Pressure 1=Cast iron or Plastic 2=Other
23. Other manure Storage
24. Ditch
25. Other NR 812 Waste Source

5. Drillhole Dimensions and Construction Method — Upper Enlarged Drillhole — Lower Open Bedrock

Dia.(in.)	From (ft)	To (ft)
8	0 surface	126
6	126	172

X -- 1. Rotary - Mud Circulation
-- 2. Rotary - Air
-- 3. Rotary - Air and Foam
-- 4. Drill-Through Casing Hammer
-- 5. Reverse Rotary
-- 6. Cable-tool Bit _ in. dia
-- 7. Temp. Outer Casing _ in. dia. ____ depth ft. Removed ?
Other

Geol. Code	Geol. Descrip.	From (ft)	To (ft)
_C_	CLAY	0	4
_G_	GRAVEL	4	11
_L_	LIMEROCK	11	40
_N_	SANDROCK	40	172

6. Casing Liner Screen — Material, Weight, Specification, Manufacturer & Method of Assembly

Dia. (in.)	Material, Weight, Specification, Manufacturer & Method of Assembly	From (ft.)	To (ft.)
6	STD BLK PIPE 280 WALL WELD JOINTS A53 SAWHILL	surface	126

Dia.(in.)	Screen type, material & slot size	From	To

9. Static Water Level: 30 feet B ground surface A=Above B=Below
10. Pump Test: Pumping level 63 ft. below surface; Pumping at 20 GPM 1 Hrs
11. Well Is: 18 in. A Grade A=Above B=Below; Developed? Y; Disinfected? Y; Capped? Y

7. Grout or Other Sealing Material
Method: TREMIE PUMPED
Kind of Sealing Material: GROUT — From (ft.): 0 surface — To (ft.): 126 — # Sacks Cement: 38 S

12. Did you notify the owner of the need to permanently abandon and fill all unused wells on this property?
If no, explain

13. Initials of Well Constructor or Supervisory Driller: JV — Date Signed: 09/27/1995
Initials of Drill Rig Operator (Mandatory unless same as above): SCK — Date Signed: 09/27/1995

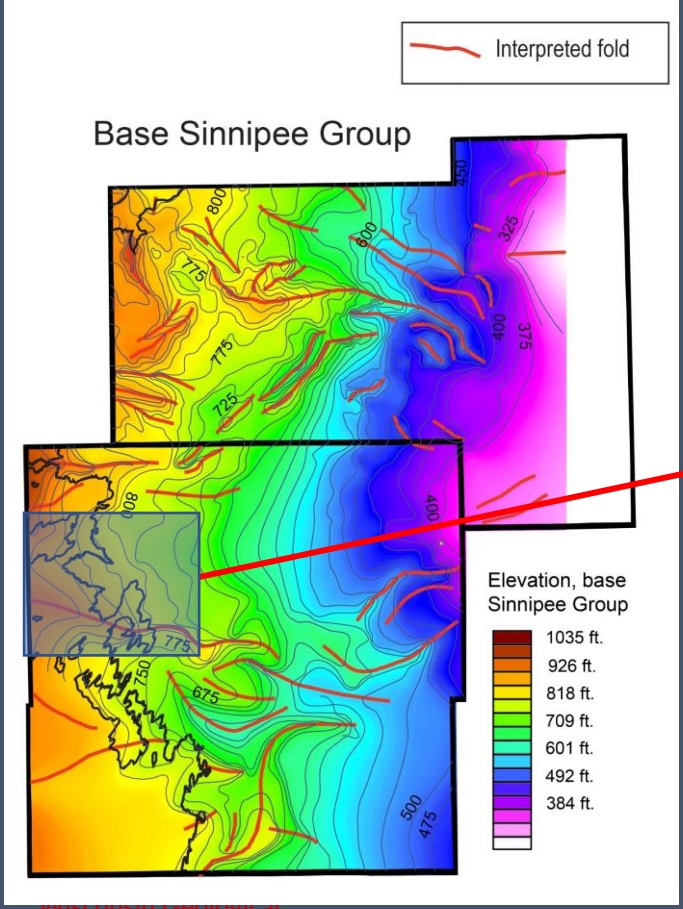
Additonal Comments? — Owner Sent Label? Y — Variance Issued? — More Geology?
Batch 381

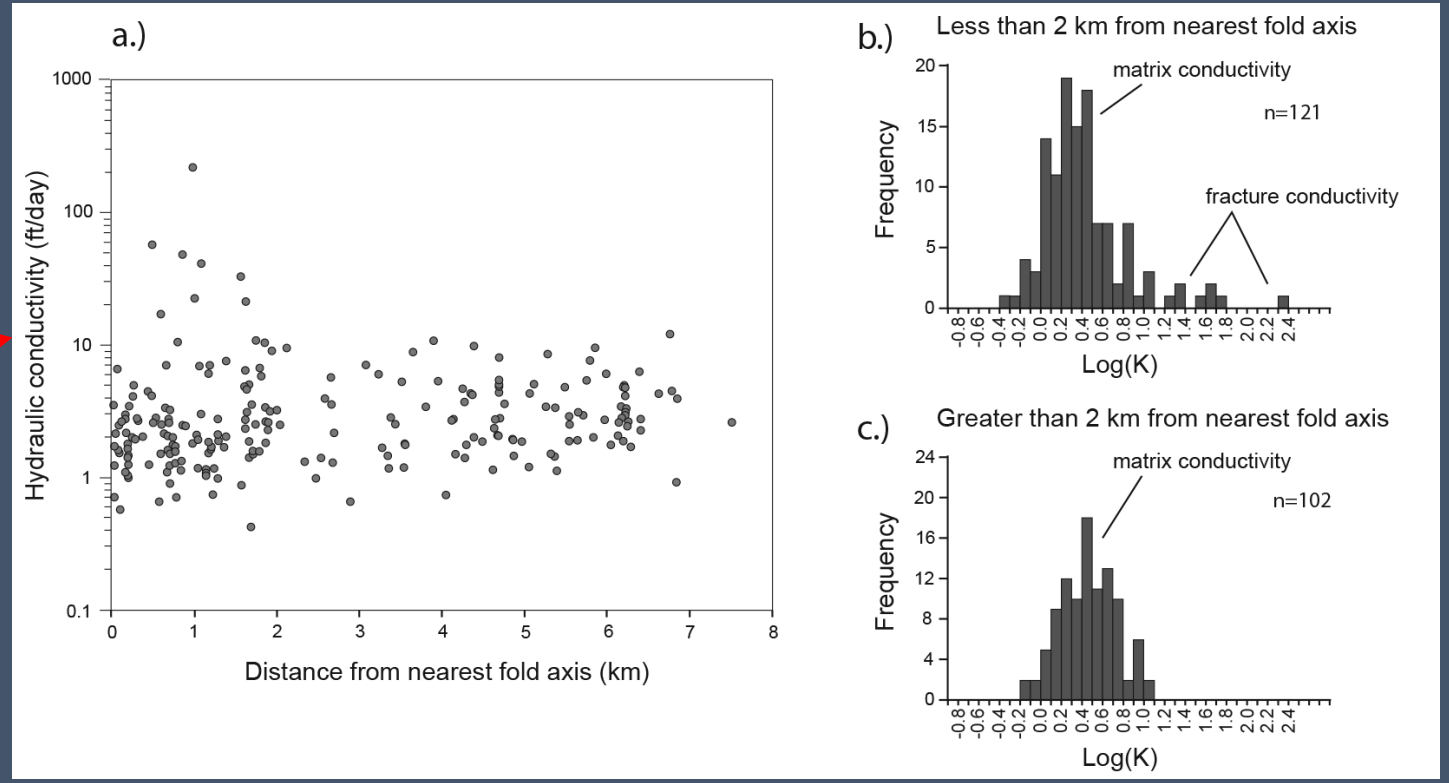
Hydraulic conductivity (K) = measure of how easily water moves through rock

Testing the field and core observations with well data

- Estimated hydraulic conductivity (K) from specific capacity tests in wells (Bradbury and Rothschild, 1985)
- High K values in the St. Peter Formation tend to concentrate near mapped structures, suggesting they may be areas of increased fracturing and groundwater flow

Hydraulic conductivity (K) = measure of how easily water moves through rock

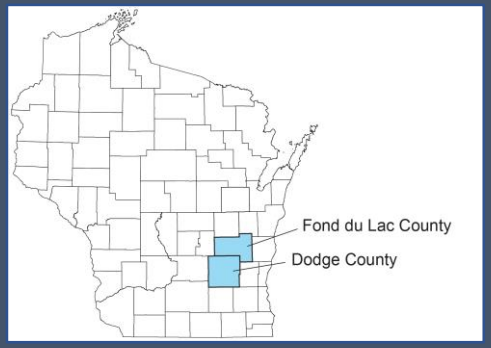




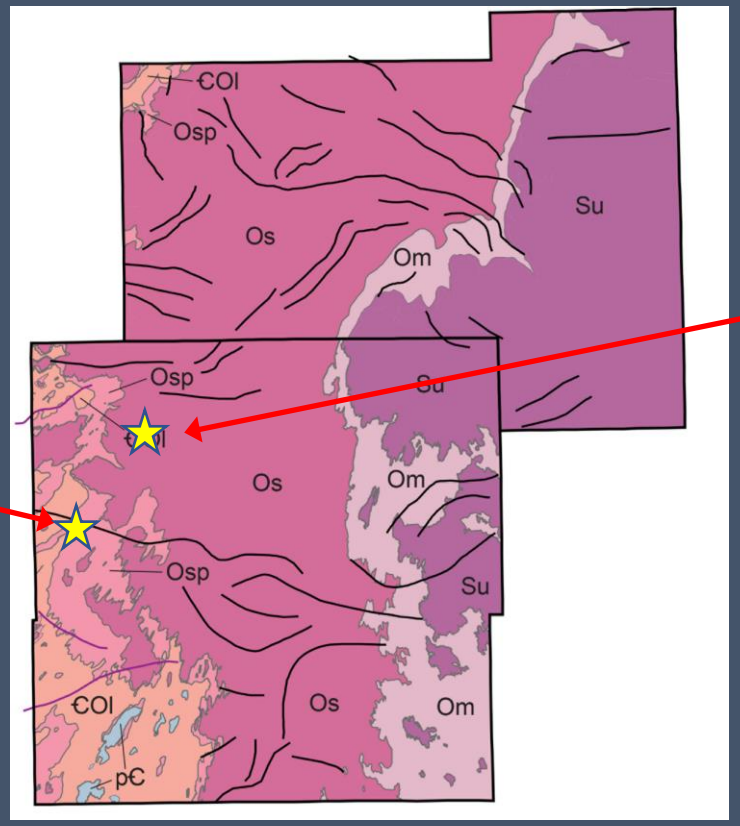
Stewart and others (2021)

Fracturing in core in Dodge County

- Mississippi Valley type sulfide mineralization common in Paleozoic section
- Iron sulfides contain arsenic impurities that can lead to well contamination

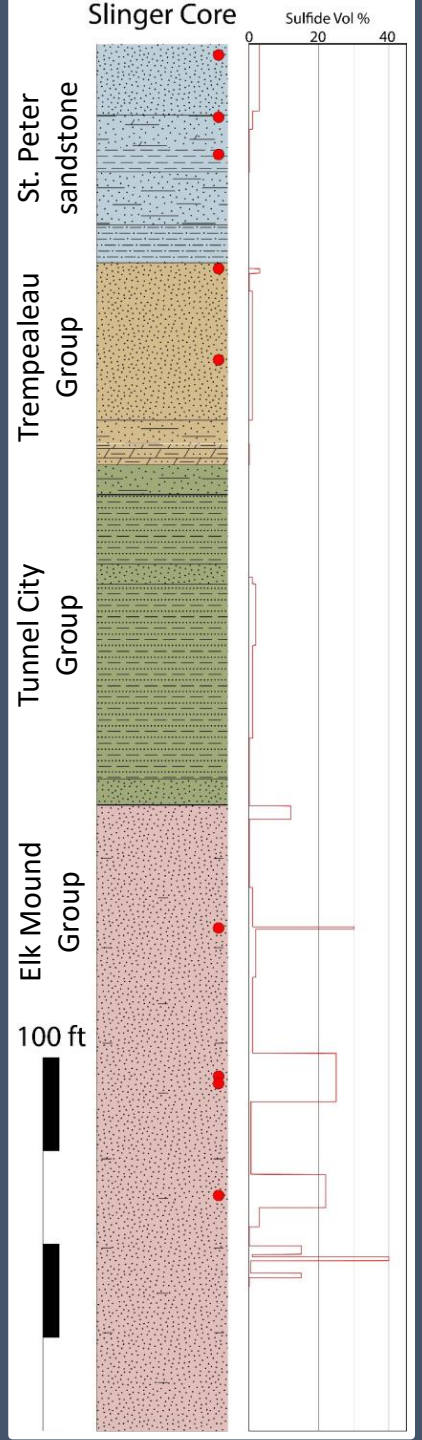


Near mapped folds, fracture density is higher and sulfides often fill vertical fractures



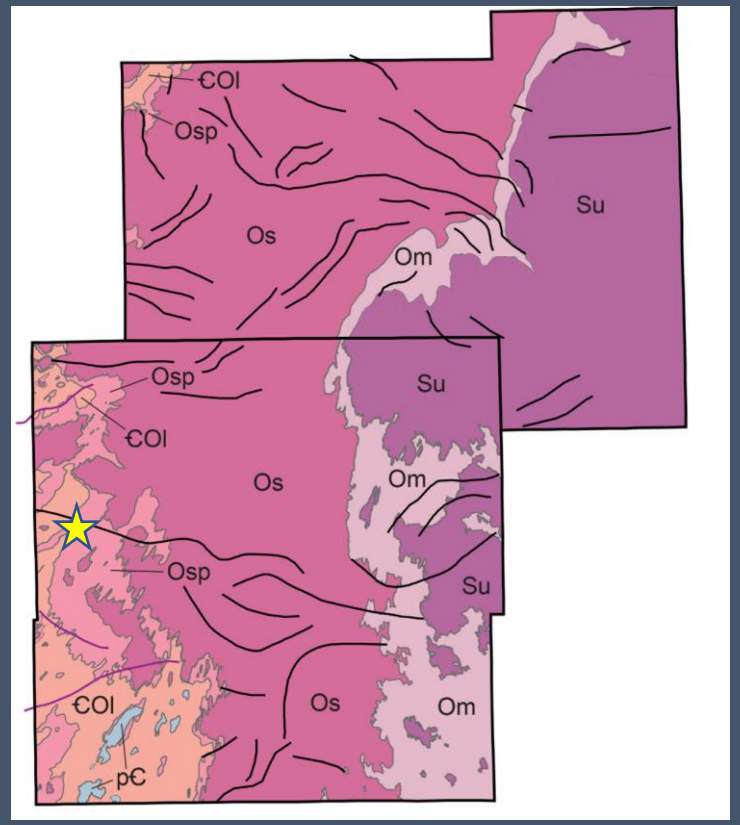
★ Core location

- From from folds/faults, little sulfide below the St. Peter Formation



- Near the Beaver Dam anticline, sulfides are more abundant than other cores, and present throughout the stratigraphic section.

Dodge County
Highlighted stars = core locations



★ Core location

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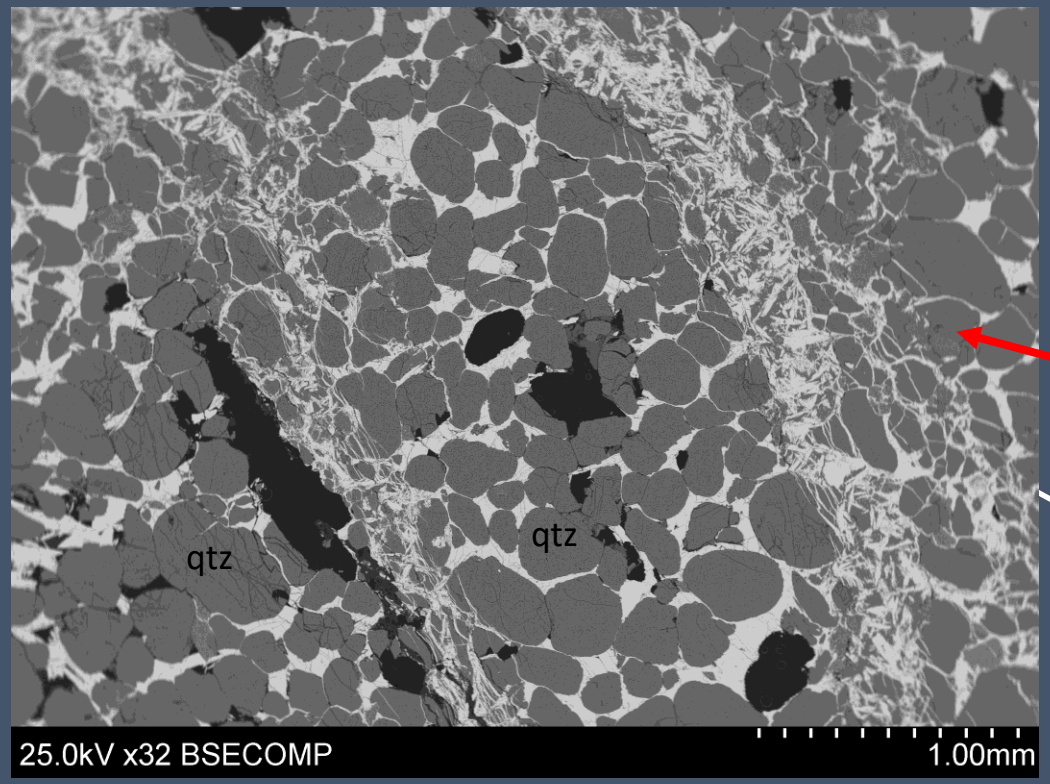
Sulfide mineralization

BSE image

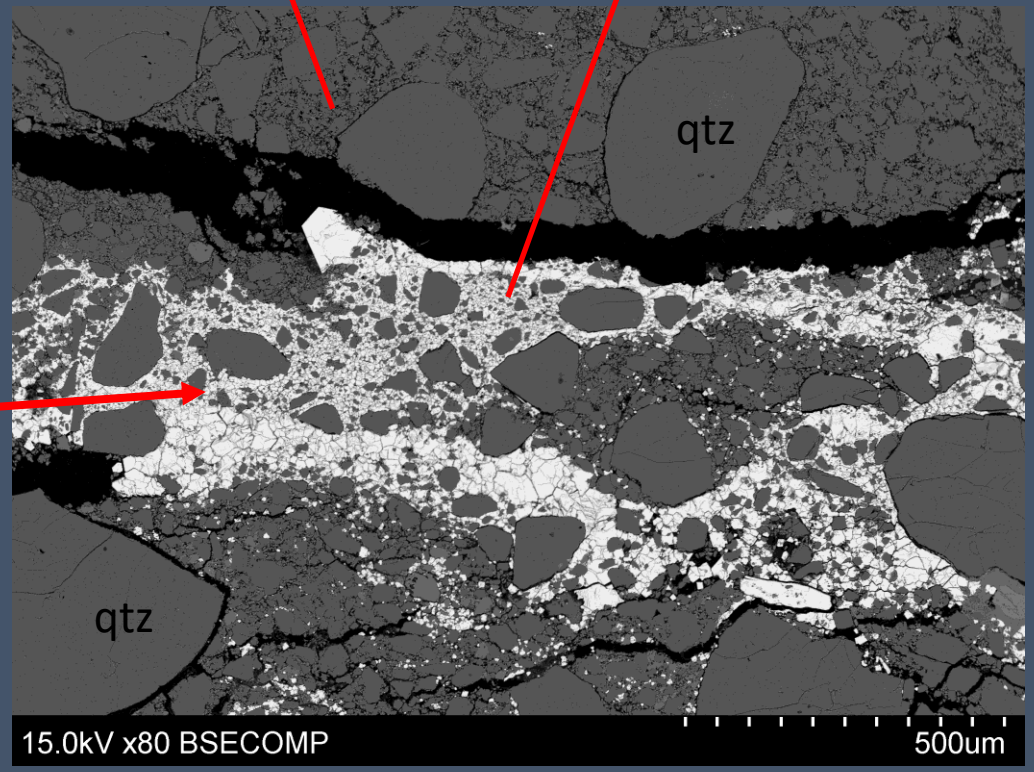


Marcasite-rich bands and cement (light gray)

Qtz+marcasite matrix

Qtz+dolomite matrix

BSE image



Cataclastic deformation bands with marcasite fill

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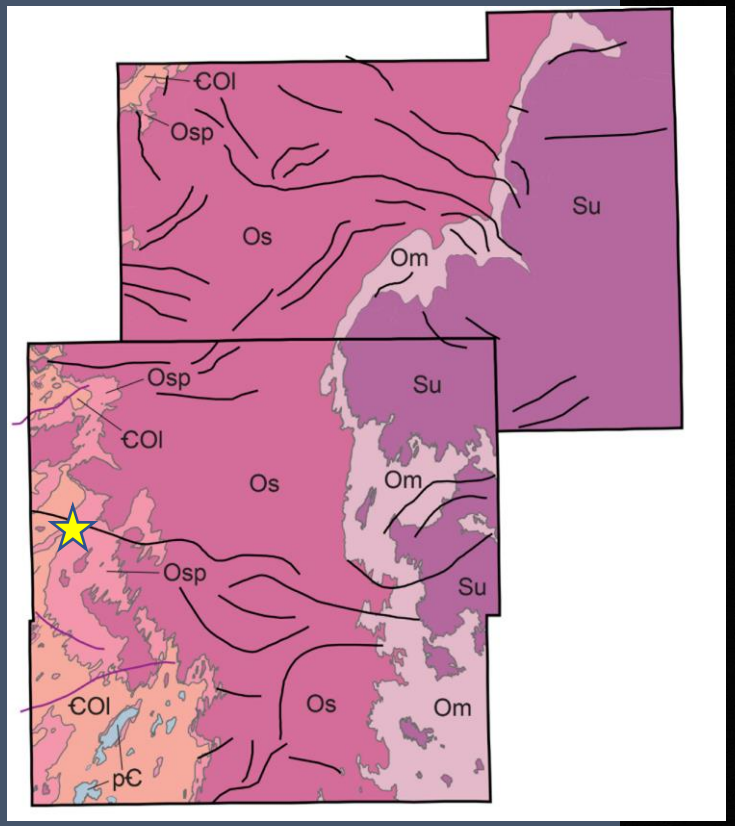
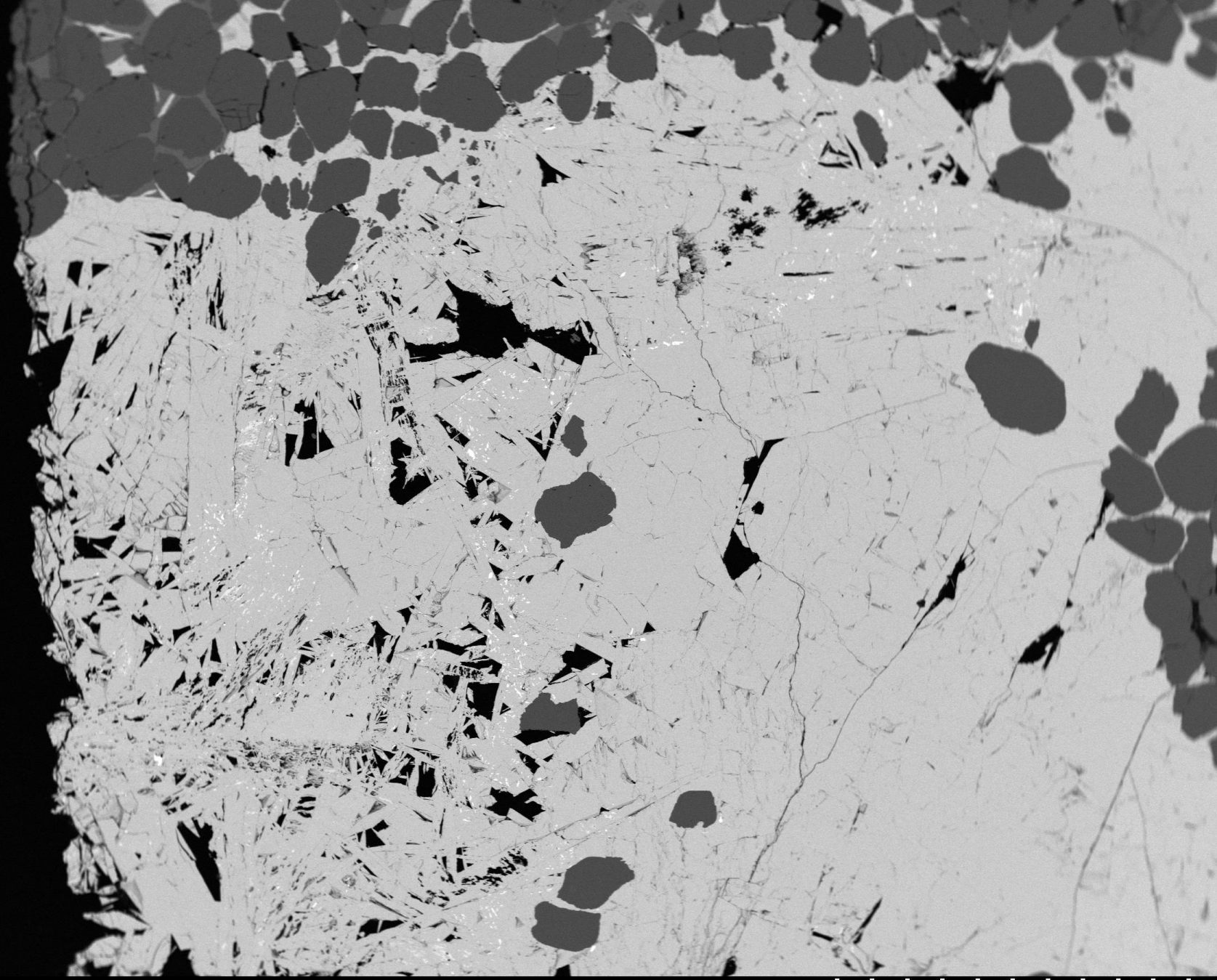


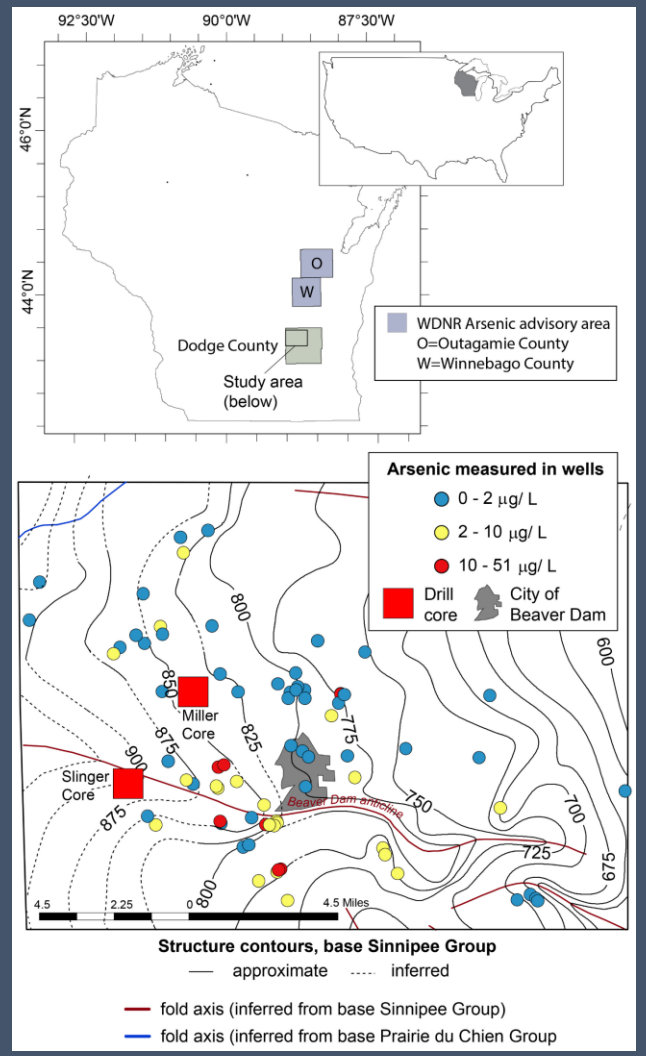
★ Core location



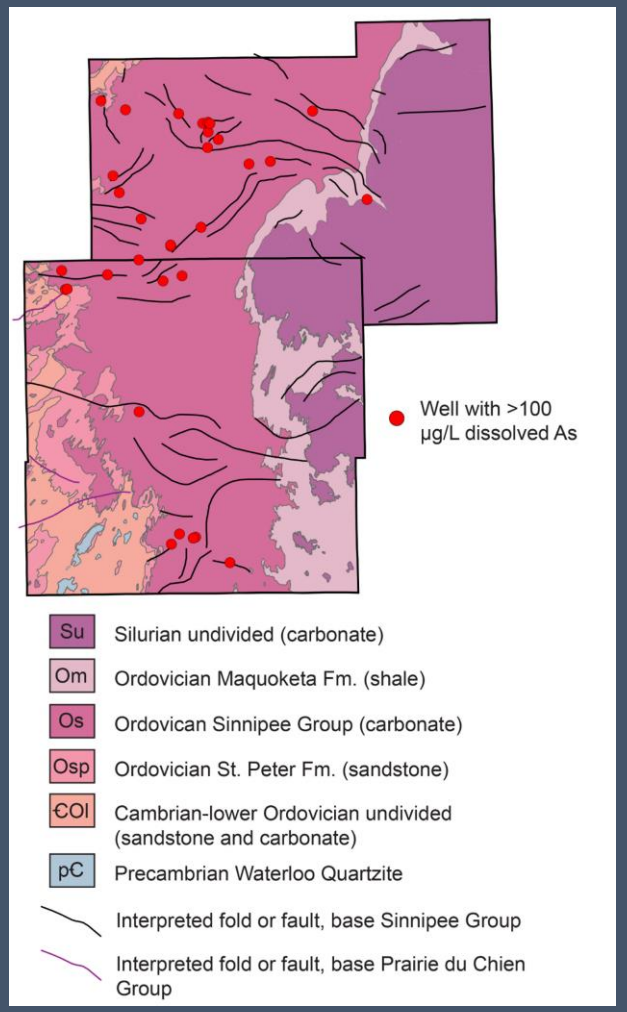
15.0kV x32 BSECOMP

1.00mm

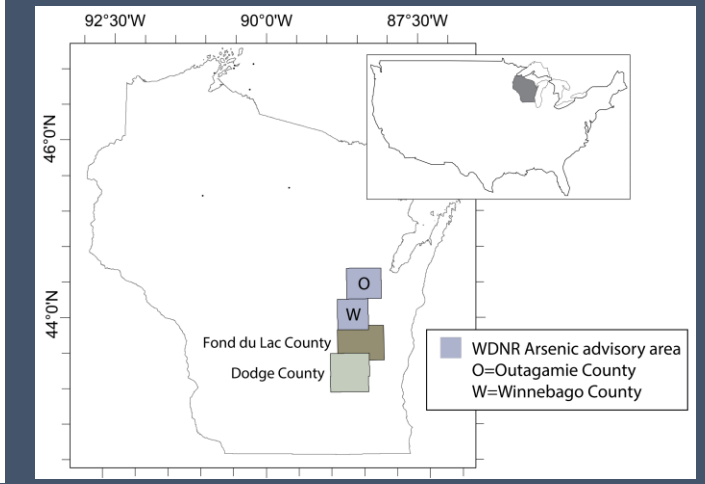
Groundwater data compilation – high, moderate and low arsenic values focused near mapped structures



Stewart and others (2021)



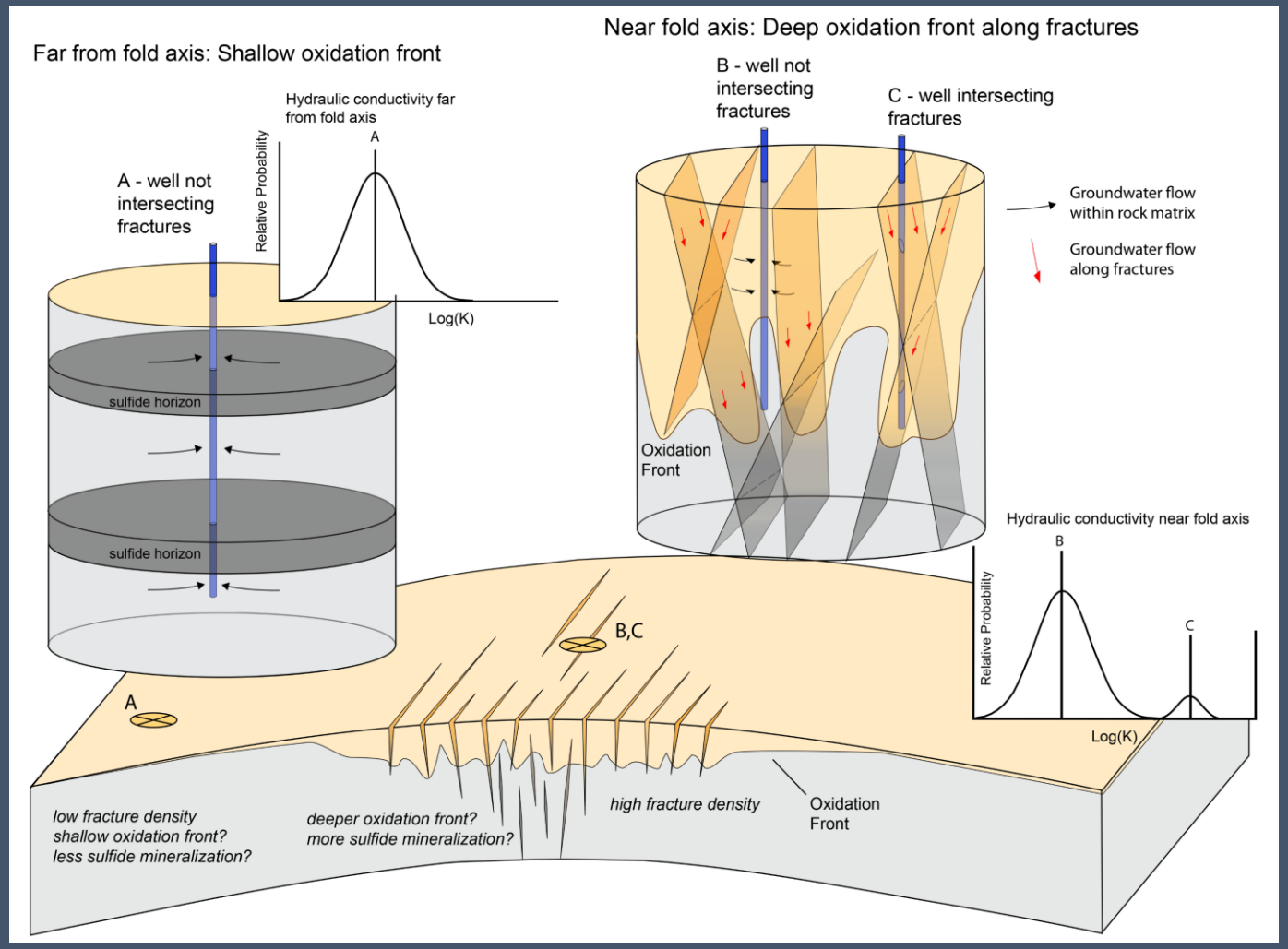
EPA limit is 10 µg/L



This map only shows groundwater wells with high arsenic values (>100µg/L)

Conceptual model – role of folds on hydraulic conductivity and arsenic detection

Higher fracture density near folds leads to more sulfide mineralization and/or a deeper oxidation front – perhaps higher arsenic risk for groundwater wells



Stewart and others (2021)

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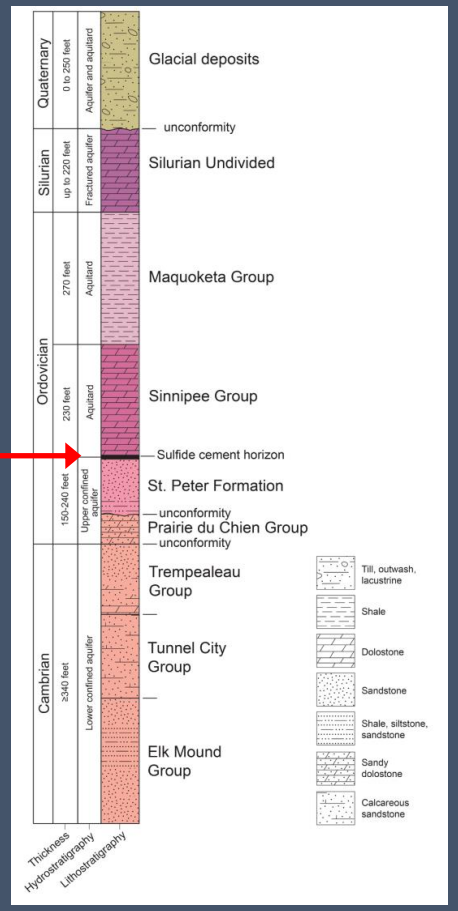
Overview

- Folds and faults in Paleozoic rocks of Wisconsin
  - They are very small –how do we find them and how do they form?
- How do folds and faults alter bedrock units?
- **Stratigraphic and well construction controls on arsenic in wells**
- What matters to communities?
  - GRAC project investigating a link between groundwater contamination and folding
- Summary – What we've learned

Other causes of arsenic in groundwater wells

- Stratigraphic control

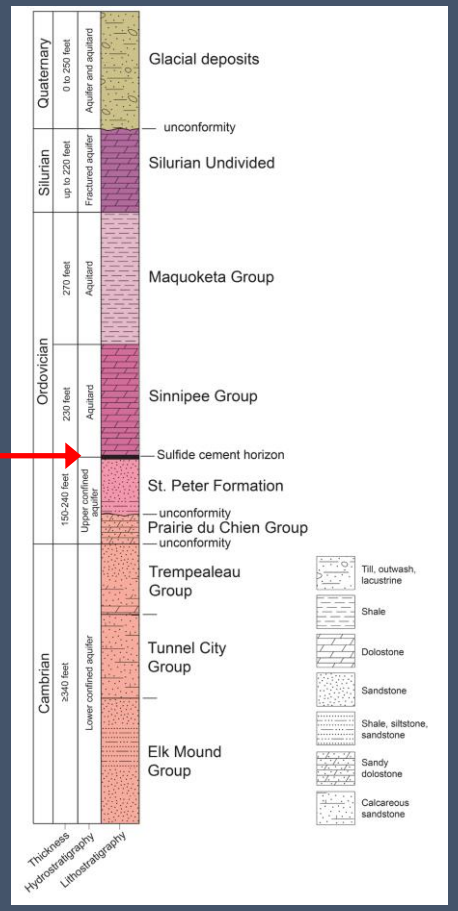
Sulfide cement horizon (SCH) High in arsenic



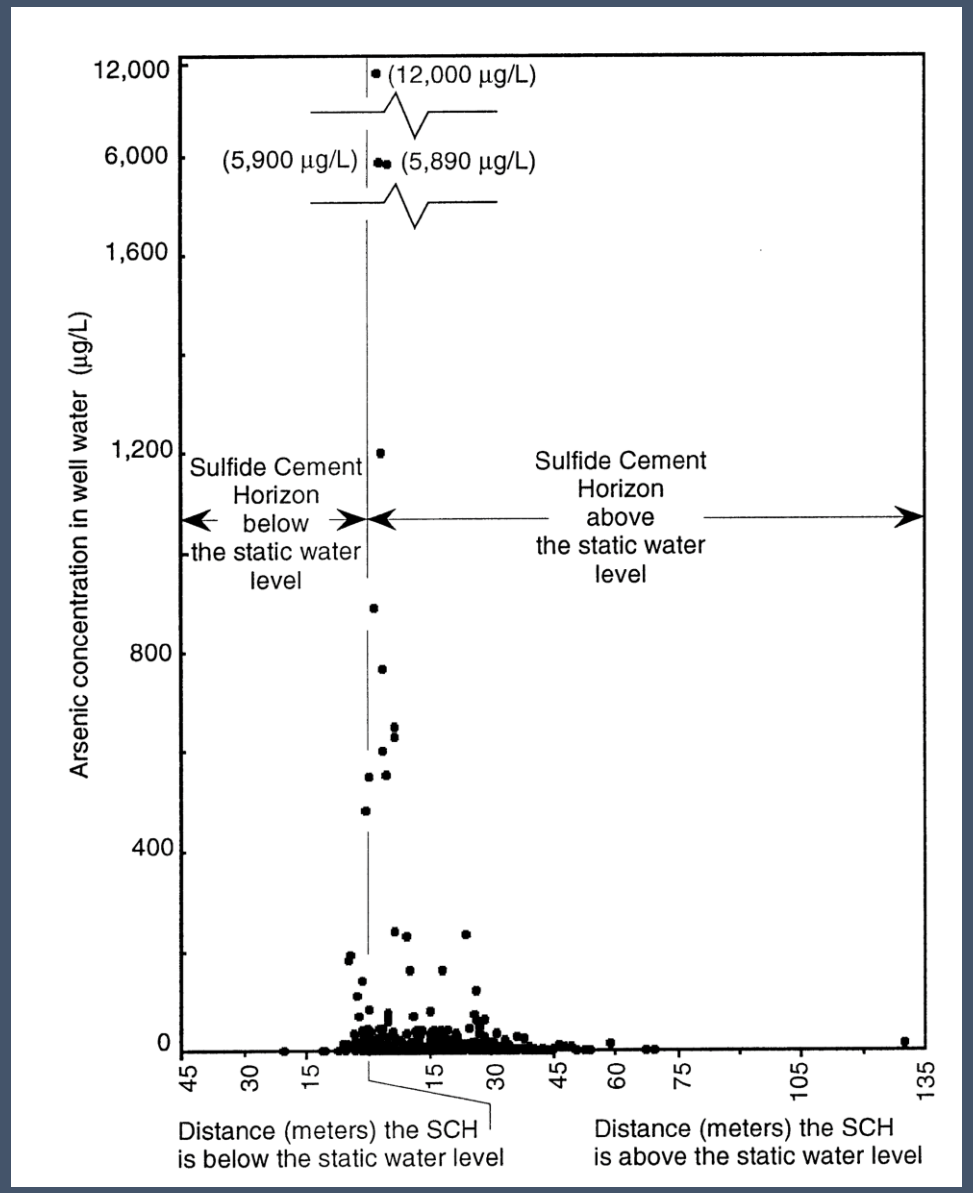
Stratigraphic sources leading to elevated arsenic?

- Sulfide cement horizon (SCH) is a major source of high arsenic concentrations in Winnebago and Outagamie counties

Sulfide cement horizon (SCH)



Role of stratigraphy - Schreiber et al. 2000



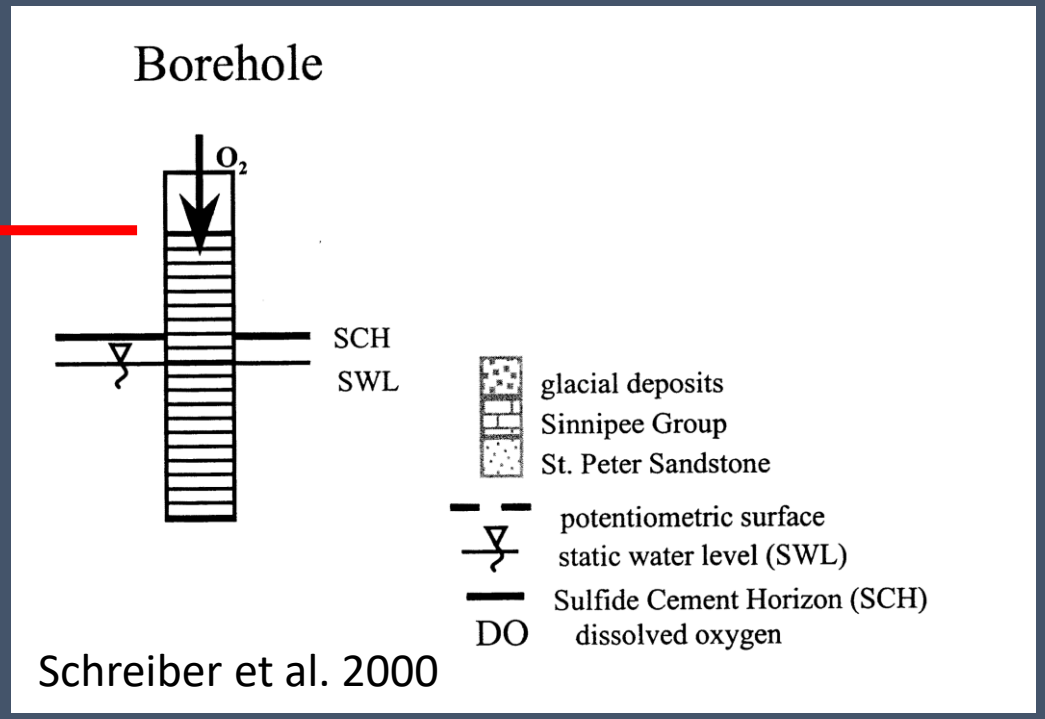
What about stratigraphic sources and well construction characteristics?

- Sulfide cement horizon (SCH) is a major source of high arsenic concentrations in Winnebago and Outagamie counties

Role of well construction - Schreiber et al. 2000

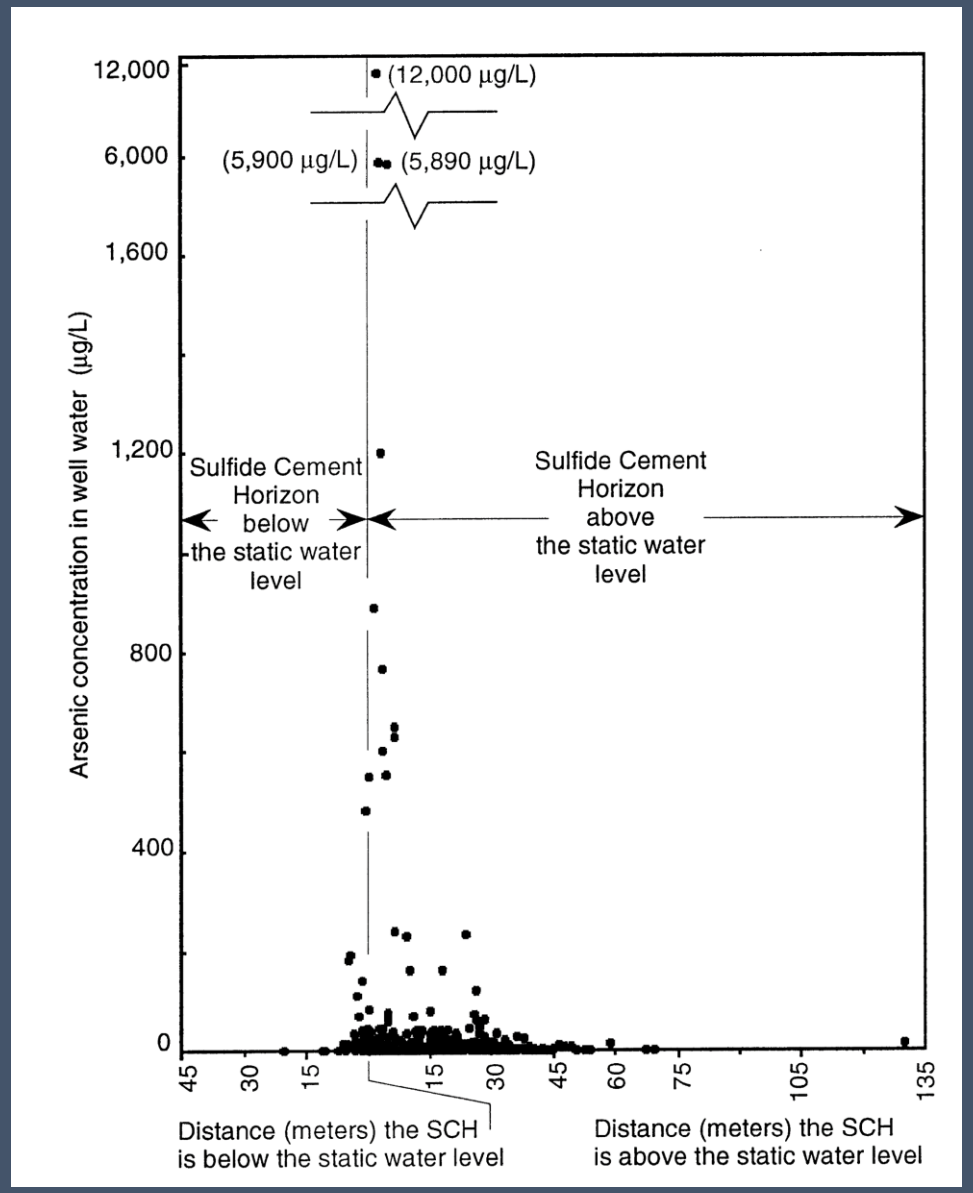
Casing present

Casing not present



Schreiber et al. 2000

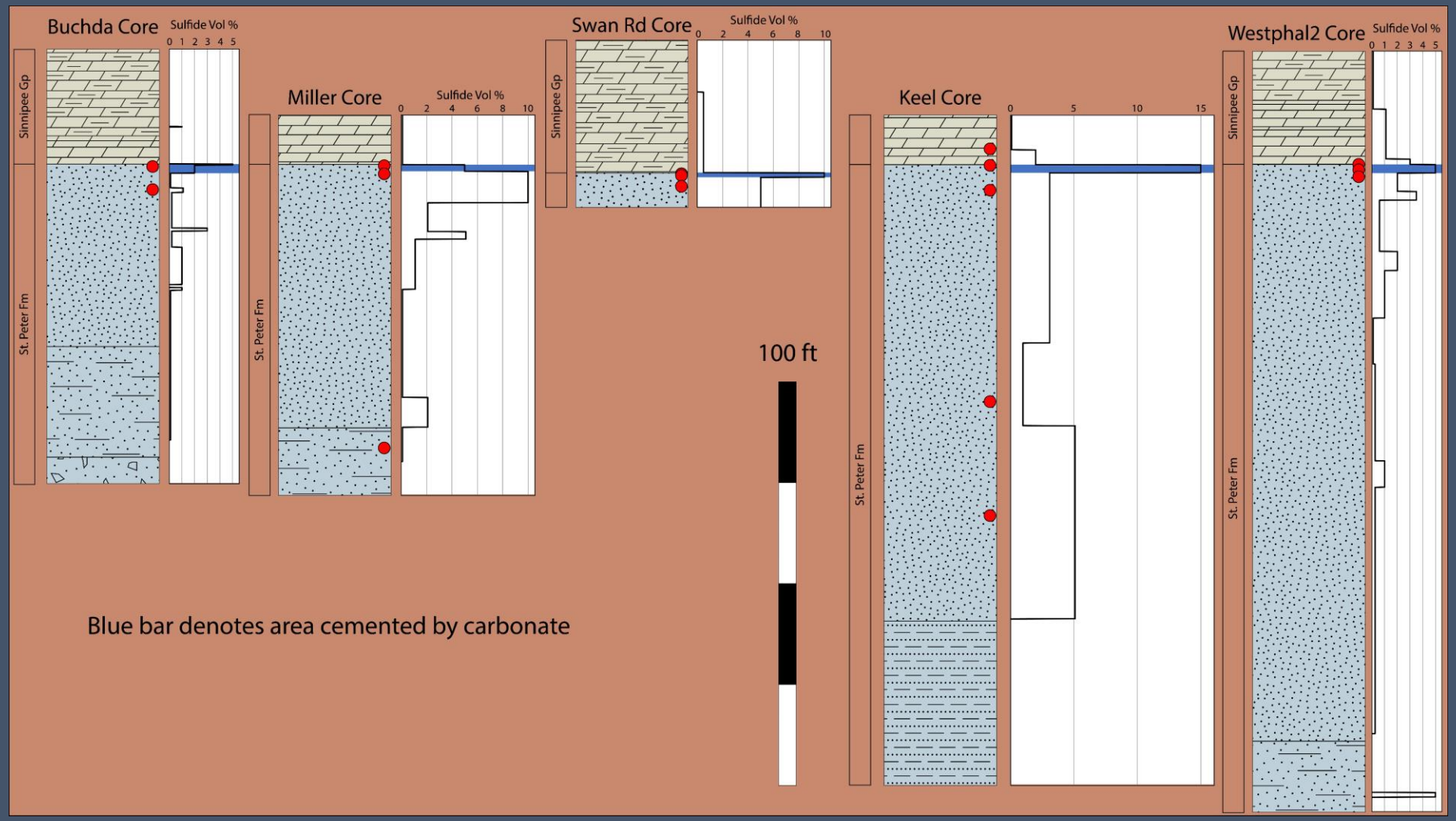
Role of stratigraphy - Schreiber et al. 2000



Far from folds and faults, sulfides are focused in the St. Peter sandstone, particularly at the contact with the overlying Sinnipee Group

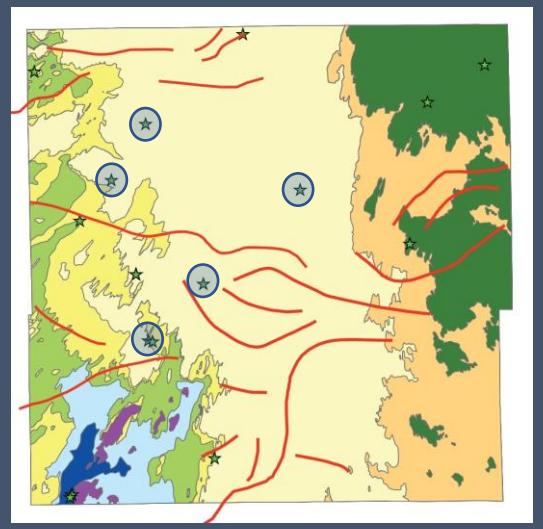
North

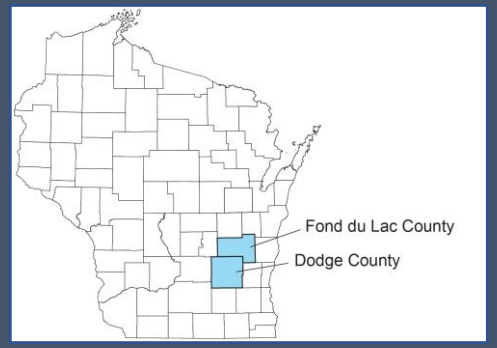
South



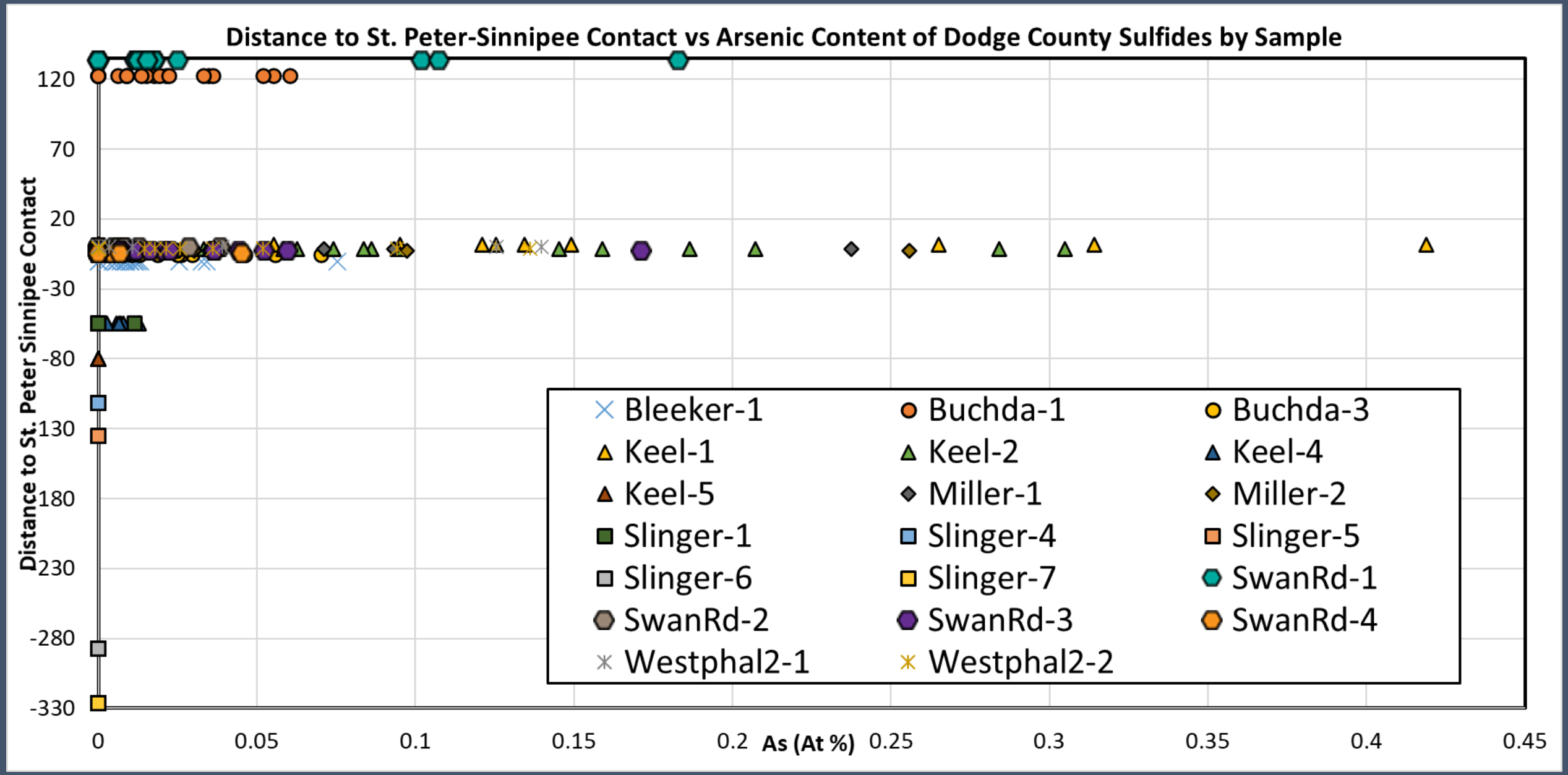
Dodge County

Highlighted stars = core locations





Typical iron sulfide grain composition (electron microprobe data)



Despite the abundance of iron sulfide, little arsenic low in section

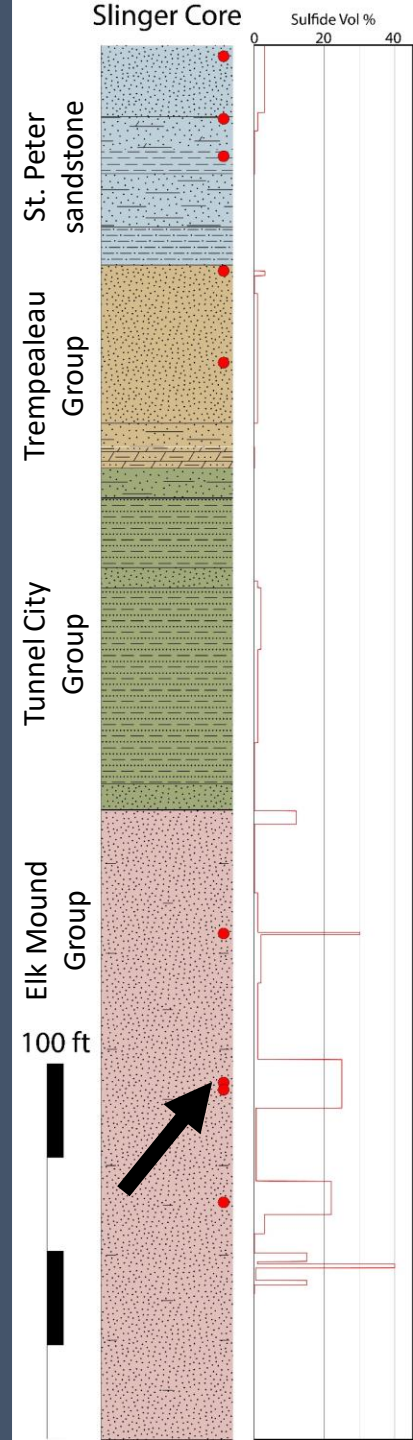
Sulfide vein and sulfide cemented sandstone

- 57% SiO2
- 17.4 wt% Fe
- **< 5 ppm arsenic**
- 18 wt% S

Whole-rock geochemistry

Sulfide vein and sulfide cemented sandstone

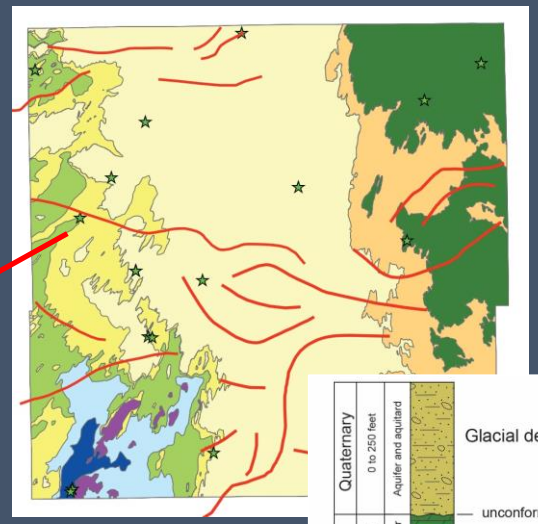
- 63.2 wt% SiO2
- 13.15 wt% Fe
- **< 5 ppm arsenic**
- 12.35 wt% S

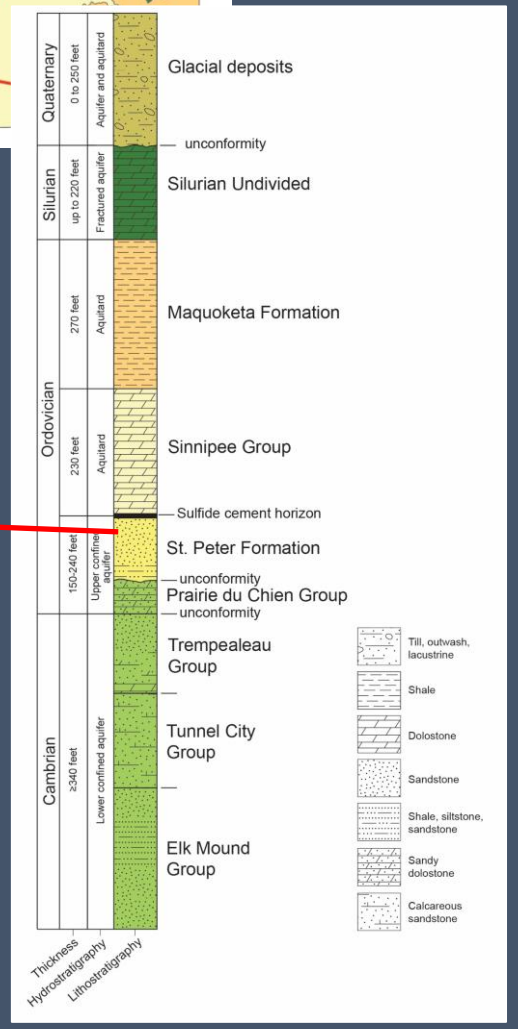


Other well construction characteristics leading to increased arsenic potential in wells – Fe-(hydr)oxides present near bedrock surface

- Sulfides can be oxidized, particularly near the bedrock surface (near atmosphere)
- Fe-(hydr)oxides strongly adsorb dissolved As
- If Fe-(hydr)oxides become unstable in the well borehole, they can release As into well water (e.g. Gotkowitz et al., 2004)

Oxidized sulfide vein





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Whole-rock composition

Wells not cased far below the bedrock surface may be more prone to arsenic problems

Oxide-cemented sandstone

- 95.6% SiO_2
- 1.61 Fe_2O_3
- **4.5 ppm arsenic**

Oxide-cemented sandstone

- 95.4% SiO_2
- 2.52 Fe_2O_3
- **4.7 ppm arsenic**

Oxidized sulfide concretion in sandstone

- 75.5 wt% SiO_2
- 19.05 wt% Fe_2O_3
- **155 ppm arsenic**
- 0.03 wt% S

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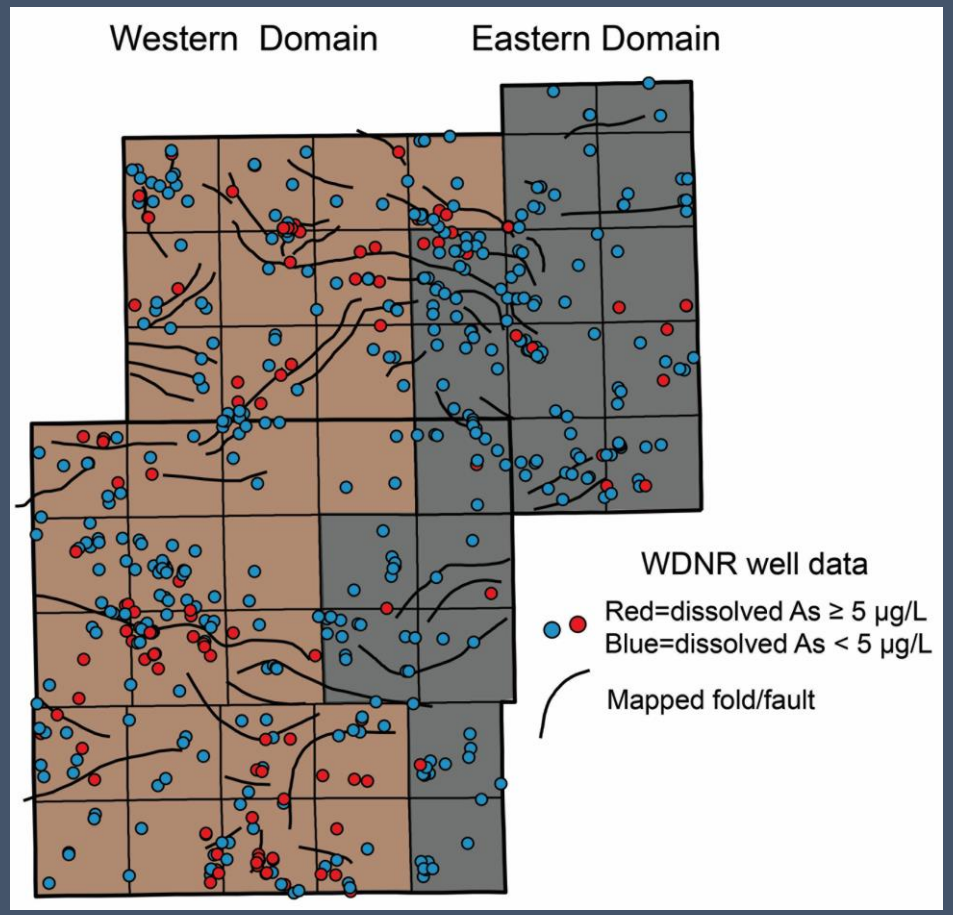
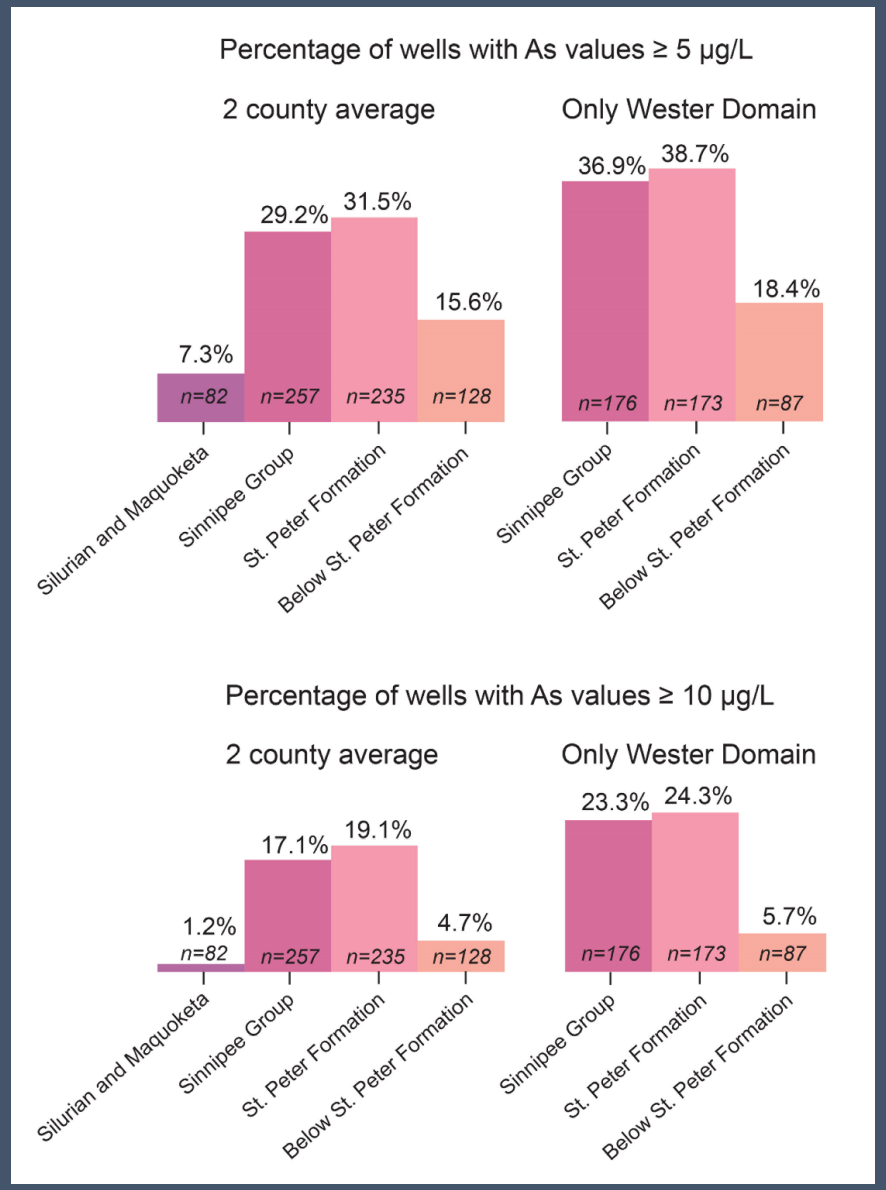
What about stratigraphic sources for low and moderate arsenic concentrations?

Geographic divide in counties – arsenic problems more common in west

EPA limit = 10 ug/L



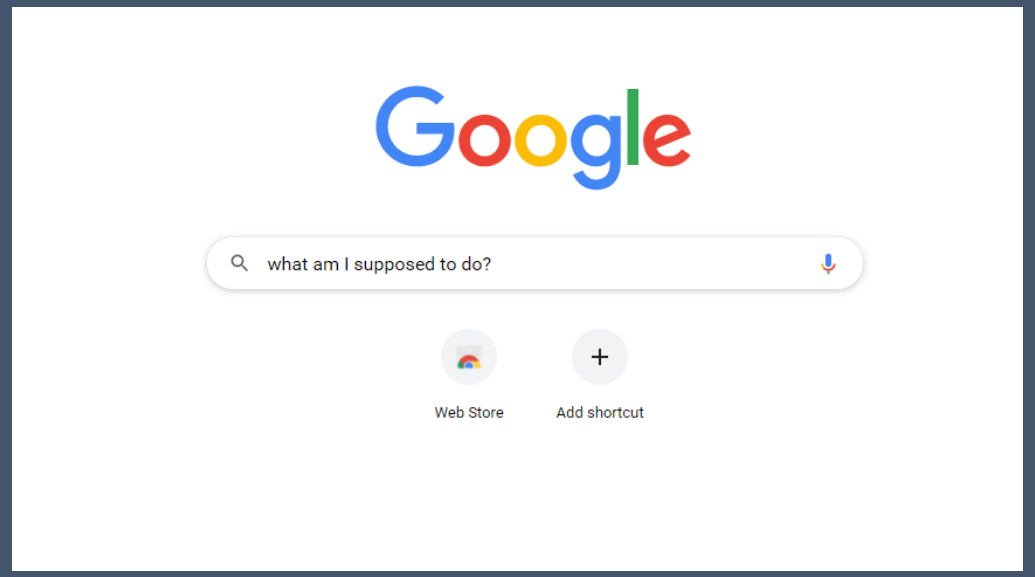


Overview

- Folds and faults in Paleozoic rocks of Wisconsin
  - They are very small –how do we find them and how do they form?
- How do folds and faults alter bedrock units?
- Stratigraphic and well construction controls on arsenic in wells
- **What matters to communities?**
  - **GRAC project investigating a link between groundwater contamination and folding**
- Summary – What we've learned

Need some sort of test to determine significance of observations

- Lots of variables might be contributing (folds/faults, sulfide cement horizon, casing versus static water level, casing versus bedrock surface, stratigraphic unit), how do we know relative importance of each?
- Start with Google

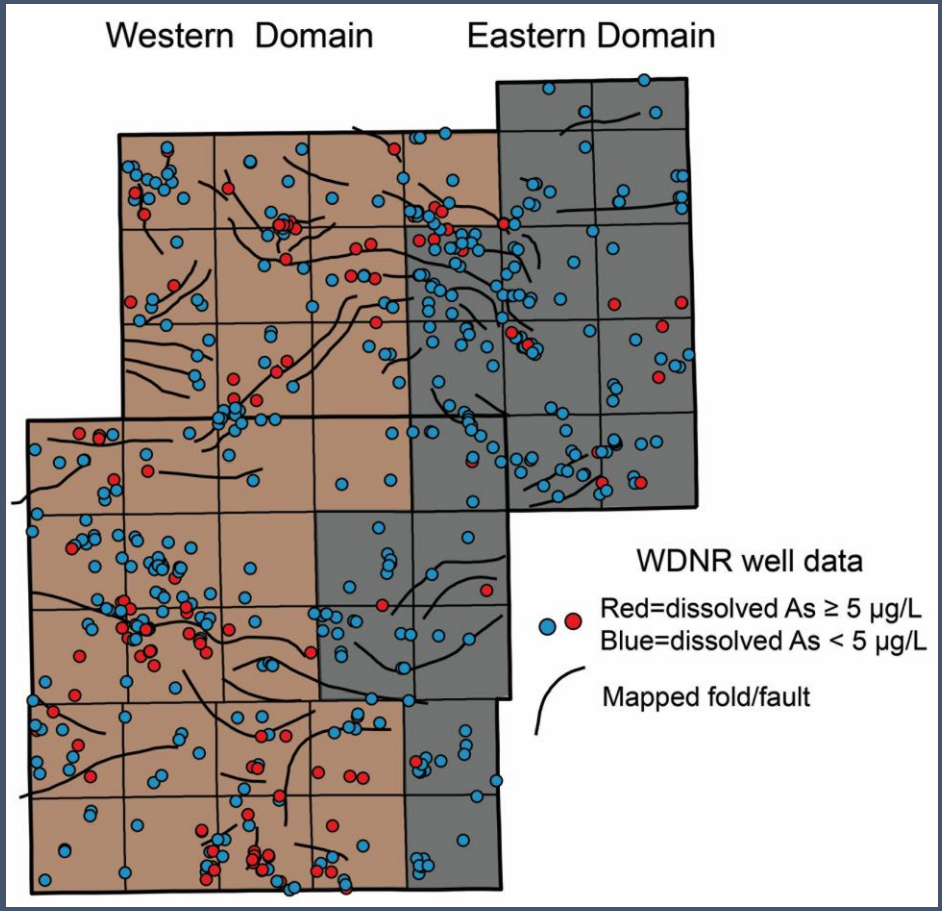


Logistic regression

Test the importance of folds and other variables using logistic regression, a tool that assesses whether a variable(s) changes the probability of an event occurring

Yes event ≥ x µg/L dissolved As (where x = 2, 5 or 10 µg/L)
No event < x µg/L dissolved As

Tested variables include geologic units, distance to nearest mapped fold, and different well construction parameters



n=464

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3 significant variables for each cutoff

Bold values are statistically significant results

Table 1 Final model (95% confidence intervals in parentheses)							
		2 µg/L cutoff (n=283)		5 µg/L cutoff (n=283)		10 µg/L cutoff (n=228)	
Variable	Variable Type	Variable (b_i) coefficient (multivariate)	Odds ratio	Variable (b_i) coefficient (multivariate)	Odds ratio	Variable (b_i) coefficient (multivariate)	Odds ratio
Intercept	N/A	**0.8398** (0.3556, 1.4274)	N/A	**-0.3082** (-0.8791, 0.2581)	N/A	**-0.3126** (-0.8671, 0.3436)	N/A
Distance to nearest fold axis	Continuous	**-0.3454** (-0.5215, -0.2254)	0.7079 (0.5936, 0.7982)	**-0.2553** (-0.4276, -0.1226)	0.7747 (0.6521, 0.8846)	**-0.2689** (-0.5821, -0.0900)	0.7642 (0.5587, 0.9139)
Well open to St. Peter Formation	Categorical	**0.6532** (0.1197, 1.2225)	1.9216 (1.1271, 3.3956)	**0.6805** (0.1910, 1.2400	1.9748 (1.2104, 3.4555)	N/A	N/A
Well open to units below St. Peter	Categorical	N/A	N/A	N/A	N/A	**-1.0684** (-2.9185, -0.1396)	0.3436 (0.0540, 0.8697)
Casing depth minus depth to bedrock	Continuous	**-0.0056** (-0.0092, -0.0026)	0.9945 (0.9908, 0.9974)	**-0.0058** (-0.0108, -0.0025)	0.9942 (0.9892, 0.9975)	N/A	N/A
Casing depth minus depth to static water level	Continuous	N/A	N/A	N/A	N/A	**-0.0125** (-0.0245, -0.0008)	0.9876 (0.9758, 0.9992)

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3 significant variables for each cutoff

Bold values are statistically significant results

Distance to nearest fold/fault significant at cutoffs of 2, 5 and 10

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Final model (95% confidence intervals in parentheses)

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3 significant variables for each cutoff

Bold values are statistically significant results

Role of St. Peter important at 2, 5 and 10

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3 significant variables for each cutoff

Bold values are statistically significant results

Well construction also important. At 10 µg/L casing depth relative to the static water level becomes significant

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Well open to St. Peter Formation	Categorical	**0.6532** (0.1197, 1.2225)	1.9216 (1.1271, 3.3956)	**0.6805** (0.1910, 1.2400	1.9748 (1.2104, 3.4555)	N/A	N/A
Well open to units below St. Peter	Categorical	N/A	N/A	N/A	N/A	**-1.0684** (-2.9185, -0.1396)	0.3436 (0.0540, 0.8697)
Casing depth minus depth to bedrock	Continuous	**-0.0056** (-0.0092, -0.0026)	0.9945 (0.9908, 0.9974)	**-0.0058** (-0.0108, -0.0025)	0.9942 (0.9892, 0.9975)	N/A	N/A
Casing depth minus depth to static water level	Continuous	N/A	N/A	N/A	N/A	**-0.0125** (-0.0245, -0.0008)	0.9876 (0.9758, 0.9992)

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How can we use these results? Model risk and impact of regulations

Bold values are statistically significant results

Table 1 Final model (95% confidence intervals in parentheses)							
		2 µg/L cutoff (n=283)		**5 µg/L cutoff (n=283)**		**10 µg/L cutoff (n=228)**	
Variable	Variable Type	Variable (b_i) coefficient (multivariate)	Odds ratio	Variable (b_i) coefficient (multivariate)	Odds ratio	Variable (b_i) coefficient (multivariate)	Odds ratio
Intercept	N/A	**0.8398** (0.3556, 1.4274)	N/A	**-0.3082** (-0.8791, 0.2581)	N/A	**-0.3126** (-0.8671, 0.3436)	N/A
Distance to nearest fold axis	Continuous	**-0.3454** (-0.5215, -0.2254)	0.7079 (0.5936, 0.7982)	**-0.2553** (-0.4276, -0.1226)	0.7747 (0.6521, 0.8846)	**-0.2689** (-0.5821, -0.0900)	0.7642 (0.5587, 0.9139)
Well open to St. Peter Formation	Categorical	**0.6532** (0.1197, 1.2225)	1.9216 (1.1271, 3.3956)	**0.6805** (0.1910, 1.2400	1.9748 (1.2104, 3.4555)	N/A	N/A
Well open to units below St. Peter	Categorical	N/A	N/A	N/A	N/A	**-1.0684** (-2.9185, -0.1396)	0.3436 (0.0540, 0.8697)
Casing depth minus depth to bedrock	Continuous	**-0.0056** (-0.0092, -0.0026)	0.9945 (0.9908, 0.9974)	**-0.0058** (-0.0108, -0.0025)	0.9942 (0.9892, 0.9975)	N/A	N/A
Casing depth minus depth to static water level	Continuous	N/A	N/A	N/A	N/A	**-0.0125** (-0.0245, -0.0008)	0.9876 (0.9758, 0.9992)

$$L = \boldsymbol{b_0} + \boldsymbol{b_1} x_1 + \boldsymbol{b_2} x_2 \ldots$$

$$\text{Probability} = \frac{e^L}{(1+e^L)}$$

Where x_i are significant variables from the previous slide → Variables known for 3200 wells in the two counties

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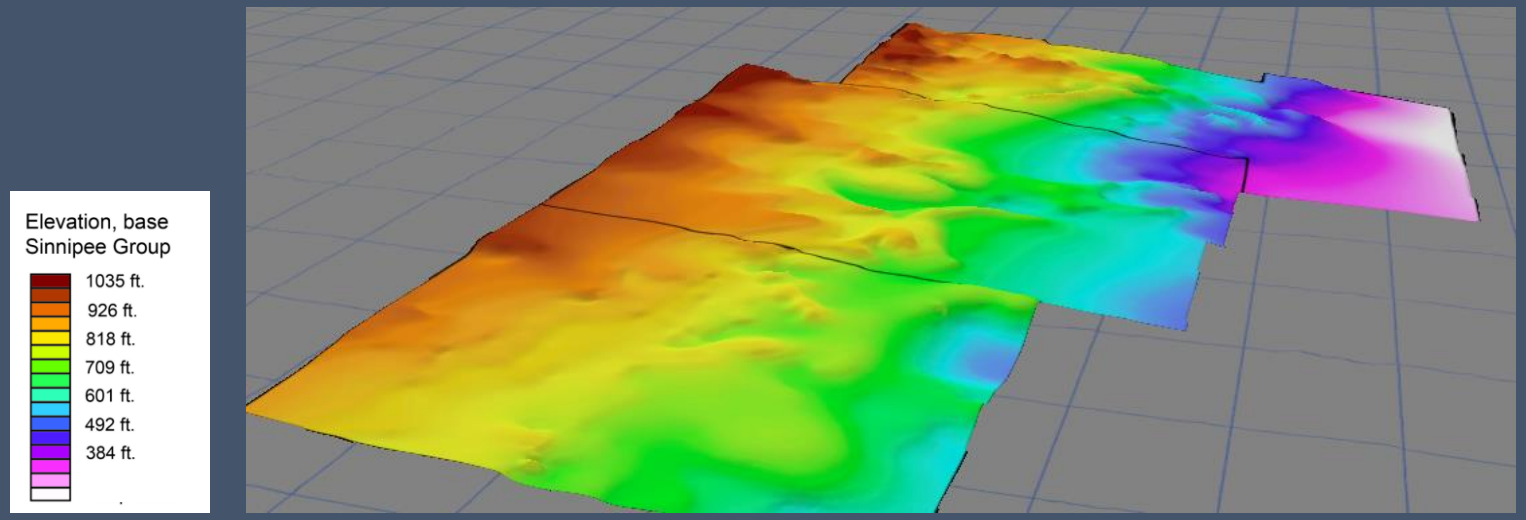

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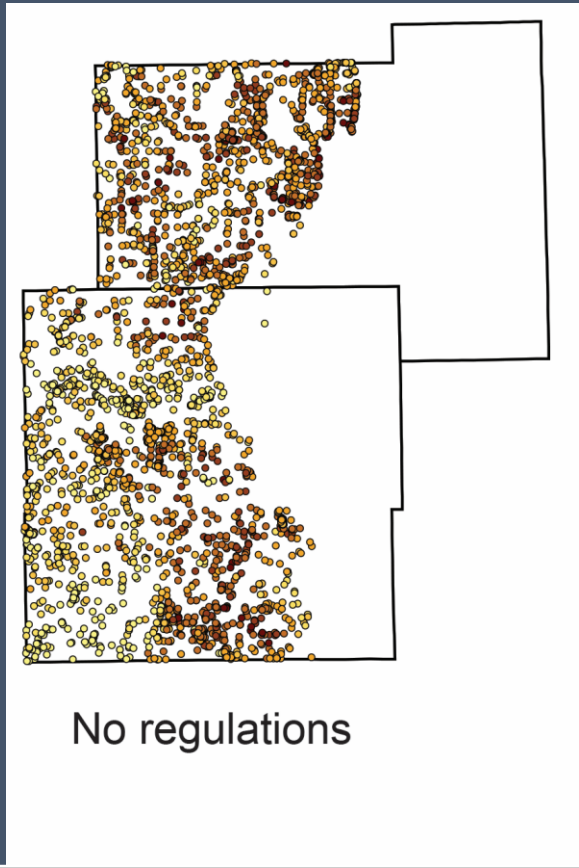
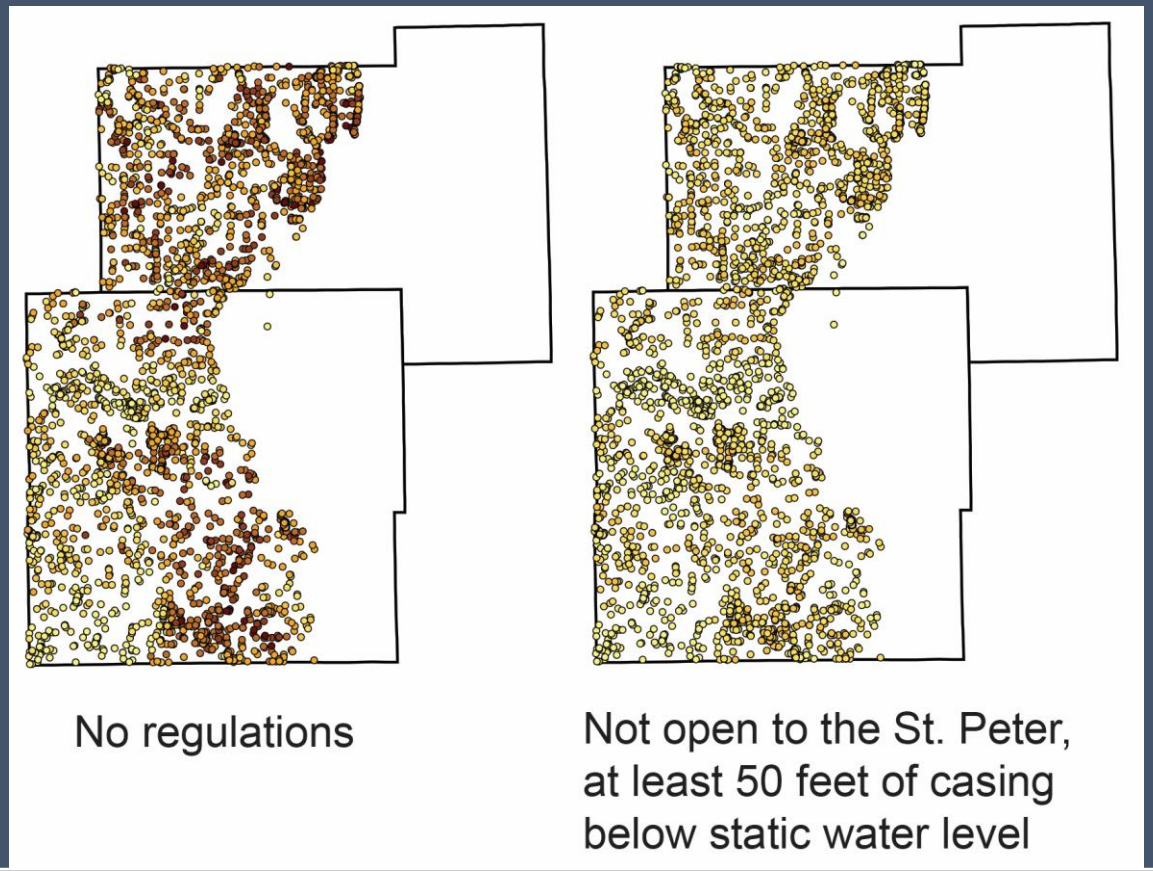


Probability groundwater well exceeds EPA limit in arsenic

- 0-5%
- 5-10%
- 10-15%
- 15-25%
- 25-35%
- 35-45%
- 45-62.5%

Impact of casing regulations for groundwater wells in western Dodge and Fond du Lac counties if all wells met criteria			
	Bulk average - No regulations		
Probability ≥2 µg/L	56.7%		
Probability ≥5 µg/L	35.4%		
Probability ≥ 10 µg/L	20.3%		

How can we use these results? Model risk and impact of regulations



Probability groundwater well exceeds EPA limit in arsenic

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Impact of casing regulations for groundwater wells in western Dodge and Fond du Lac counties if all wells met criteria			
	Bulk average - No regulations	Casing extends 50 feet below the static water level, and well cased through the St. Peter Fm.	
Probability ≥2 µg/L	56.7%	46.2%	
Probability ≥5 µg/L	35.4%	25.1%	
Probability ≥ 10 µg/L	20.3%	7.3%	

How can we use these results? Model risk and impact of regulations

Impact of casing regulations for groundwater wells in western Dodge and Fond du Lac counties if all wells met criteria			
	Bulk average - No regulations	Casing extends 50 feet below the static water level, and well cased through the St. Peter Fm.	Casing extends 100 feet below the static water level, and well cased through the St. Peter Fm
Probability ≥2 µg/L	56.7%	46.2%	40.6%
Probability ≥5 µg/L	35.4%	25.1%	20.7%
Probability ≥ 10 µg/L	20.3%	7.3%	4.3%

Summary

- Wells drilled near folds (faults?) have a higher probability of detecting arsenic, perhaps due to more sulfide or arsenic-bearing hydroxides
- Wells drilled in the St. Peter Formation have a higher probability of detecting arsenic
- It is best for groundwater wells to case far below the bedrock surface and the static water level
- The amount of arsenic contained in sulfide minerals decreases below the sulfide cement horizon, making the stratigraphically lower units safer
- Combining 3D geologic mapping with logistic regression allows us to predict risk as well as the impact of casing regulations, which could reduce, but not eliminate arsenic risk, particularly at higher concentrations