PSE Bringing science to energy policy

Impact to Groundwater Resources from Hydraulic Fracturing in the Pavillion, WY Field

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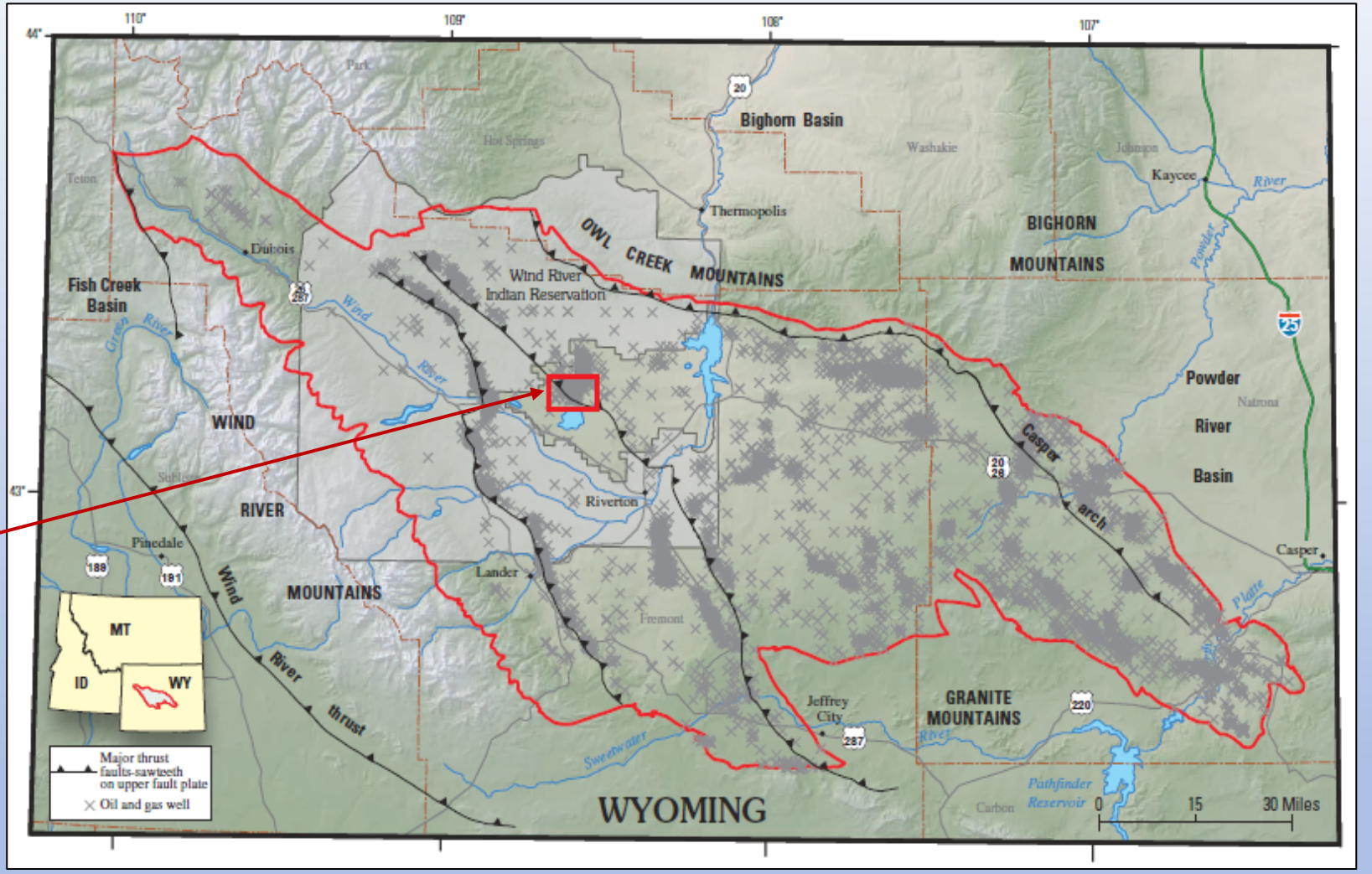
Photograph overlooking Pavillion Field

There is a need to protect fresh and brackish groundwater resources from all sources of degradation including those associated with oil and gas development.

Potential causes of degradation of groundwater resources include:

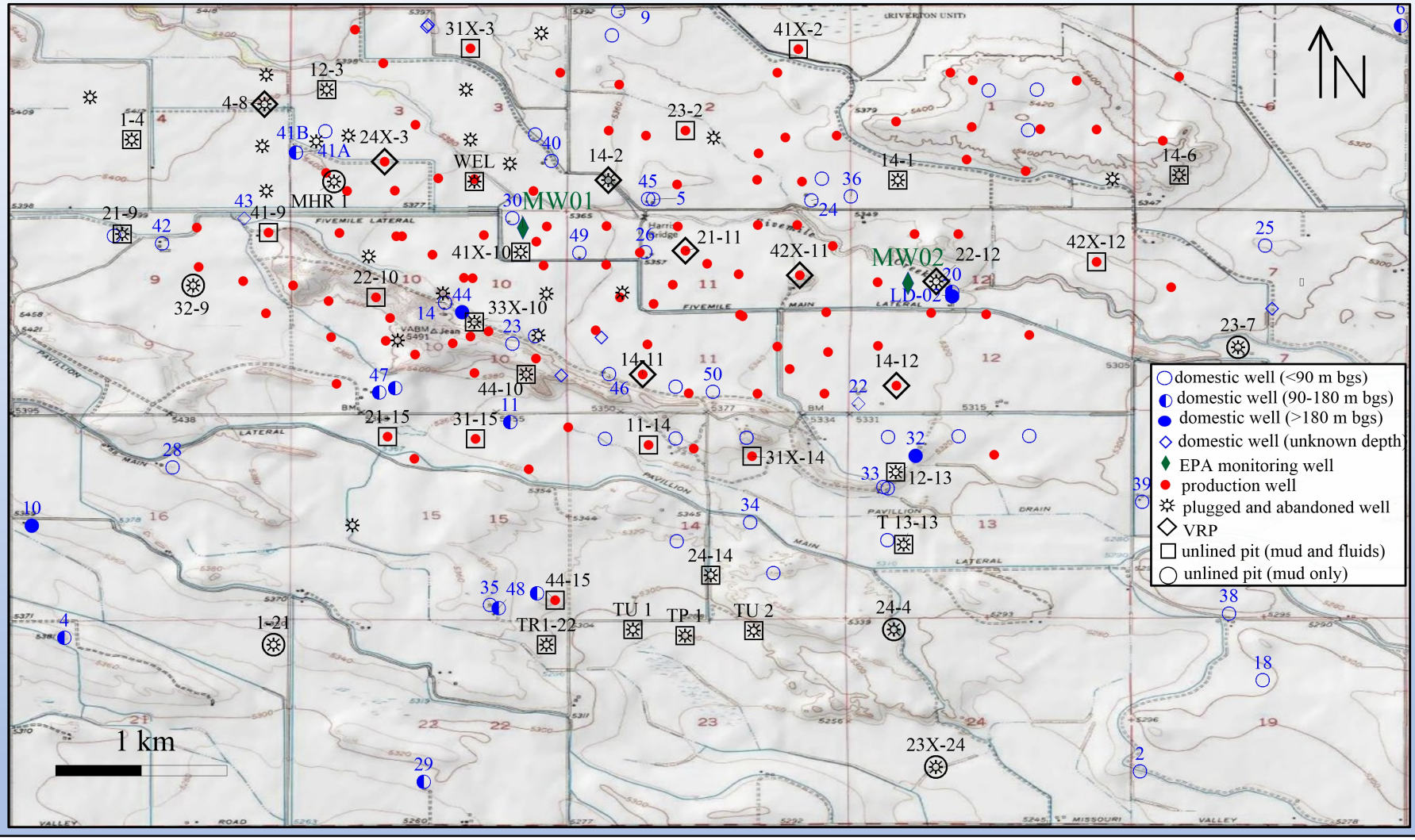
- Disposal of oil and gas wastewater into fresh and brackish aquifers (1,142,Class II disposal wells with aquifer exemptions)
- On and off pad spills of product and wastewater (thousands)
- Seepage of wastewater from impoundments and pits (In 1984, there were at least 122,000 unlined pits in U.S.).
- "Beneficial" use (disposal of wastewater using aquifer recharge, irrigation, and road spreading).
- Injection of stimulation fluids vertically near formations containing fresh and brackish groundwater
- Injection of stimulation fluids into formations containing fresh and brackish groundwater (occurrence and impact)

Pavillion, WY Field



Nelson and Kibler 2007

Center Portion of the Pavillion, WY Field



Shallow to unknown depth groundwater contamination due to disposal of diesel fuel based drilling mud and production fluids disposed in 64 unlined pits

Deeper groundwater (700 – 1000 ft) contamination from stimulation fluids.

Geology and Hydrocarbon Production in the Pavillion Field

Conventional development and hydraulic fracturing in Lower Tertiary Wind River and Fort Union Formations

Mostly gas, some oil migration via fault and fractured media

Primary source rocks

Pavillion Field

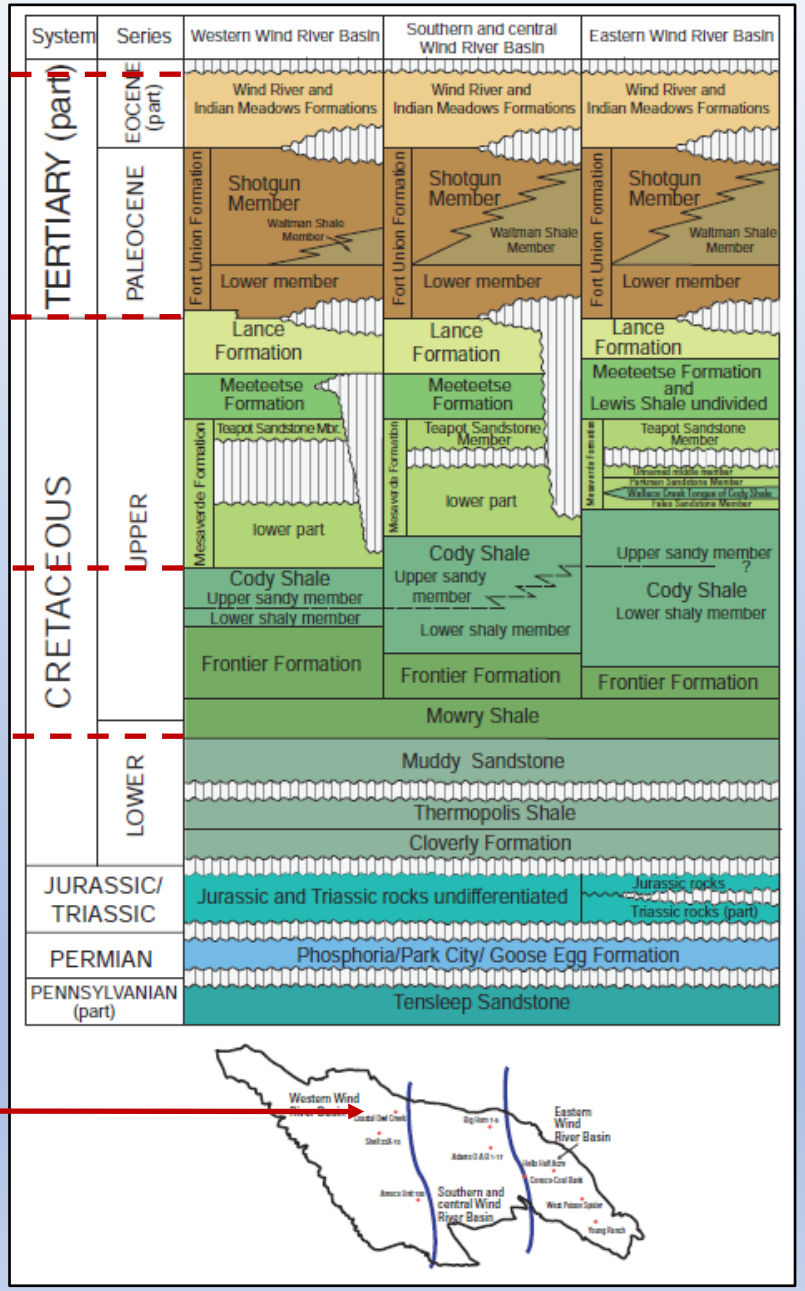
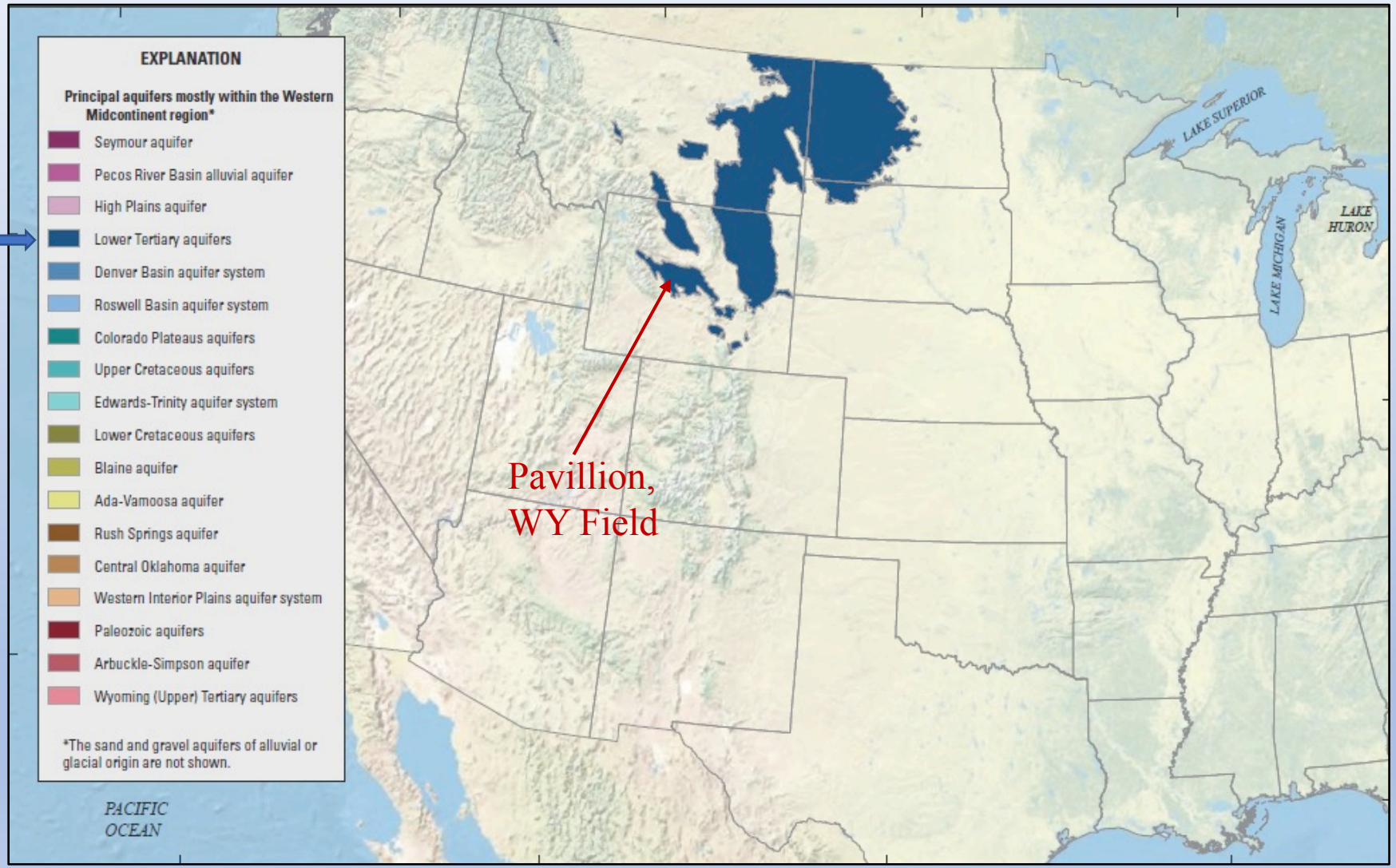


Figure modified from Roberts et al. (2007)

Principal Aquifer Systems in the Wind River Basin



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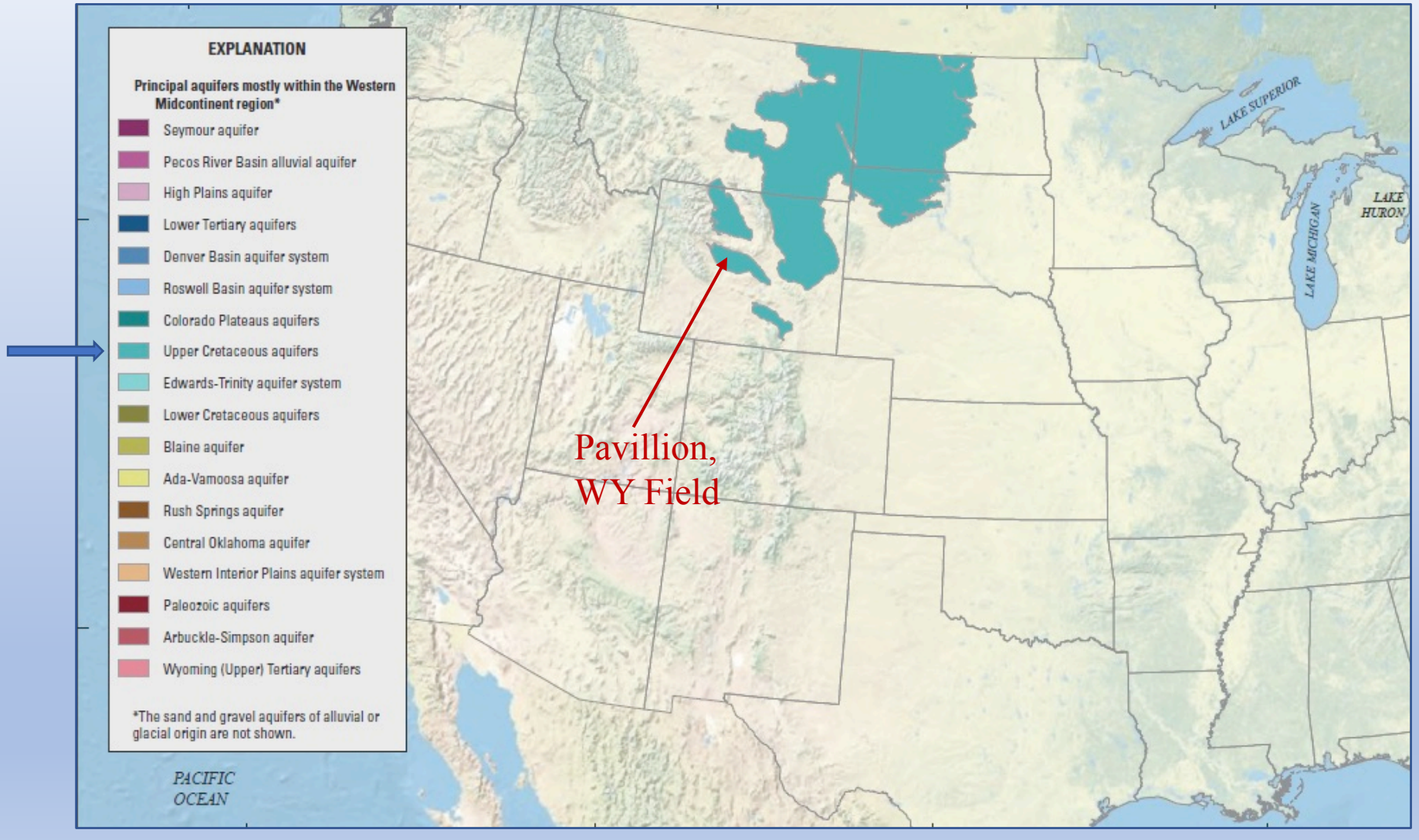

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Principal Aquifer Systems in the Wind River Basin

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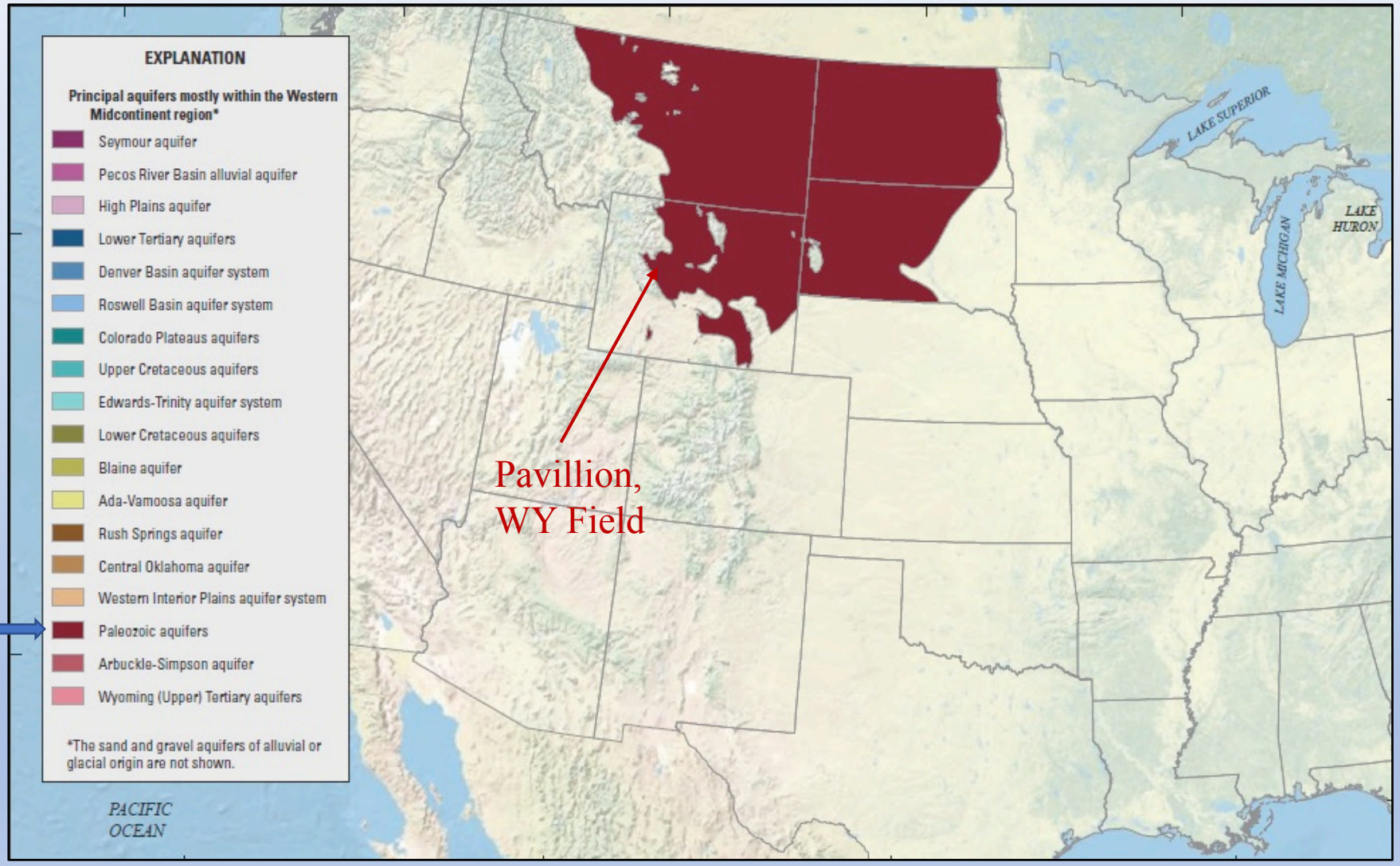
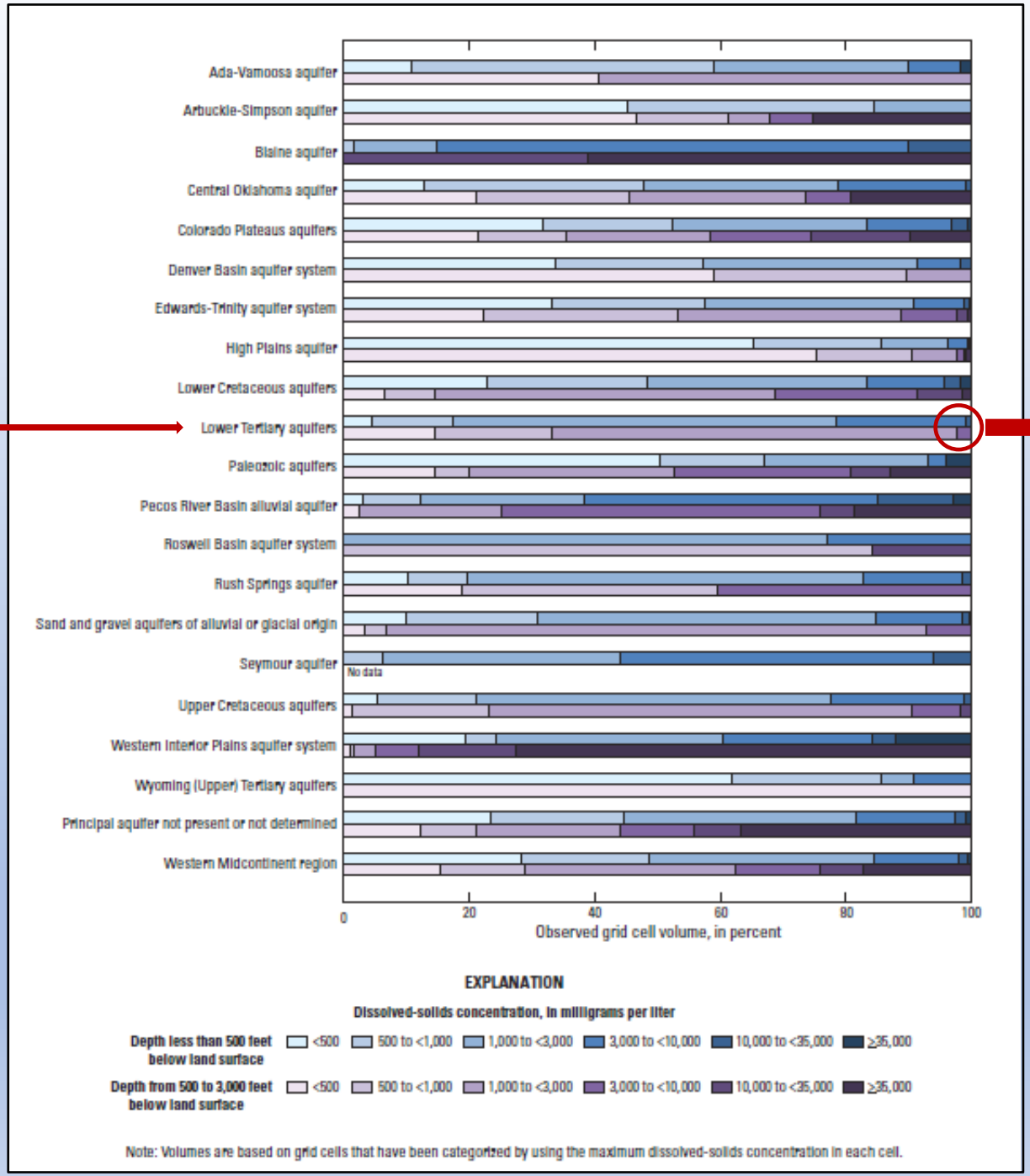
Principal Aquifer Systems in the Wind River Basin



Modified from Stanton et al. (2017)

Deep brackish groundwater resources exist in the Rocky Mountain Region

Lower Tertiary Aquifers



From 500 – 3000 ft

100% of cell volume have TDS < 10,000 mg/L.

> 95% cell volume have TDS < 3,000 mg/L.

Cell size:
10 km x 10 km

Modified from Stanton et al. (2017)

TDS and Major Ion Concentrations in Wind River Formation

Parameter	Daddow (1996) Median (Range)		Plafcan et al. (1995) Median (Range)		Pavillion Area (EPA Data) Median (Range)	
TDS	**490**	(211-5110)	**1030**	(248-5100)	**925**	(302-4921)
Ca	**10**	(1-486)	**45**	(1.7-380)	**51**	(3.3-452)
Mg	**2.2**	(0.1-195)	**8.2**	(0.095-99)	**5.3**	(0.02-147)
Na	**150**	(5-1500)	**285**	(4.5-1500)	**260**	(42-1290)
K			**2.45**	(0.1-30)	**2.45**	(0.18-10.5)
SO_4	**201**	(2-3250)	**510**	(12-3300)	**551**	(90-3640)
Cl	**14**	(2-466)	**20**	(3-420)	**21**	(2.6-78)
F	**0.7**	(0.1-8.8)	**0.9**	(0.2-4.9)	**0.9**	(0.2-4.1)

Table from DiGiulio and Jackson (2016)

Major ion chemistry in domestic wells in Pavillion Field is typical of the Wind River Formation (elevated TDS and SO_4)

Secondary Standards
TDS = 500 mg/L
SO_4 = 250 mg/L

Current Use of Wind River Formation, Potential Use of Fort Union Formation

Wind River Formation

- Primary source of drinking water throughout the Wind River Basin (Daddow 1996).
- The largest number of documented domestic well completions in Fremont County (Plafcan et al. 1995).
- 5 municipal wells in Town of Pavillion supply 20,000 gpd and 7.3 million gallons per year (James Gores & Associates 2011)
- Supplies drinking water for domestic wells in Pavillion area (James Gores & Associates 2011)

Fort Union Formation

- Wind River and Fort Union Formations defined as aquifers by Wyoming Water Development Office (WWDO 2003).
- Aquifer exemption required for injection of produced water into Fort Union Formation at Shoshone-Arapahoe 16-34 located 3.5 mi northwest of Pavillion Field (EPA 2013).
- Total dissolved solids range from about 1,000 to 5,000 ppm (McGreevy et al. 1969).

Do the Wind River and Fort Union Formations meet the definition of USDW at Depths of Stimulation in the Pavillion Field?

No, because of Wyoming's Groundwater Classification System

Wyoming Department of Environmental Quality Chapter 8 Quality Standards for Wyoming Groundwaters (WDEQ 2015)

- Class I – domestic use (TDS < 500 mg/L)
- Class II – agricultural use (TDS < 2,000 mg/L)
- Class III – livestock use (TDS < 5,000 mg/L)
- Class IV (A) – industry use
  - Class IV (A) (TDS < 10,000 mg/L)
  - Class IV (B) (TDS > 10,000 mg/L)
- Class V [no TDS criterion]
  - Class V (hydrocarbon commercial)
  - Class V (mineral commercial)
  - Class V (geothermal)
- Class VI – unsuitable for use
  - *"excessive"* TDS [undefined]
  - *"so contaminated that it would be economically or technologically impractical to make the water usable"*
  - *"located in such as way, including depth below the surface, so as the make use economically and technologically impractical."*

Yes, because:

- EPA explicitly stated that USDWs exist in the Pavillion Field: DiGiulio et al. (2011), EPA (2013), EPA (2016).
- TDS levels and groundwater yield clearly meet the definition of USDWs.
- The definition of an USDW is not dependent on a state groundwater classification system
- The presence of natural gas does not invalidate the definition of an USDW (an aquifer exemption is required for this purpose).
- Class V does not have a TDS criterion meaning that Class V groundwater can also meet Class I, II, or III water criteria as was the case at Pavillion.
- For Class VI water, there is no definition of excessive TDS.
- For Class VI, groundwater would not have been contaminated without oil and gas development.
- For Class VI, groundwater is not too deep for use (in some cases, domestic use at same depths of stimulation at Pavillion)

Production Well Stimulation Occurred at Depths of Deepest Groundwater Use in the Pavillion, WY Field

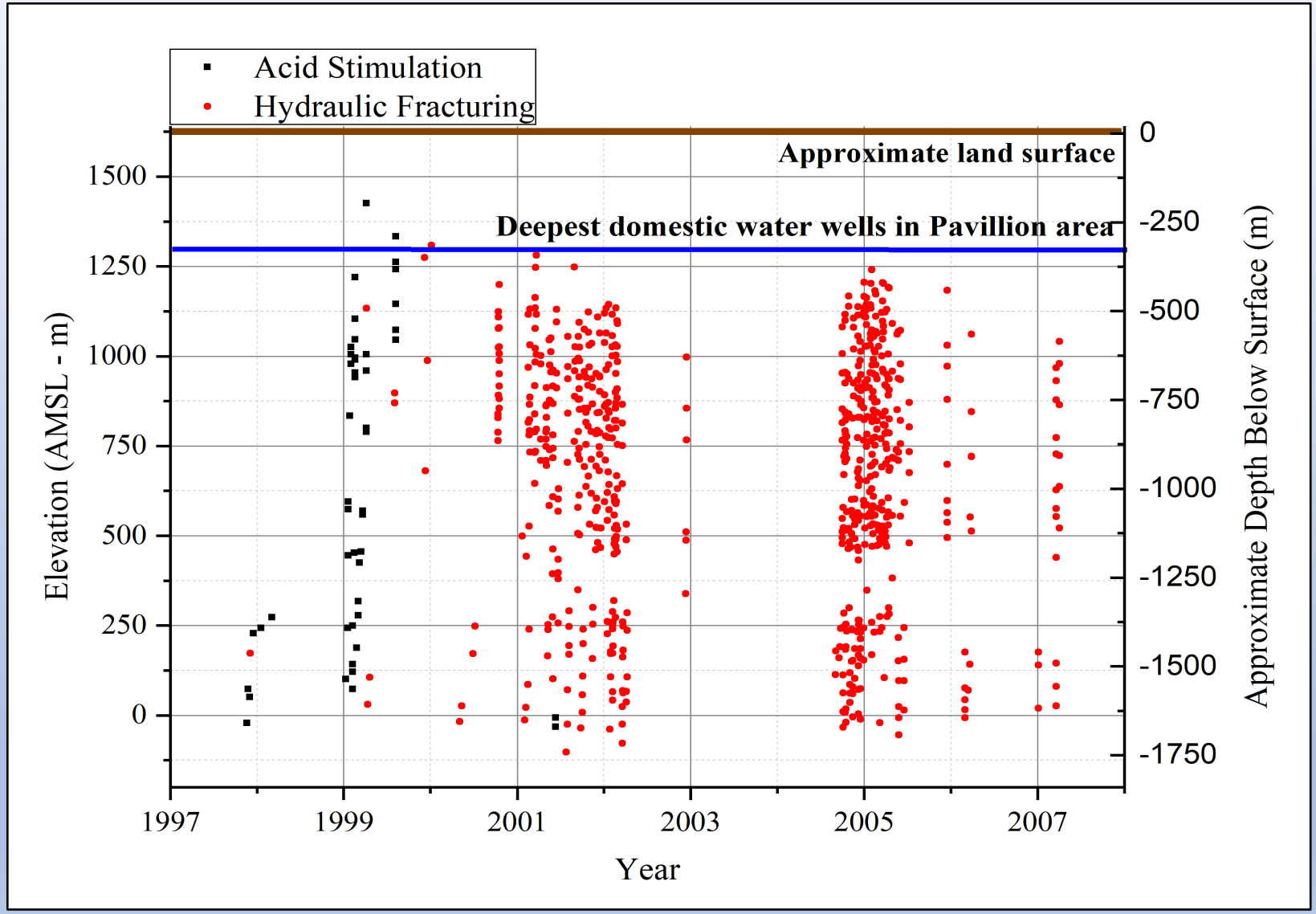


Figure from DiGiulio and Jackson (2016)

The Eocene (34-55 mya) Wind River flowed through the Pavillion Field

Pavillion Field

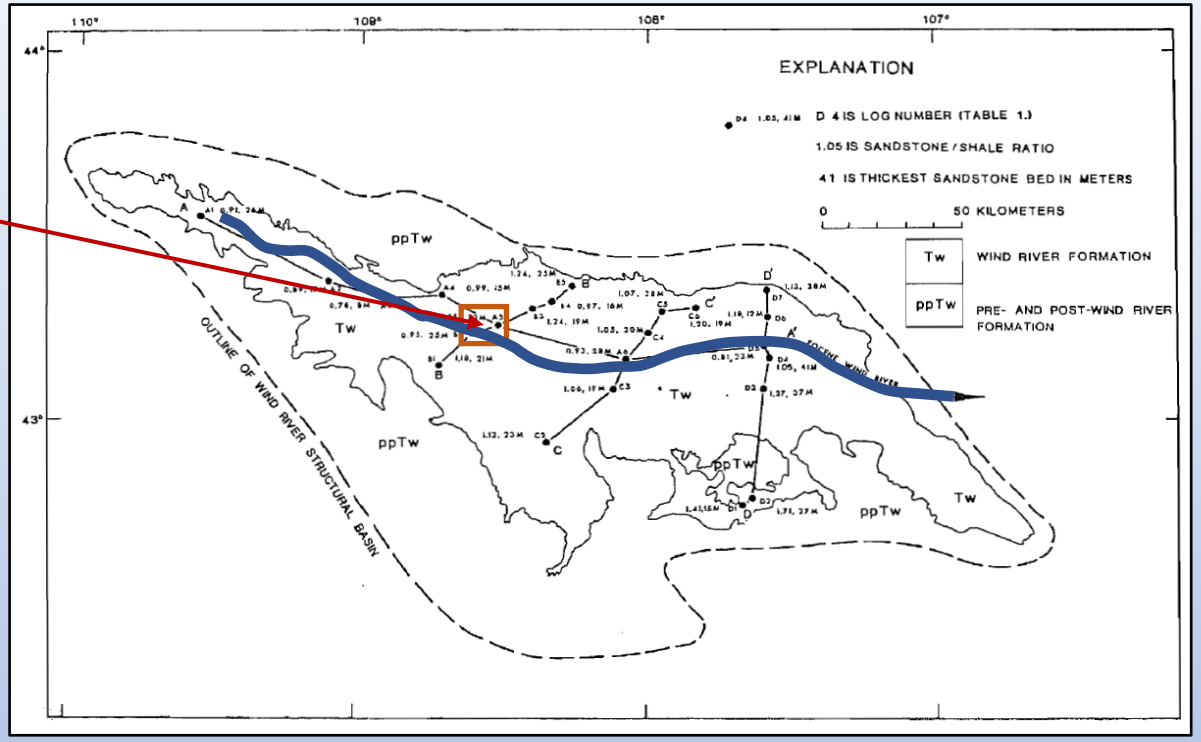


Figure modified from Seeland (1978)

Photograph from DiGiulio et al. (2011)

White coarse-grained sandstone targeted by local water well drillers and often referred to as "water sands" in Morris et al. (1959) present in Pavillion Field

The Wind River and Fort Union Formations exhibit extremely physical heterogeneity formed under fluvial depositional environments

- Contains connected, poorly connected, and unconnected water bearing sandstone units (McGreevy 1969).
- Sandstone units may be connected by fracture systems (Morris et al. 1959)
- Sandstone units surrounded by discontinuous mudstone, and shale units.
- No extensive areal confining units.

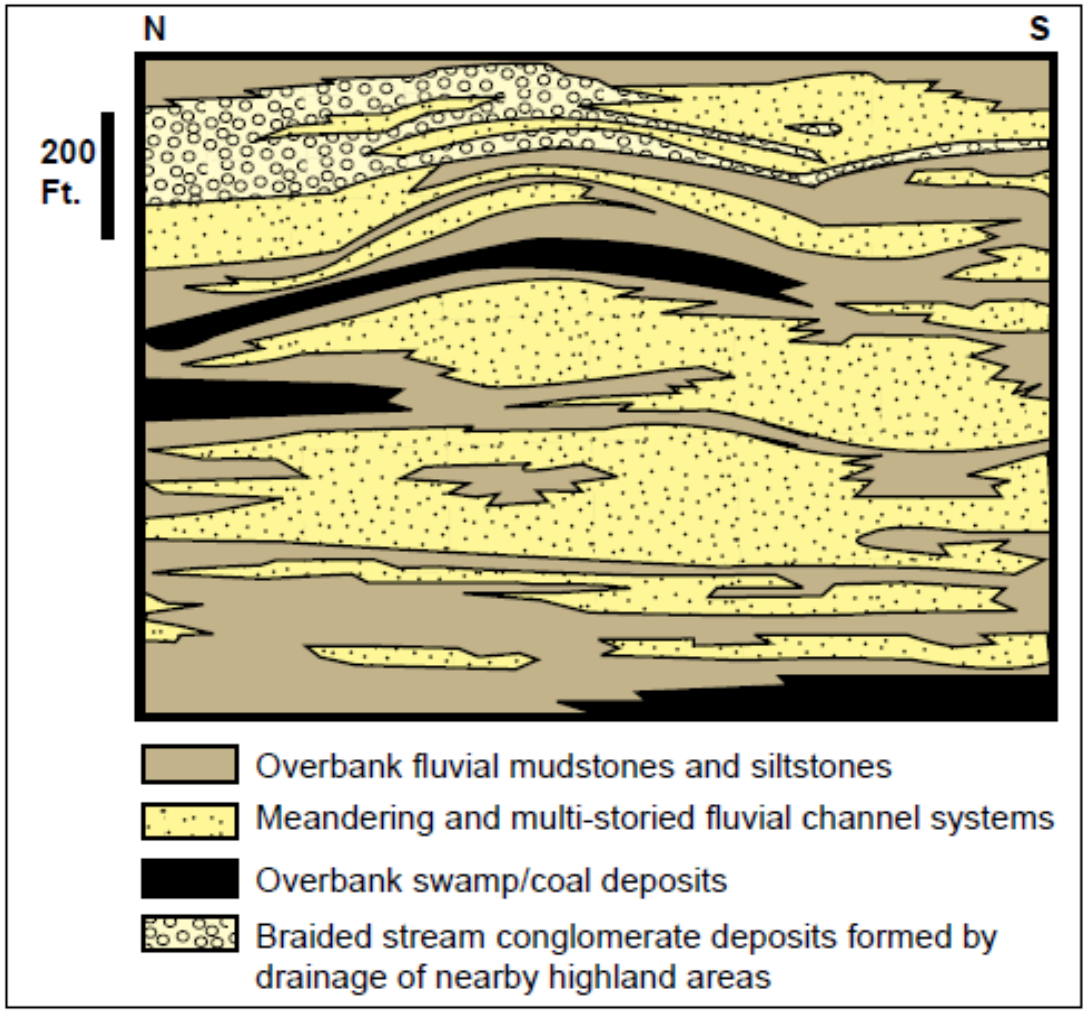


Figure from Flores and Keighin (1993)

The Wind River and Fort Union Formations are Variably Water Saturated in the Pavillion Field

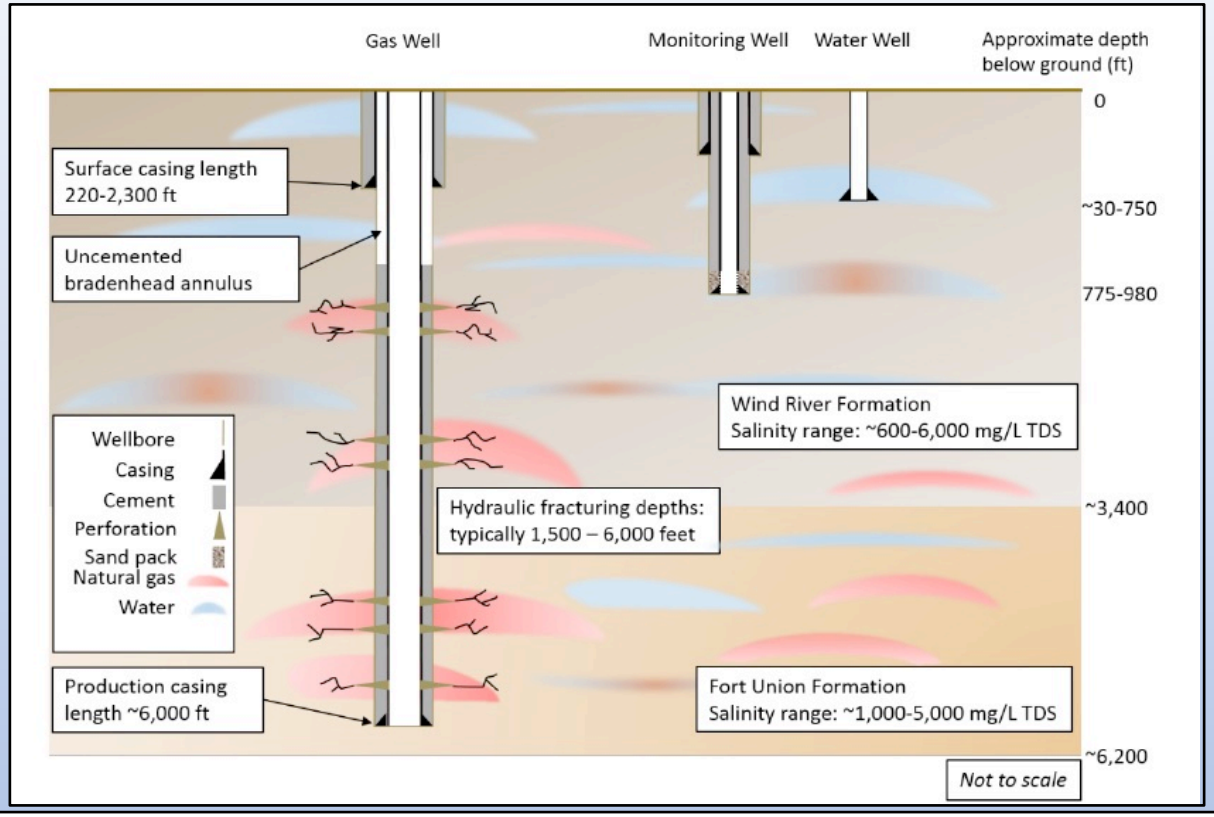
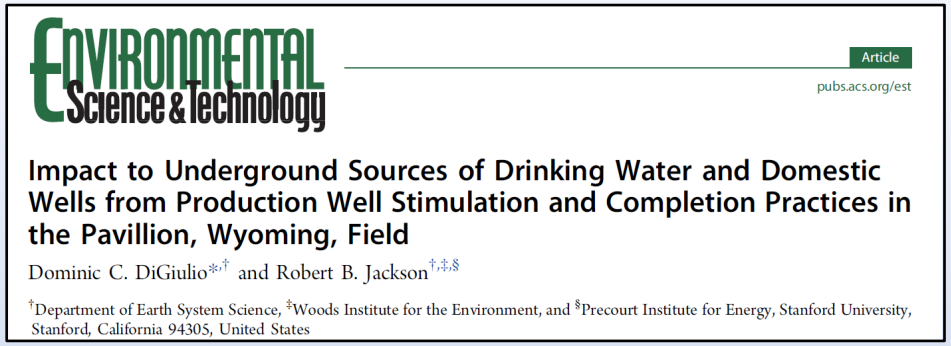


Figure from EPA (2016)

- Gas saturation in sandstone units increases with depth.
- Volumetric calculations indicate that gas saturation can be spatially extensive with low water to gas recovery rates in many production wells. **But**
- Significant groundwater resources exist within both formations at depth (noted in drilling logs or production wells shut in because of water production).
- Impact to USDWs then depends on advective-dispersive transport to water saturated sandstone units. Transport distance?

Factors Indicating Impact to USDWs in the Pavillion, WY Field



At least 41.5 million liters (or ~11 million gallons) of stimulation fluids was injected into formations containing USDWs in the Pavillion Field. The cumulative volume of well stimulation in closely spaced vertical wells in the Pavillion Field is characteristic of high volume hydraulic fracturing in shale units.

Five Lines of Reasoning

- Injection of stimulation fluids directly into water-bearing sandstone units.
- Fracture propagation and leakoff of stimulation fluids into water-bearing sandstone units (distance to water-bearing units meters or tens of meters)
- Pressure build-up during stimulation far in excess of drawdown during production.
- Loss of zonal isolation in production wells during hydraulic fracturing.
- Detection of organic compounds associated with well stimulation in EPA monitoring wells.

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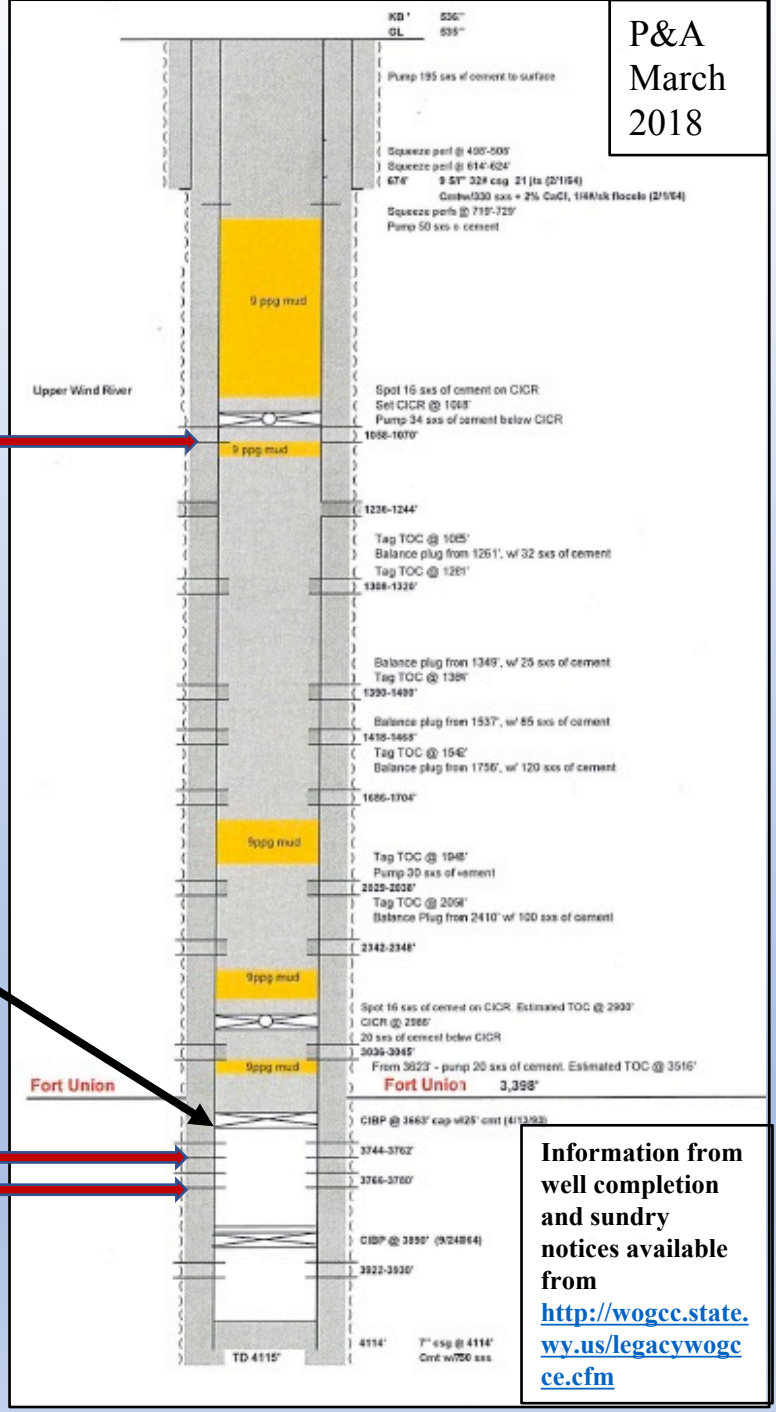
Injection of Stimulation Fluids into Water-Bearing Zones

P&A March 2018

3. On 10/16/1964, hydraulic fracturing at 1058 ft with CO_2 foam and 4,360 gallons of methanol.

2. On 3/25/1993, *"plug back water bearing perforation in the Fort Union at 3744-3780 with a 7" CIBP"*

1. On 10/16/1964, hydraulic fracturing with 12,000 gallons of #2 diesel at 3744-3780 ft



Information from well completion and sundry notices available from http://wogcc.state.wy.us/legacywogcce.cfm

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Tribal Pavillion 14-01

Fracture Propagation and Leakoff into Water-Bearing Zones

- Distances to water-bearing sandstone units in the Pavillion Field (likely on the order of meters to tens of meters).
- Leakoff increases in complex fracture networks as a result of lithologic variation over short distances and contact with permeable strata (Adachi et al 2007, Fisher and Warpinski 2011, Valkó and Economides 1999, Yarushina et al 2013) typical of the Wind River and Fort Union Formations.
- Leakoff can remove much or most of the fracturing fluid even for moderate sized induced fractures (Adachi et al 2007, Fisher and Warpinski 2011).

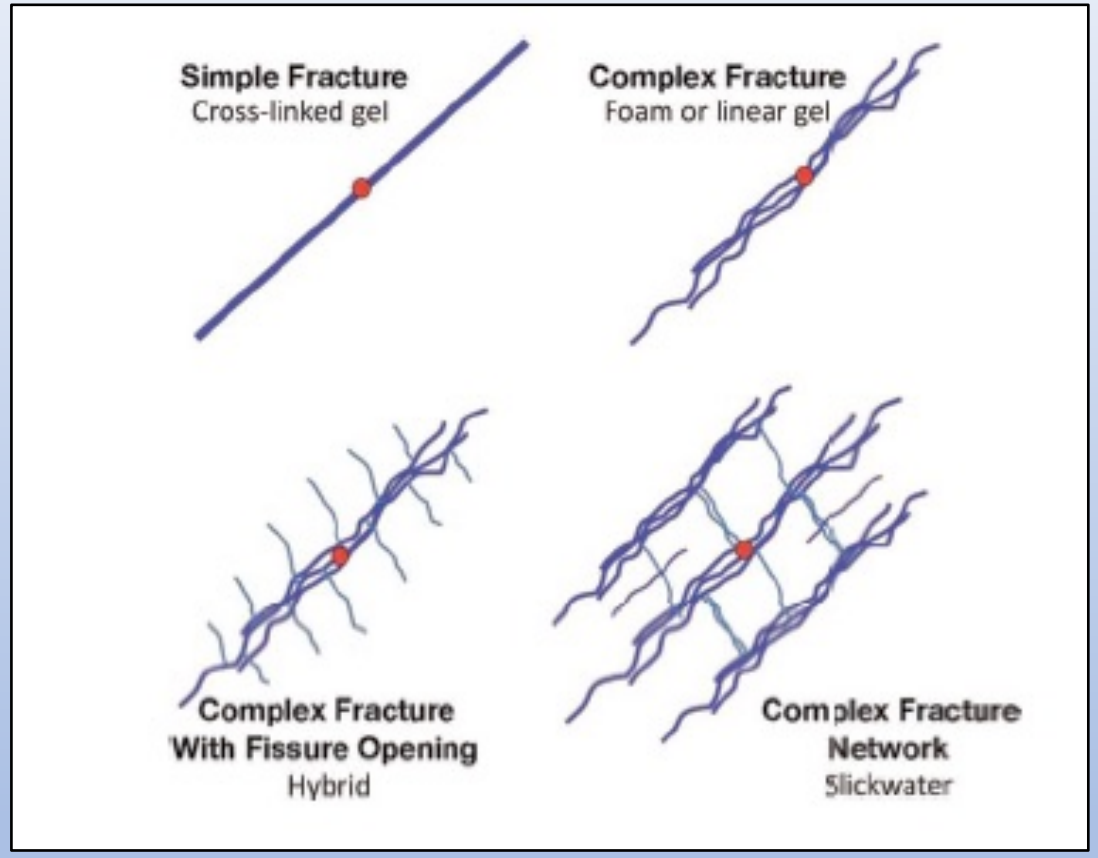


Figure from CCST (2015) modified from Warpinski (2009)

Instantaneous Shut-In Pressures Indicate Strong Hydraulic Gradients

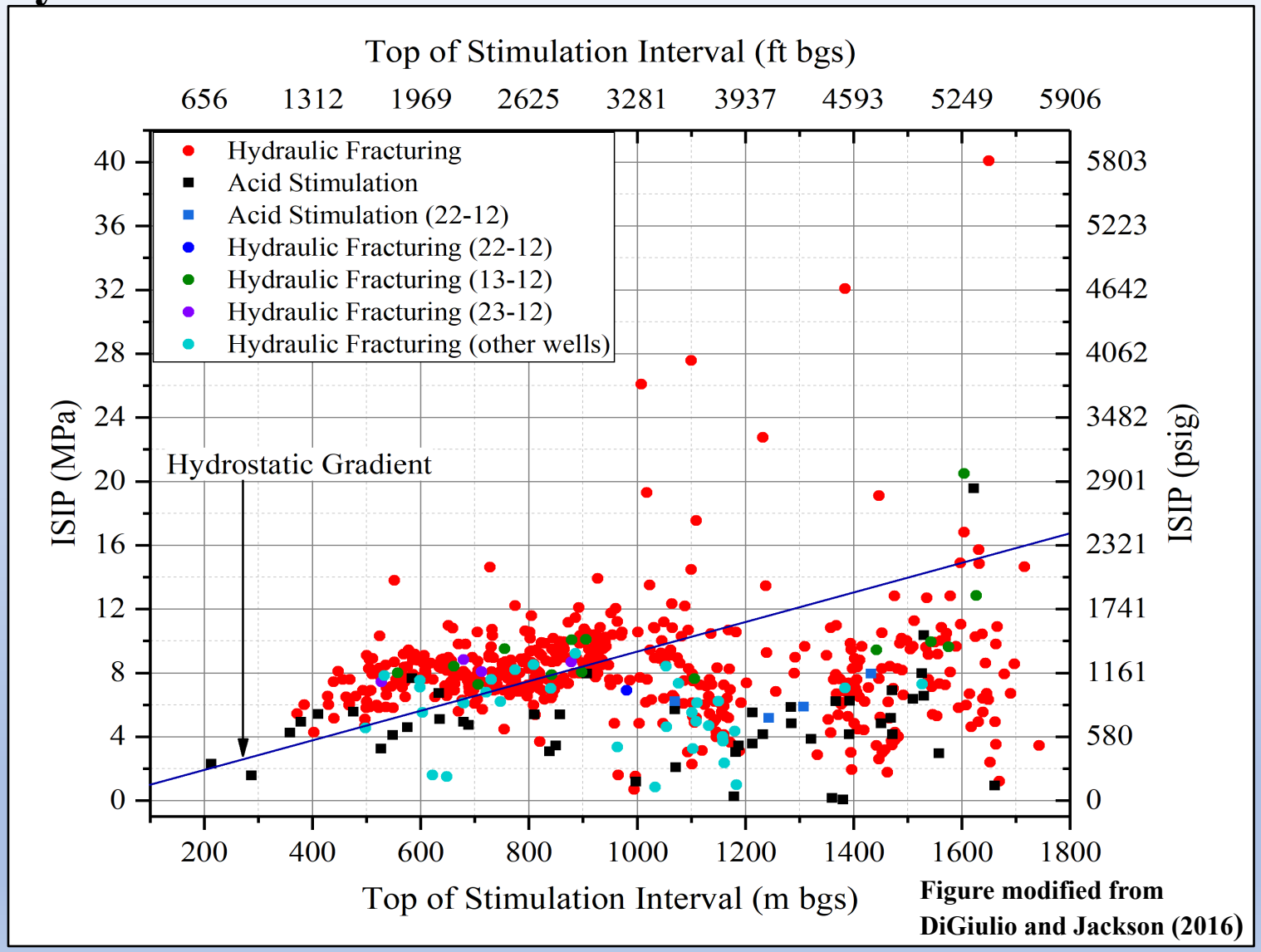
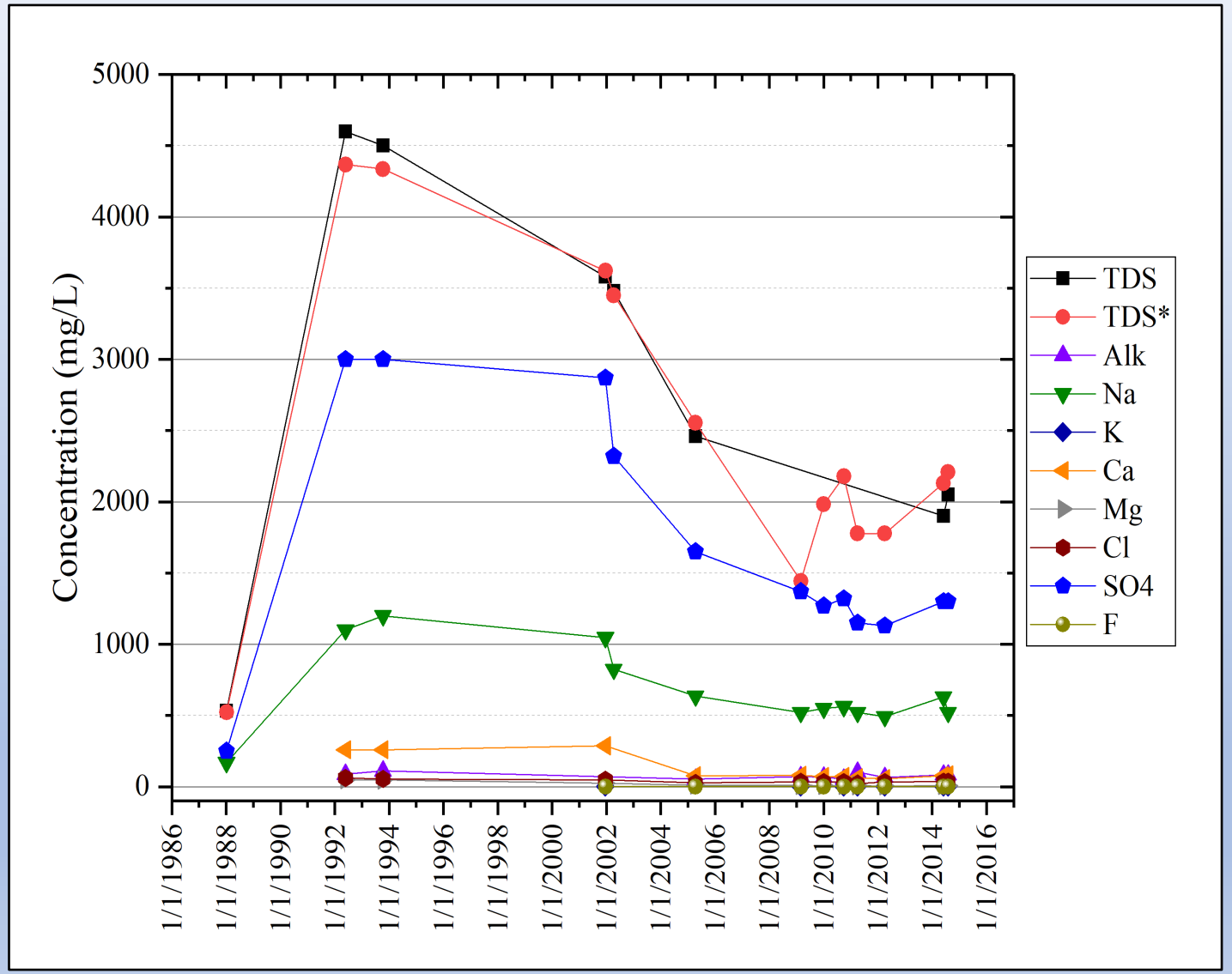


Figure modified from DiGiulio and Jackson (2016)

High pressure gradients in excess of hydrostatic pressure (up to 40.1 MPa or 4100 m of hydraulic head. Pressure buildup far in excess of drawdown during fluid recovery.

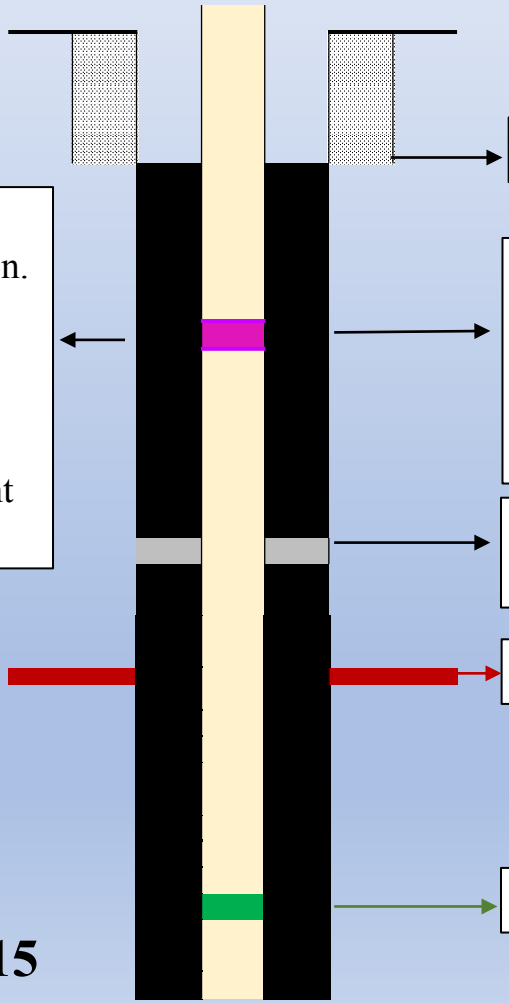
Water Chemistry Changes at PGDW20



Potential Loss of Zonal Isolation

Casing failure occurred at 5 production wells. Casing failure at Tribal 21-15 is one example.

Information from well completion and sundry notices available from http://wogcc.state.wy.us/legacywogcce.cfm



Surface casing at 619’

1. Dec 1979 – well completion. Invert mud. CBL/ VDL missing from file – depth to primary cement unknown

5. On 5/7/2012, sundry notice stated that a mechanical integrity test conducted indicated “*failed casing*” between **735’ – 1105’**. Date of failure unknown.

4. Oct 1982 - Cement squeeze at 1550’. Reason for cement squeeze not provided.

3. Sep 1982 - Acid stimulation (1000 gallons) at 2622’

2. Sep 1982 – Recompletion - packer set at 3294’

6. Letter on 8/14/2012 from WDEQ to BLM requesting information on potential release of stimulation fluids to depth of failed casing.

7. On 8/23/2012, response from BLM reiterated information in file providing no additional information.

8. To date, no casing remediation. No Bradenhead testing.

Tribal 21-15

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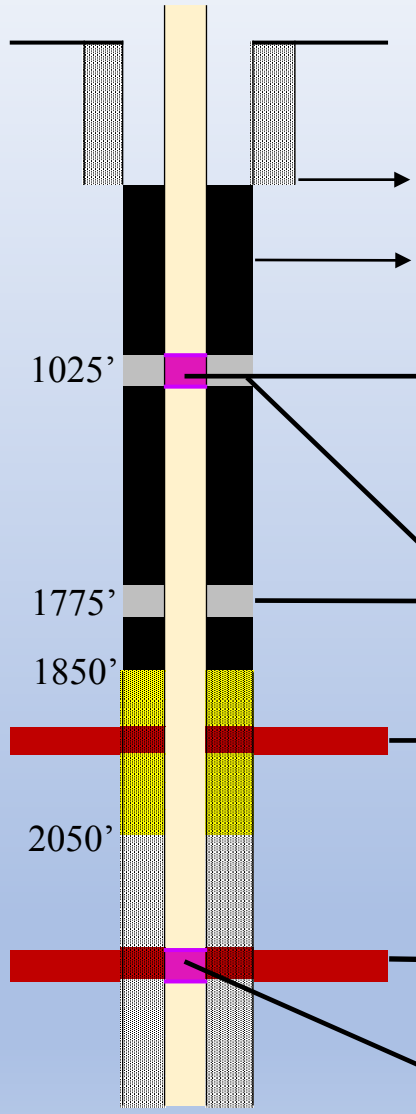
Potential Loss of Zonal Isolation

1. Completion in Mar 1977. Frac at 4870' with 102,000 gal of gel water.

2. On 1/11/2005, a cement bond-variable density log conducted at 400 psig indicated top of cement at 1850' with high amplitude to 2050'.



3. On 1/21/2005, a "*hole*" in casing at 1025'-1062' was reported. Date hole formed unknown. No cement outside casing. 1375 psig casing pressure in 1977. Hydrostatic pressure 443 psig.

4. On 1/25/2005, cement squeezes at 1062' and 1775'.

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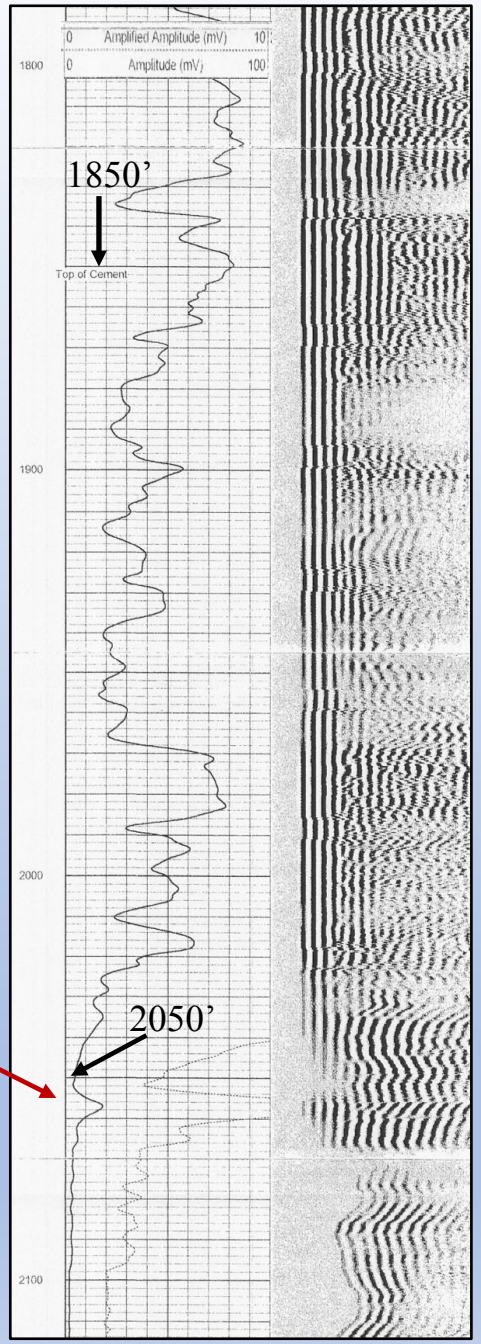
6. On 2/12/2005, slickwater frac at 2070' at 5711 psig. At most, 20' of good bonding above frac.

(burst pressure ~ 5350 psig).

5. On 2/8/2005, slickwater frac with CO_2 assist at 2671' at 5546 psig on 2/8/2005

7. In a wellbore diagram dated 10/5/2011, casing was parted at 2593' and 2597' (12/21/2006).



Blankenship 4-8

Information from well completion and sundry notices available from http://wogcc.state.wy.us/legacywogcce.cfm

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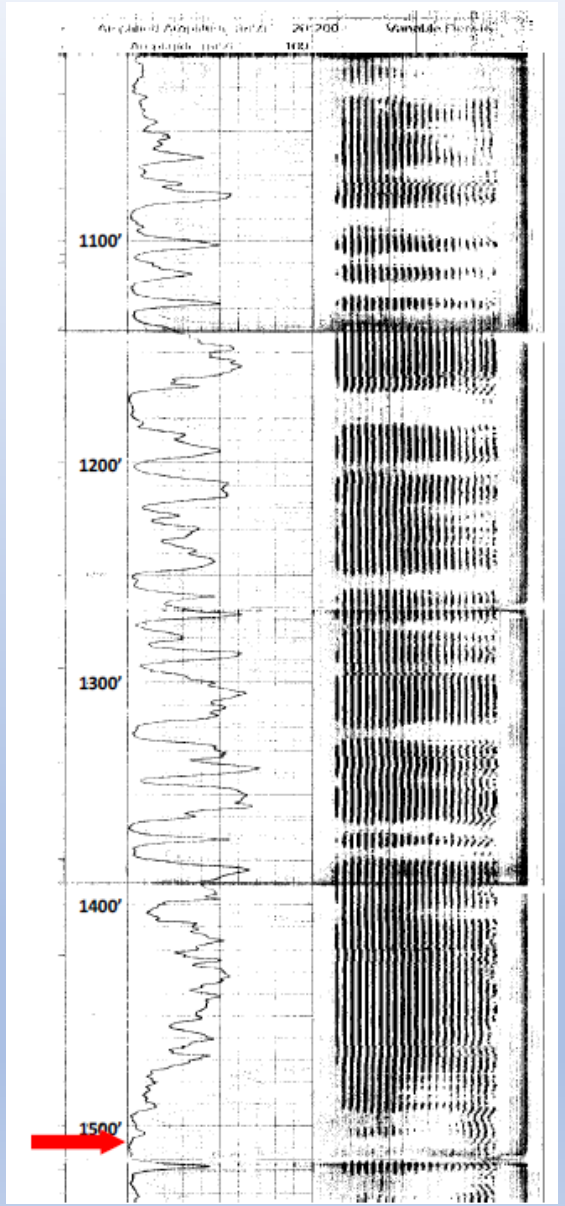
Potential Loss of Zonal Isolation

Tribal Pavillion 11-11B

Information from well completion and sundry notices available from http://wogcc.state.wy.us/legacywogcce.cfm

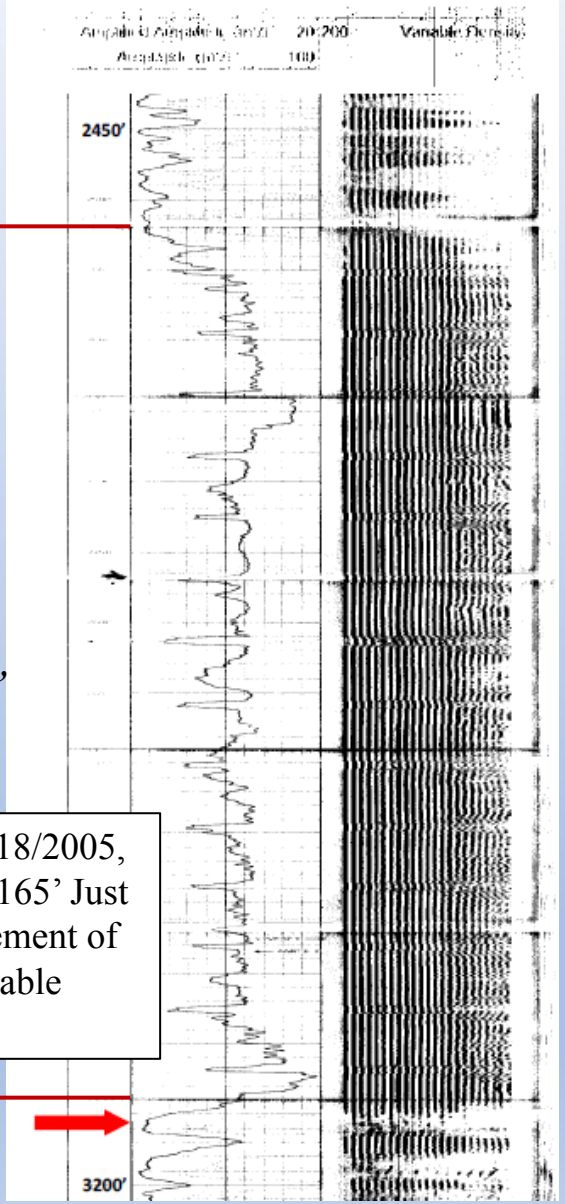
3. On 2/18/2005, frac at 1516' below cement of questionable quality.



1. CBL/VDL in Feb 2002 after completion

"void @ 2550-3150 ft"

2. On 2/18/2005, frac at 3165' Just 15' of cement of questionable quality.



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EPA Monitoring Wells

Figure from DiGiulio et al. 2011

EPA Monitoring Wells

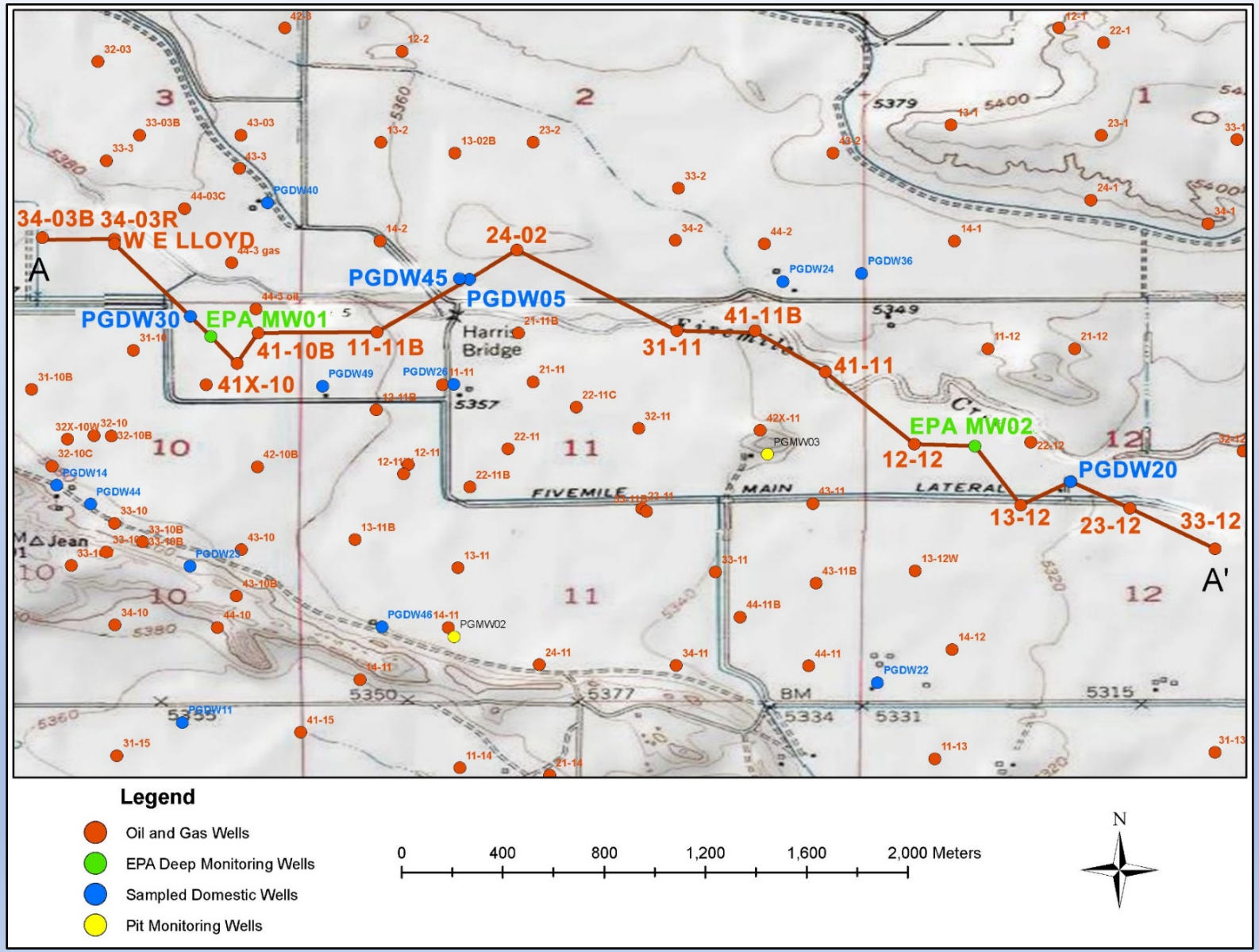

Figure from DiGiulio et al. 2011

EPA Monitoring Wells

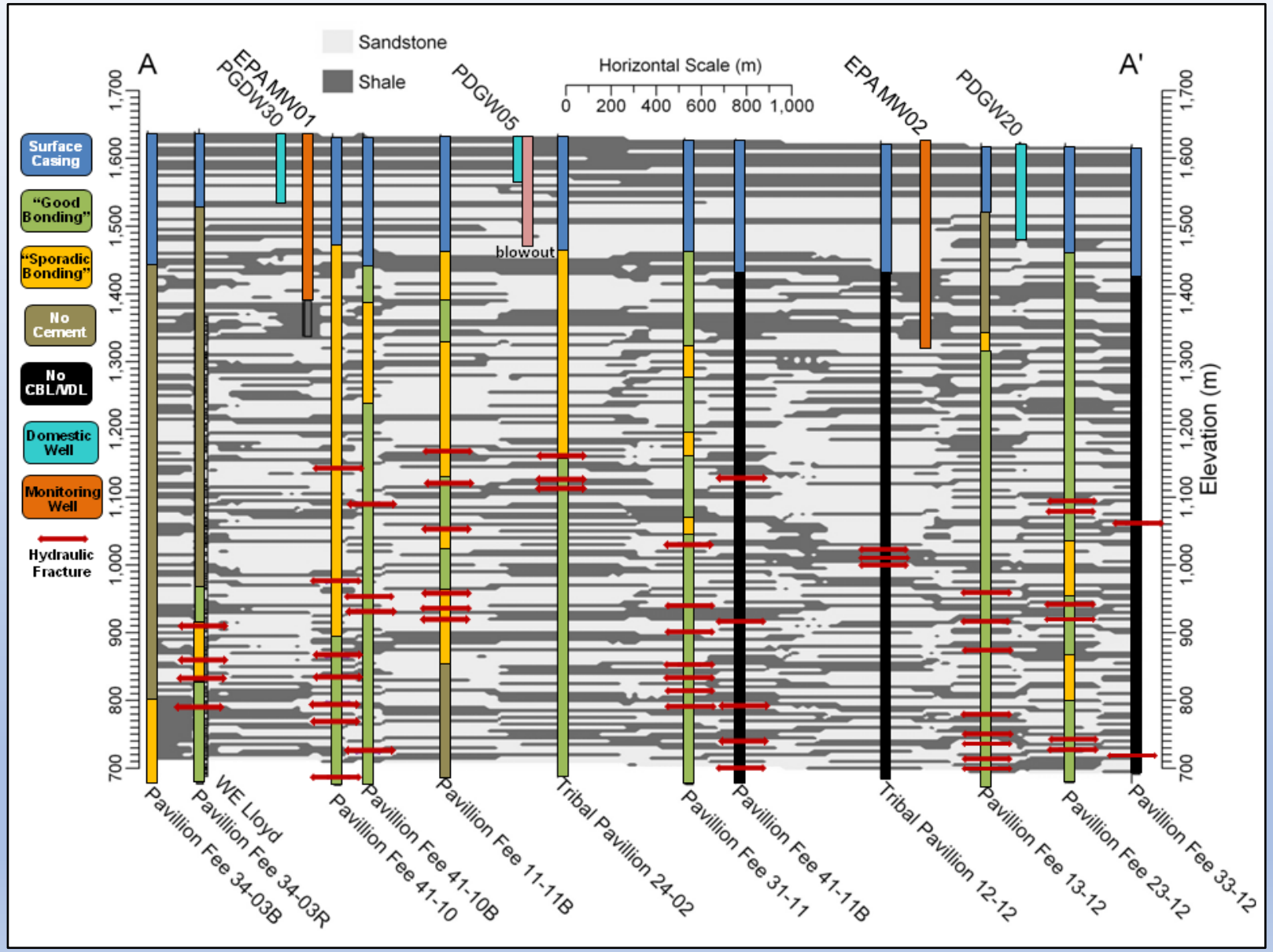

Figure from DiGiulio et al. 2011

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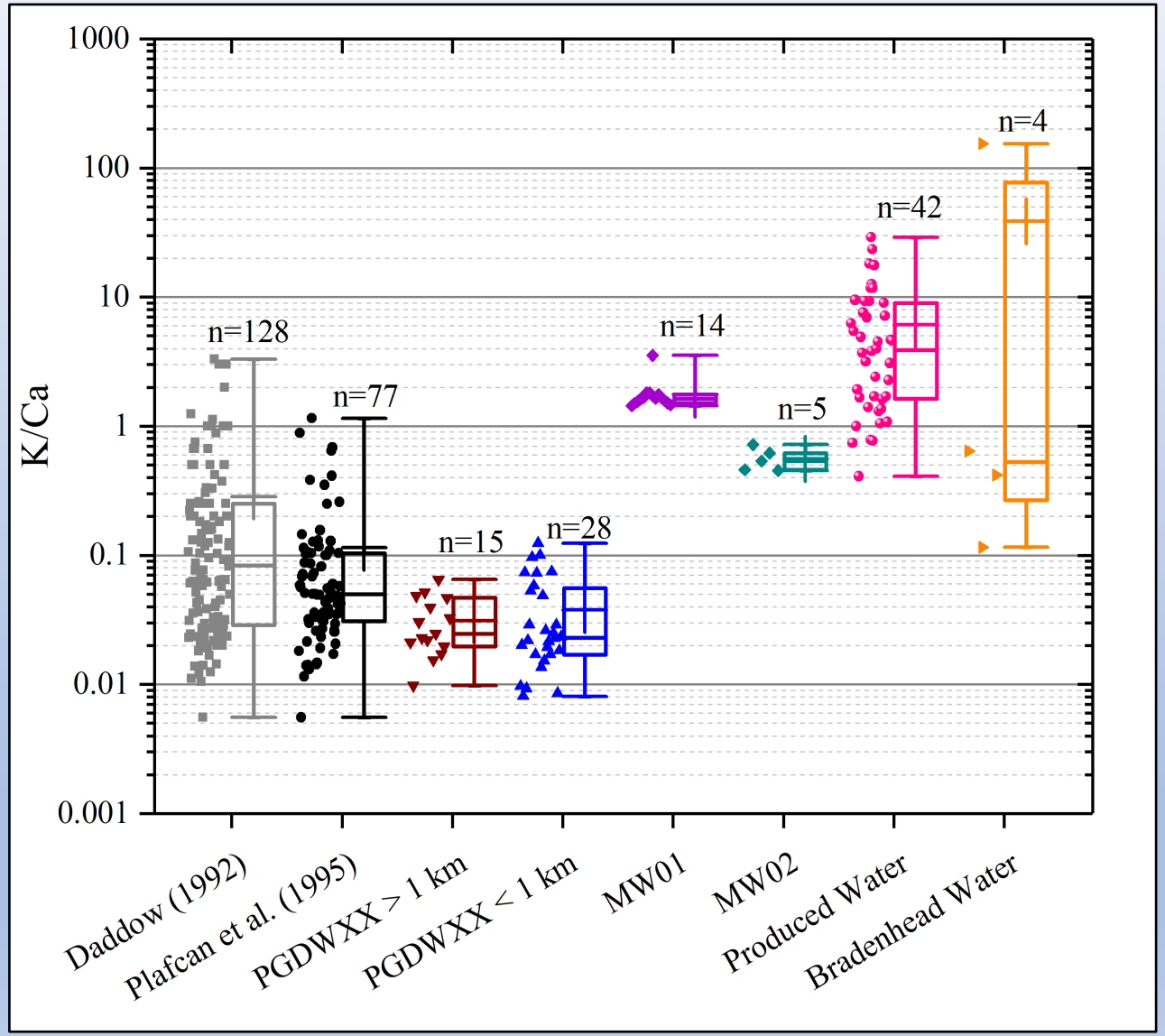
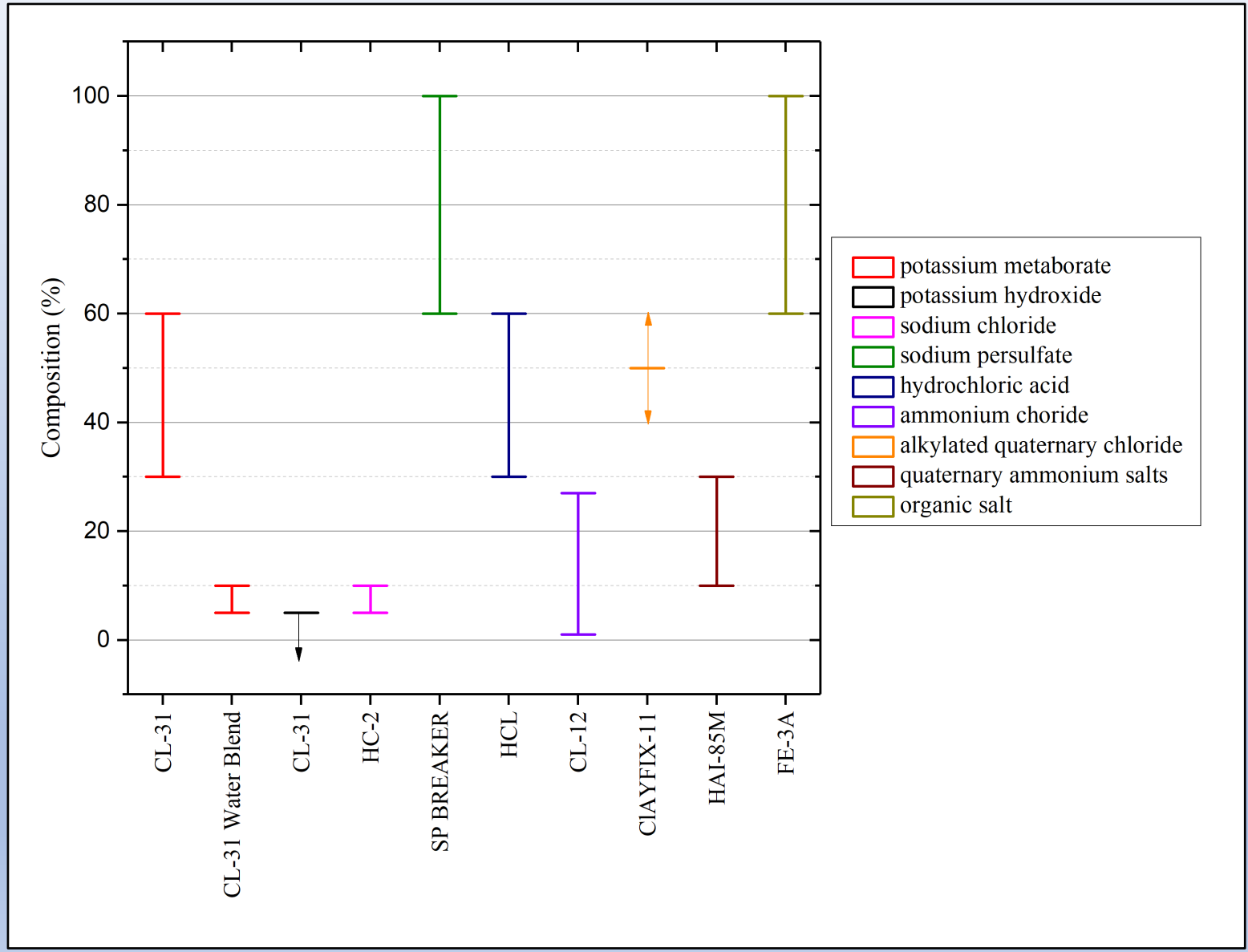
Organic Compounds Detected in EPA Monitoring Wells

Figures from DiGiulio et al. 2011

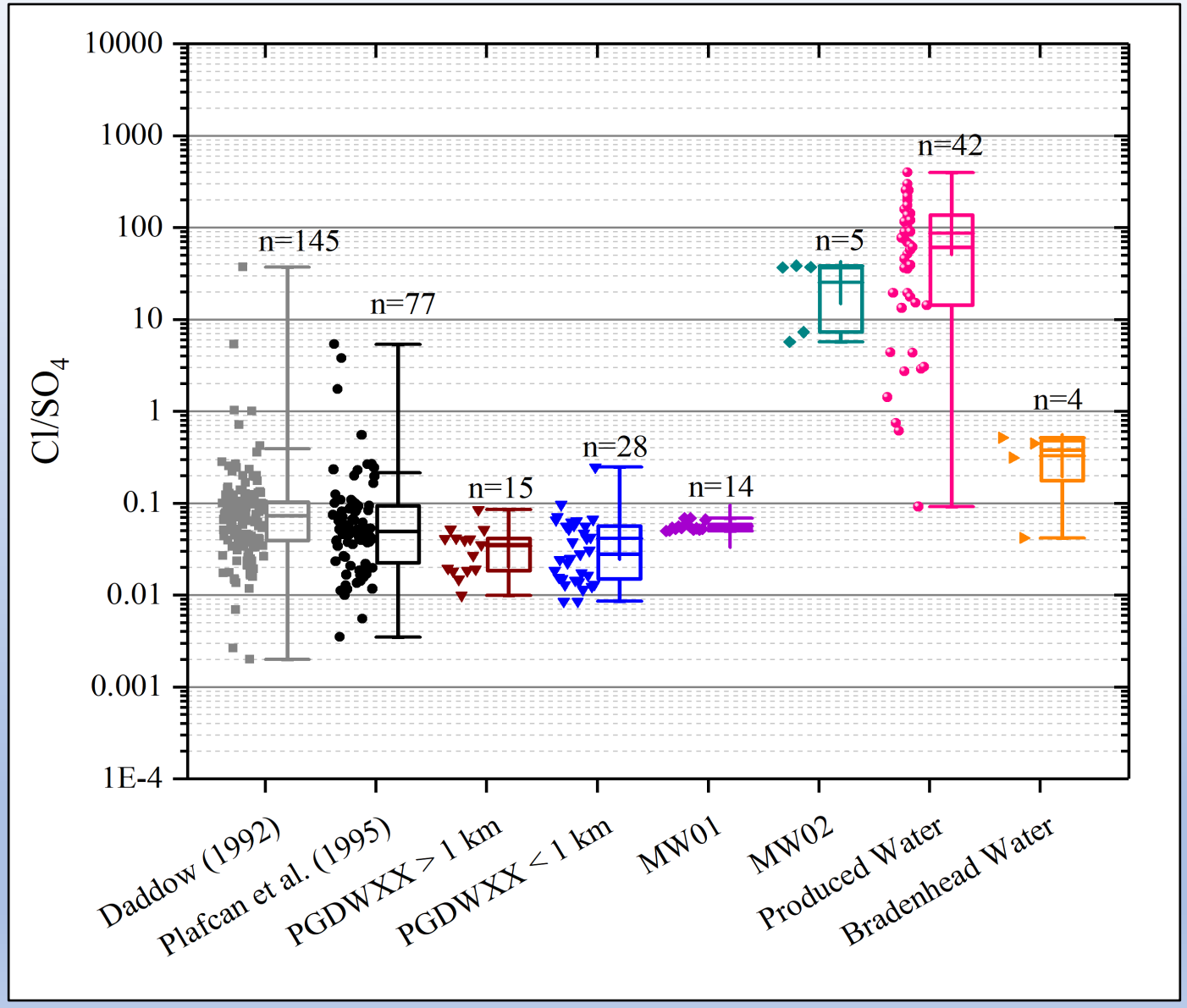
Elevated Potassium



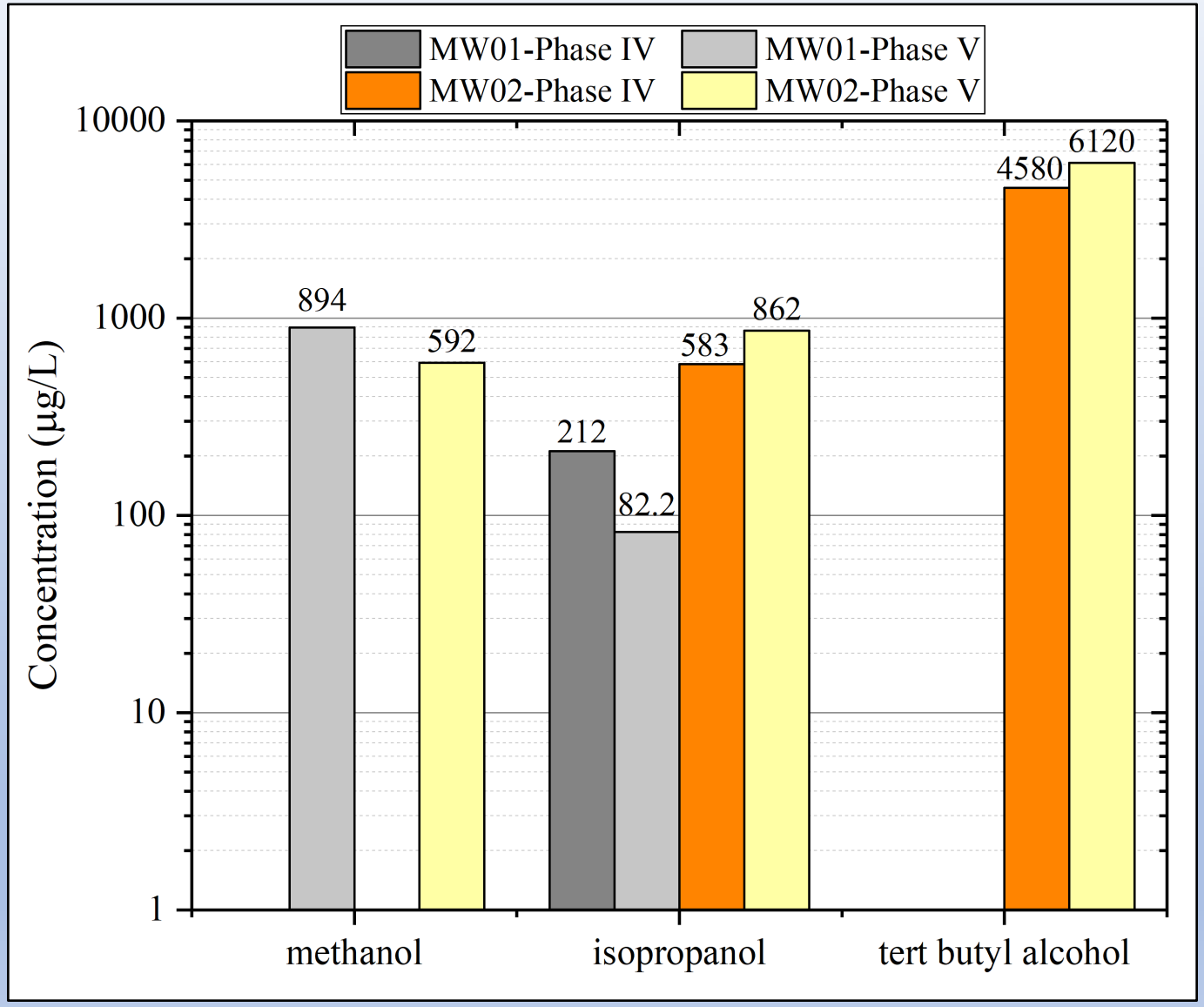
Salts Used for Stimulation



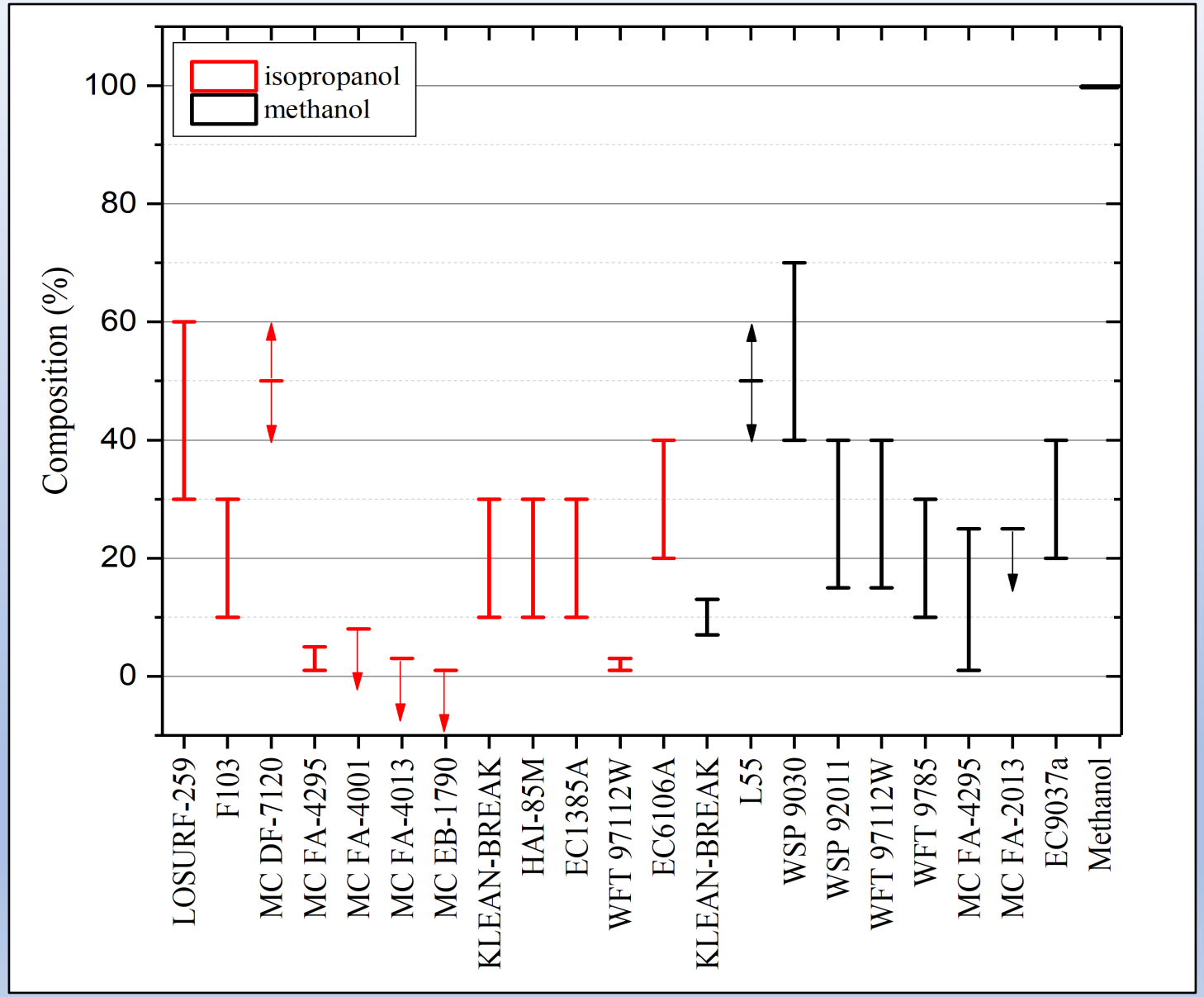
Elevated Chloride/Sulfate Ratio for MW02



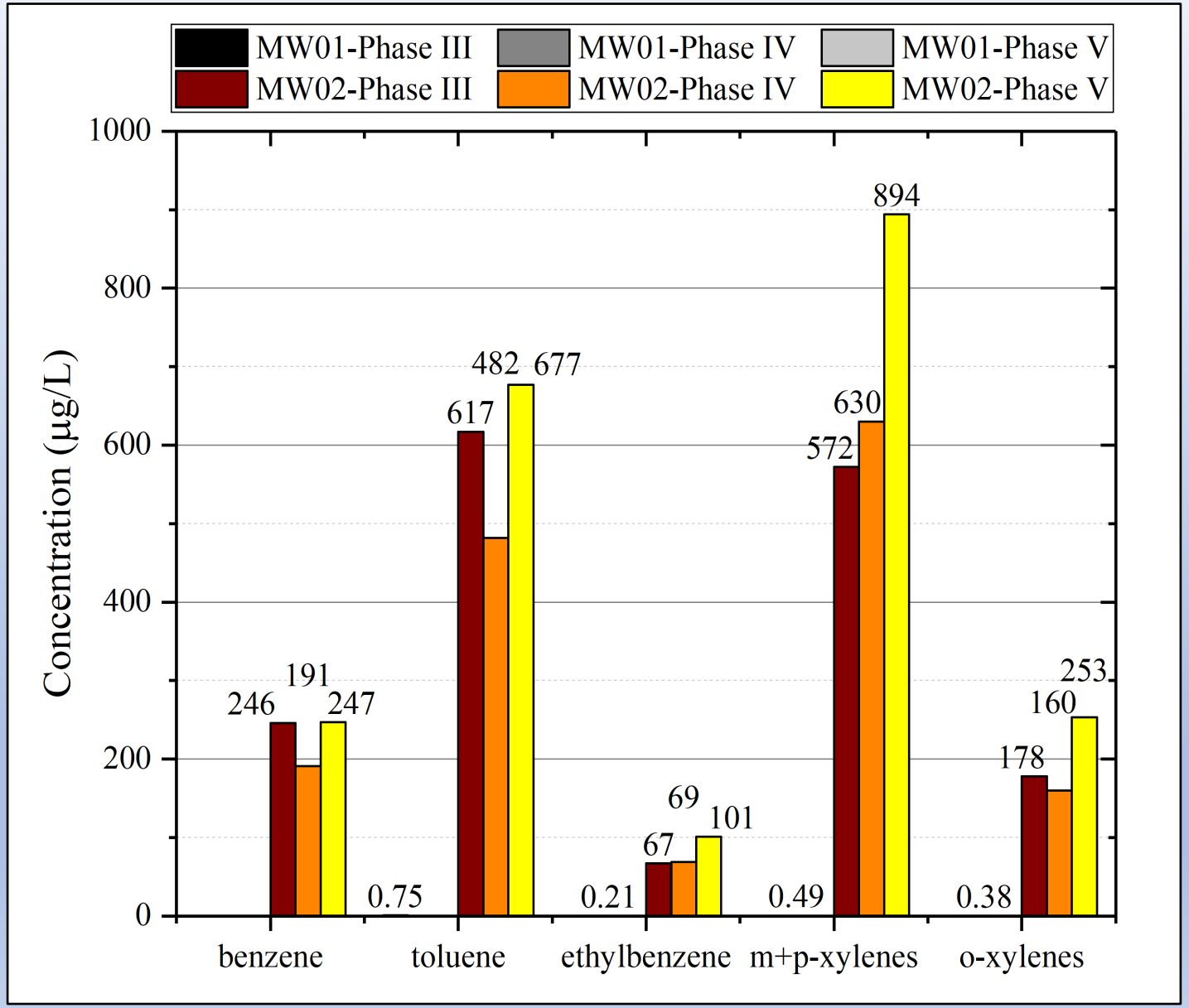
Detection of Alcohols



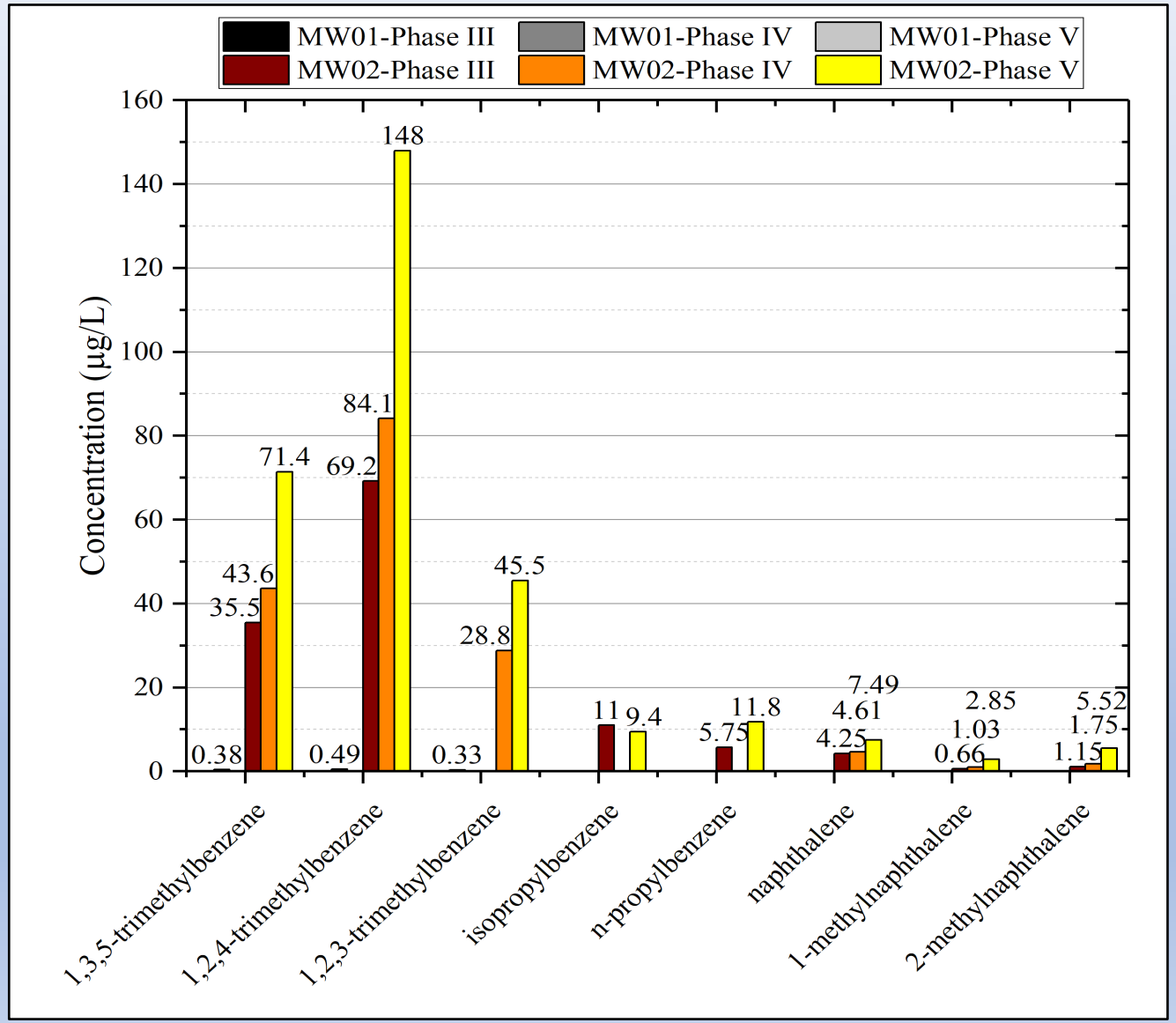
Alcohols Used for Stimulation



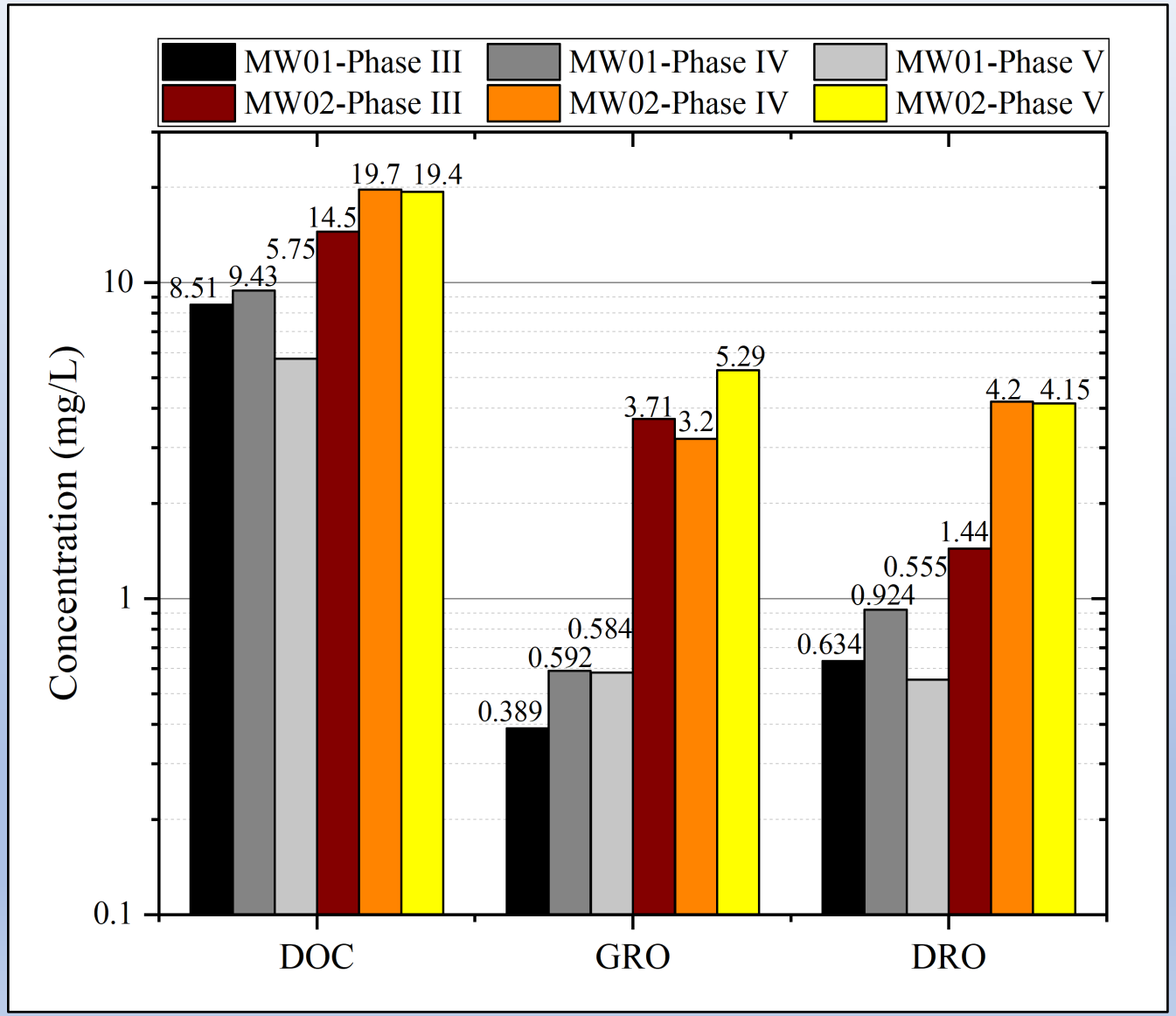
Detection of BTEX Compounds



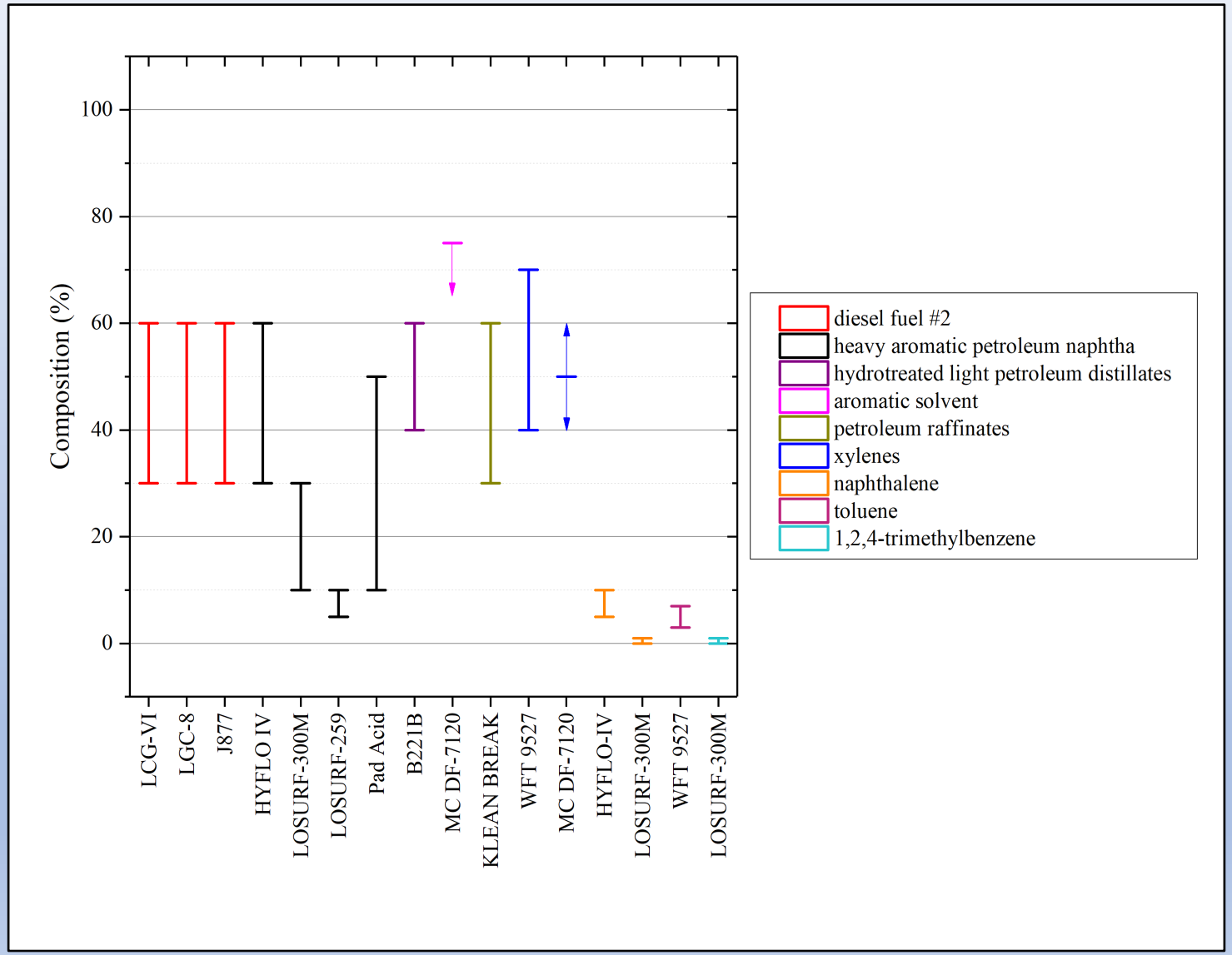
Detection of Trimethylbenzenes, Alkylbenzenes, and Naphthalenes



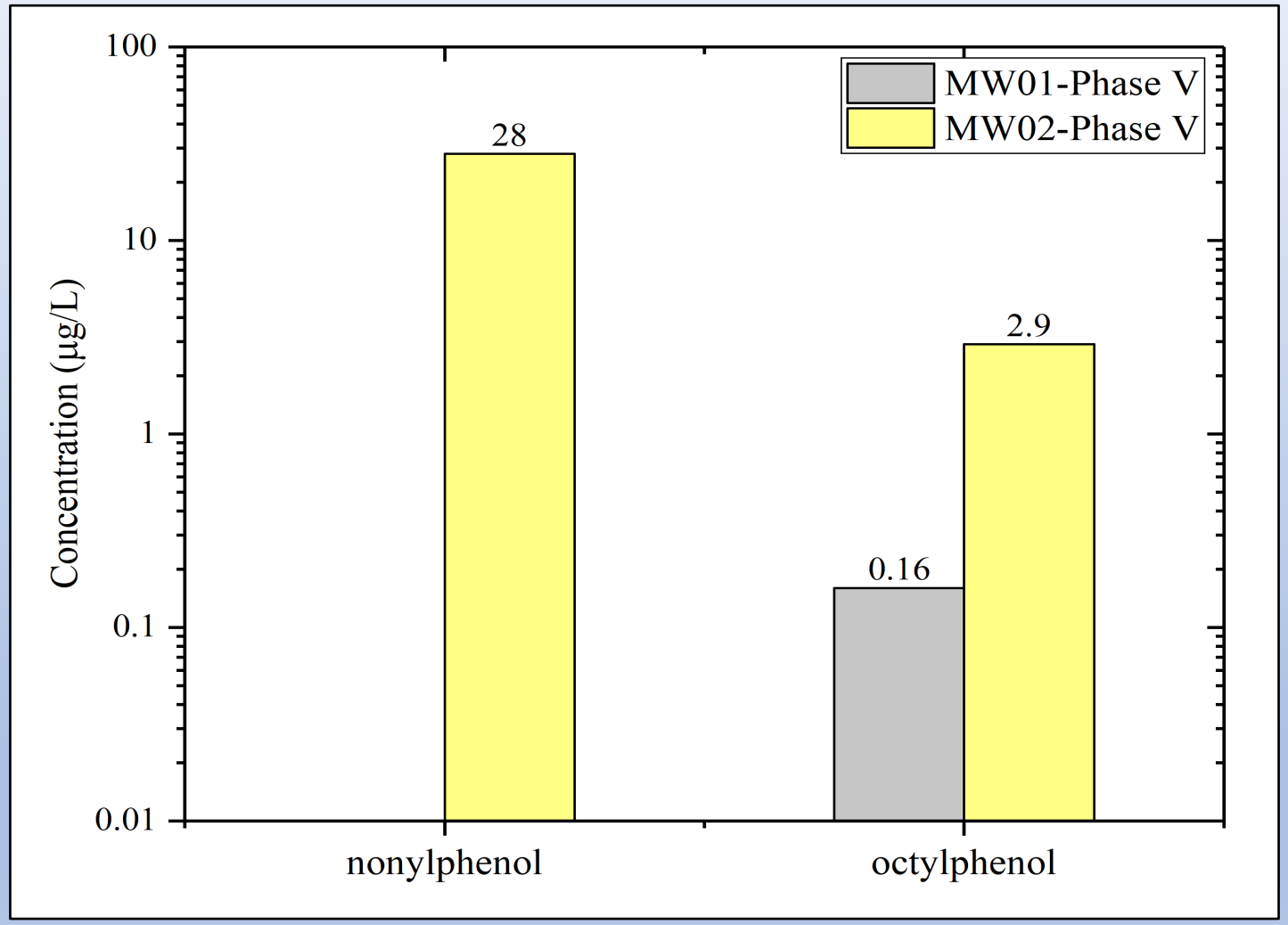
Detection of Hydrocarbons and Degradation Products



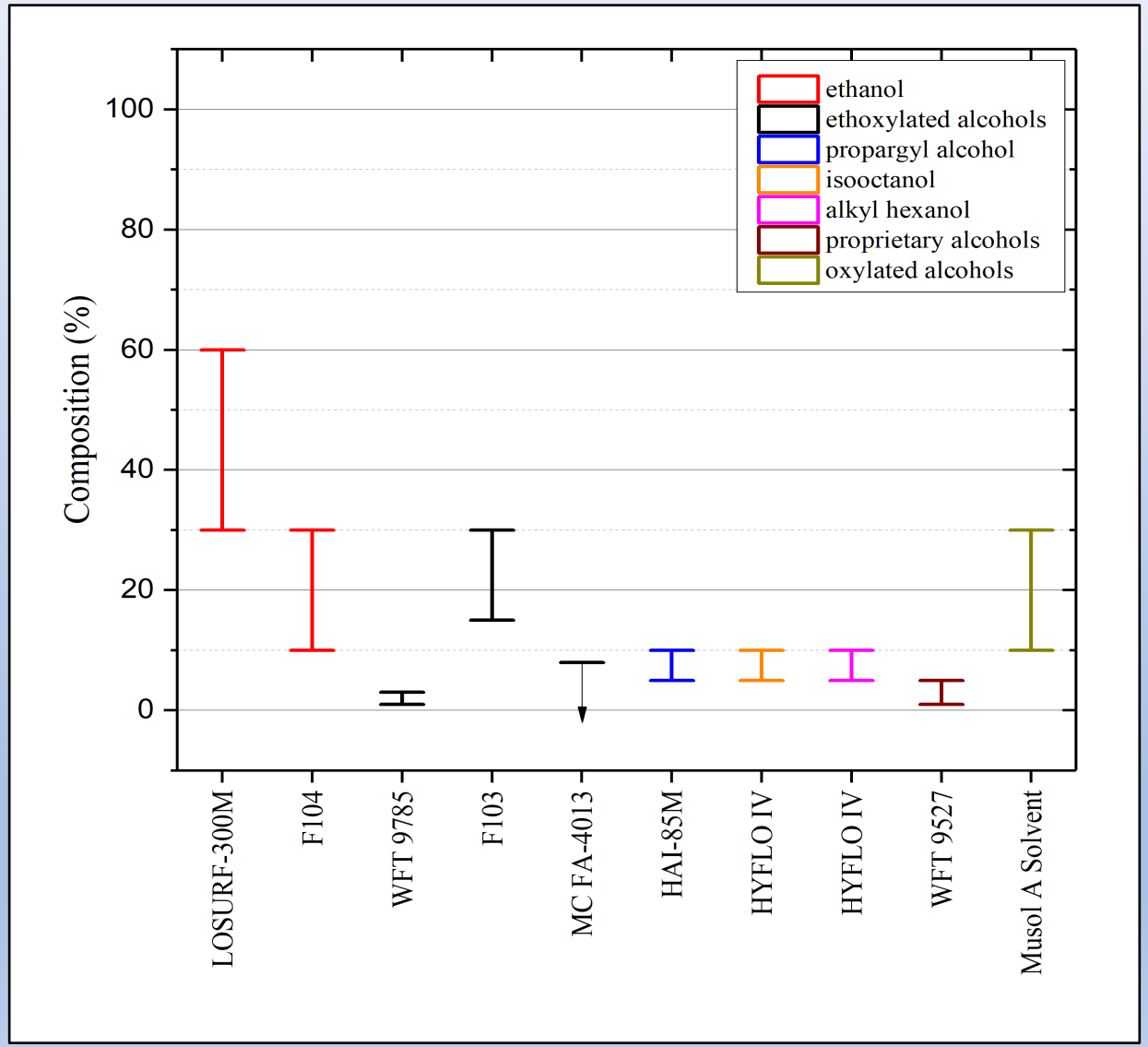
Petroleum-Based Compounds Used for Stimulation



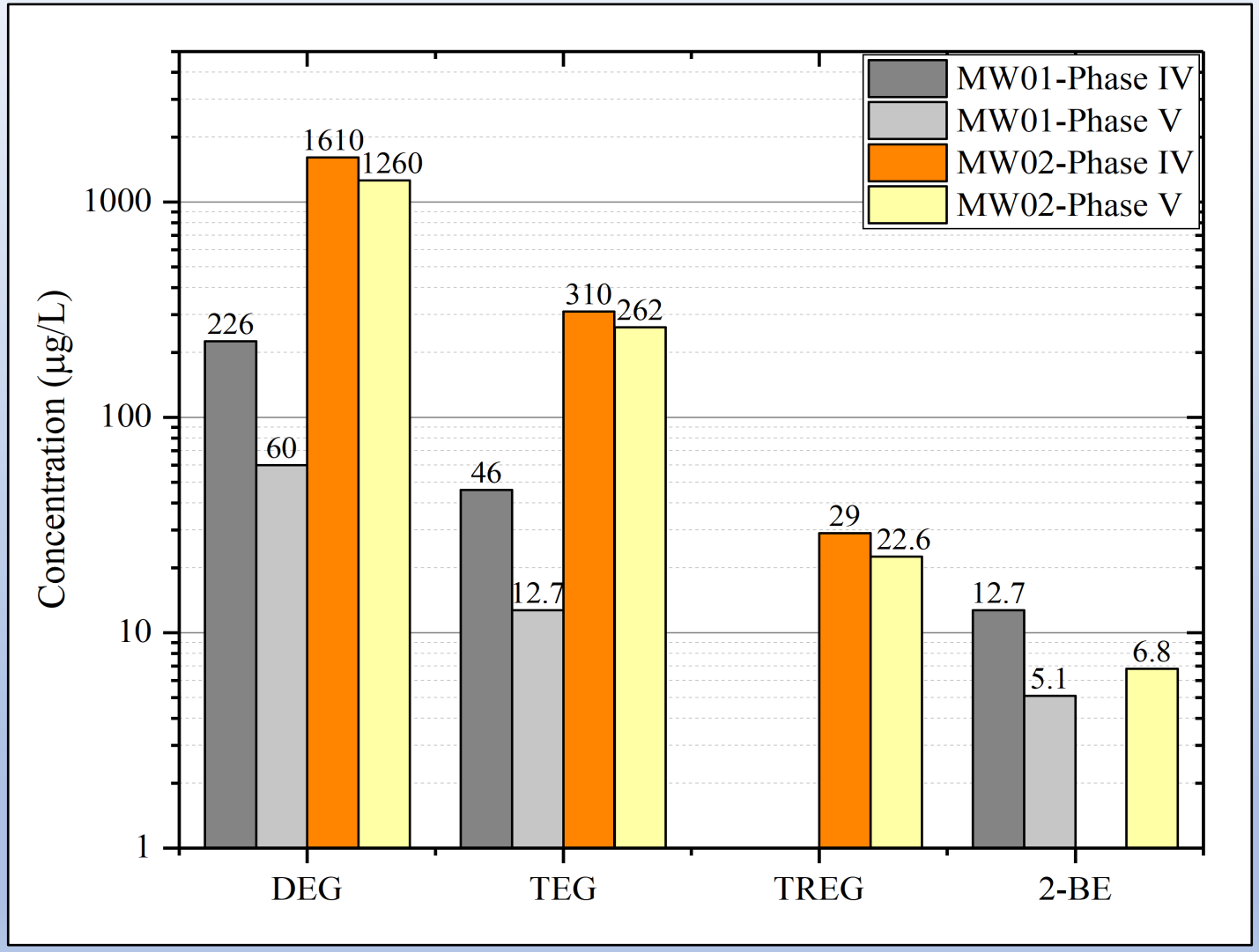
Detection of Alkylphenols



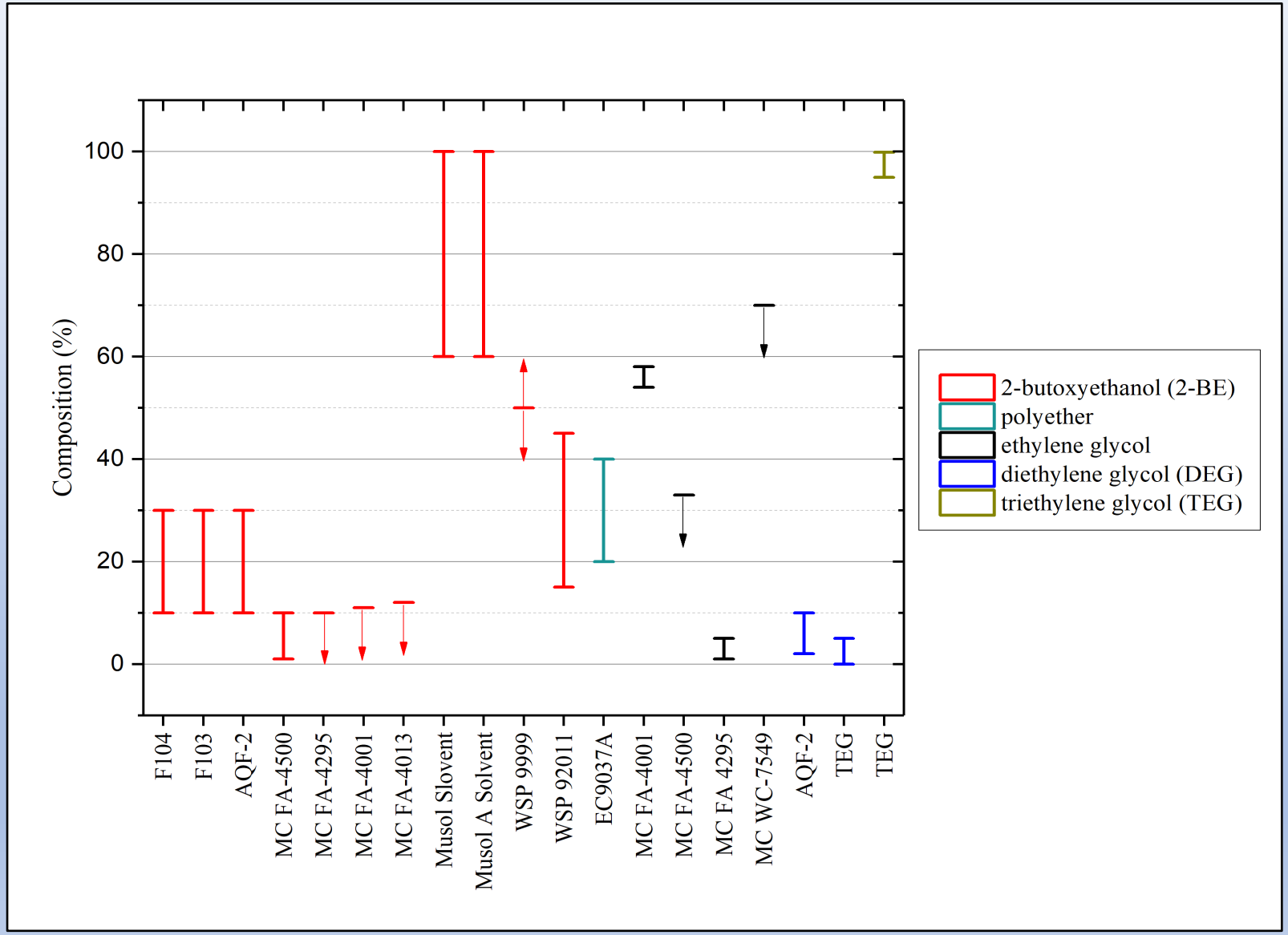
Ethoxylated Alcohols and Surfactants Used for Stimulation



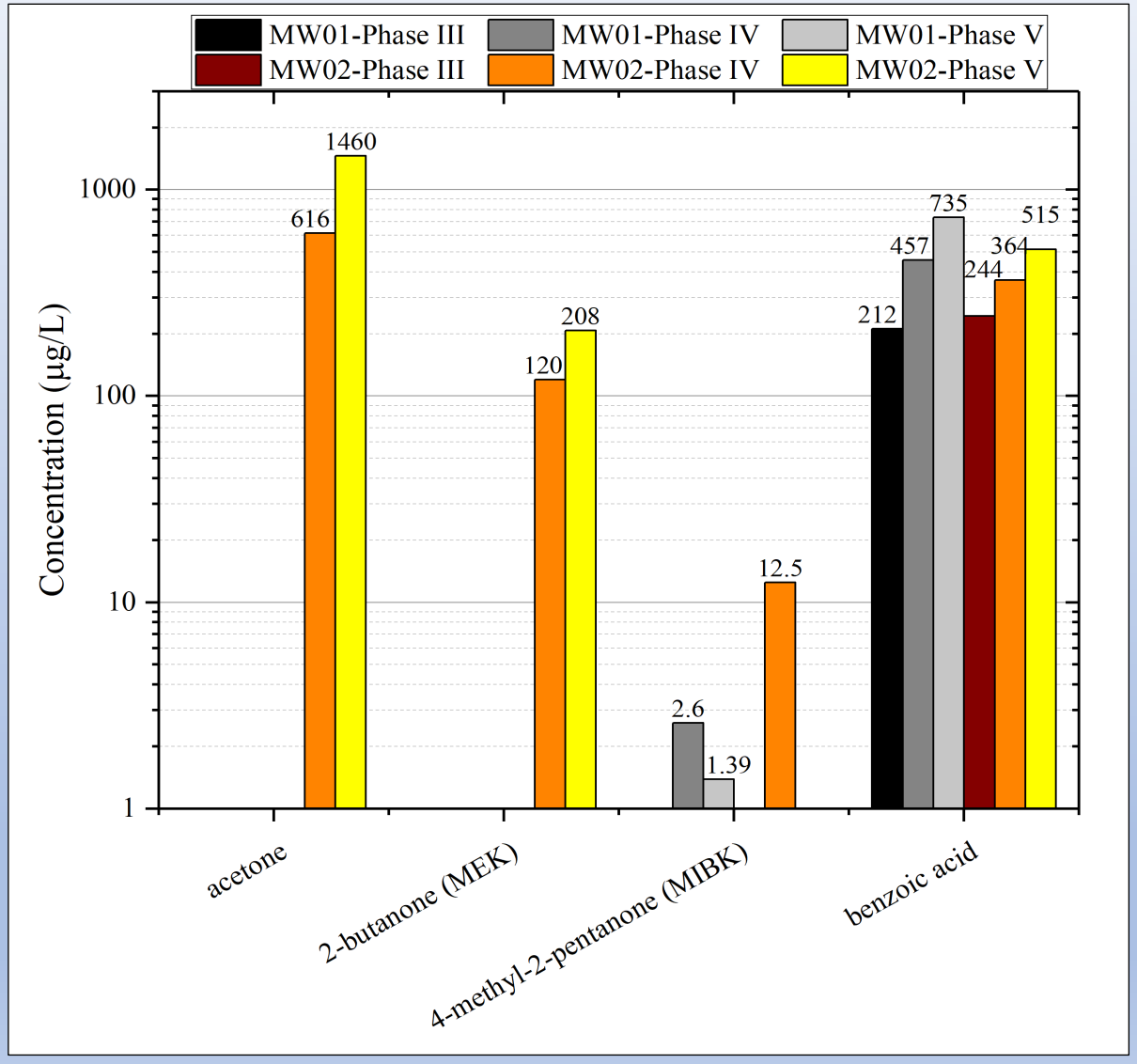
Detection of Glycols and 2-Butoxyethanol



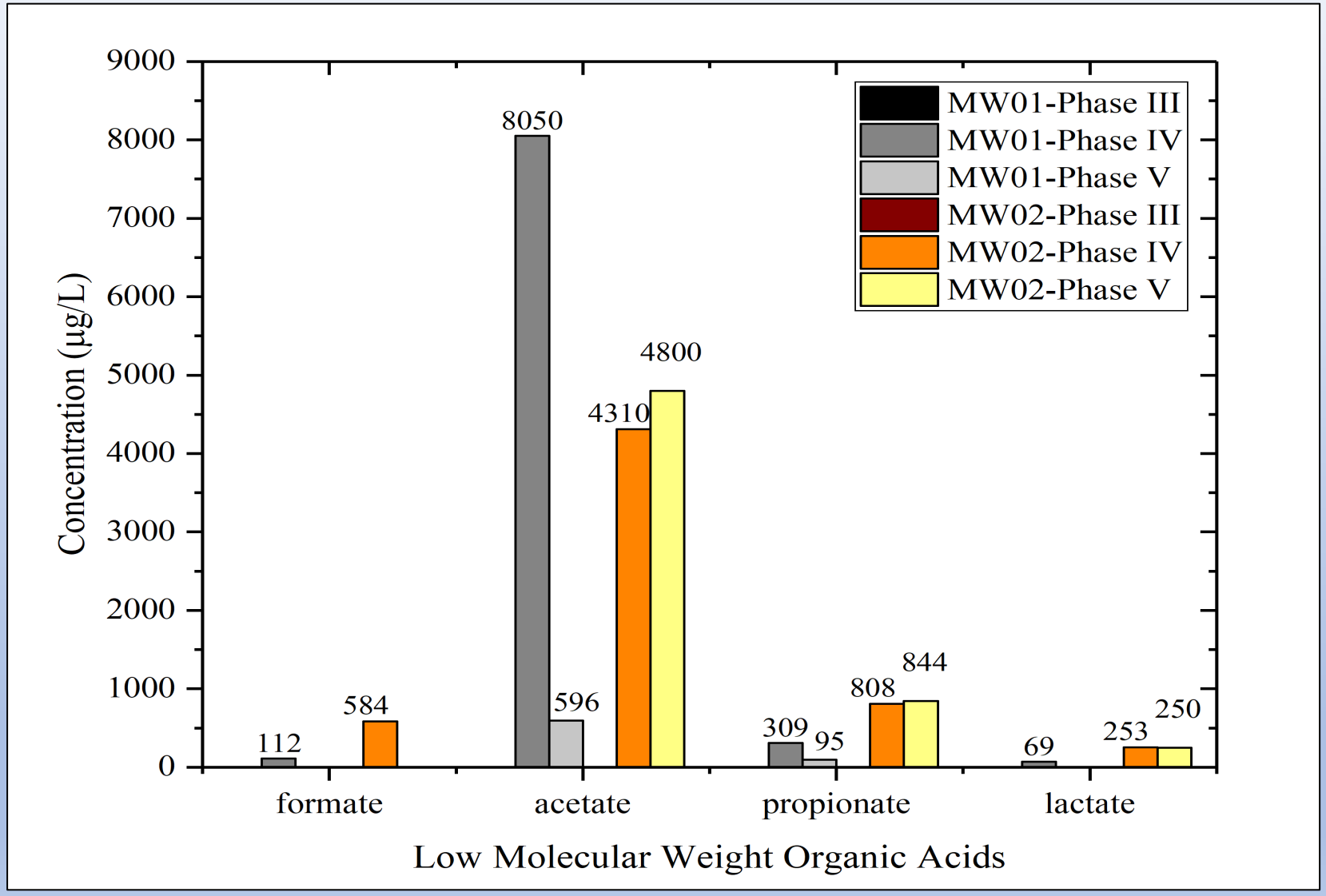
Glycols and 2-Butoxyethanol Used for Stimulation



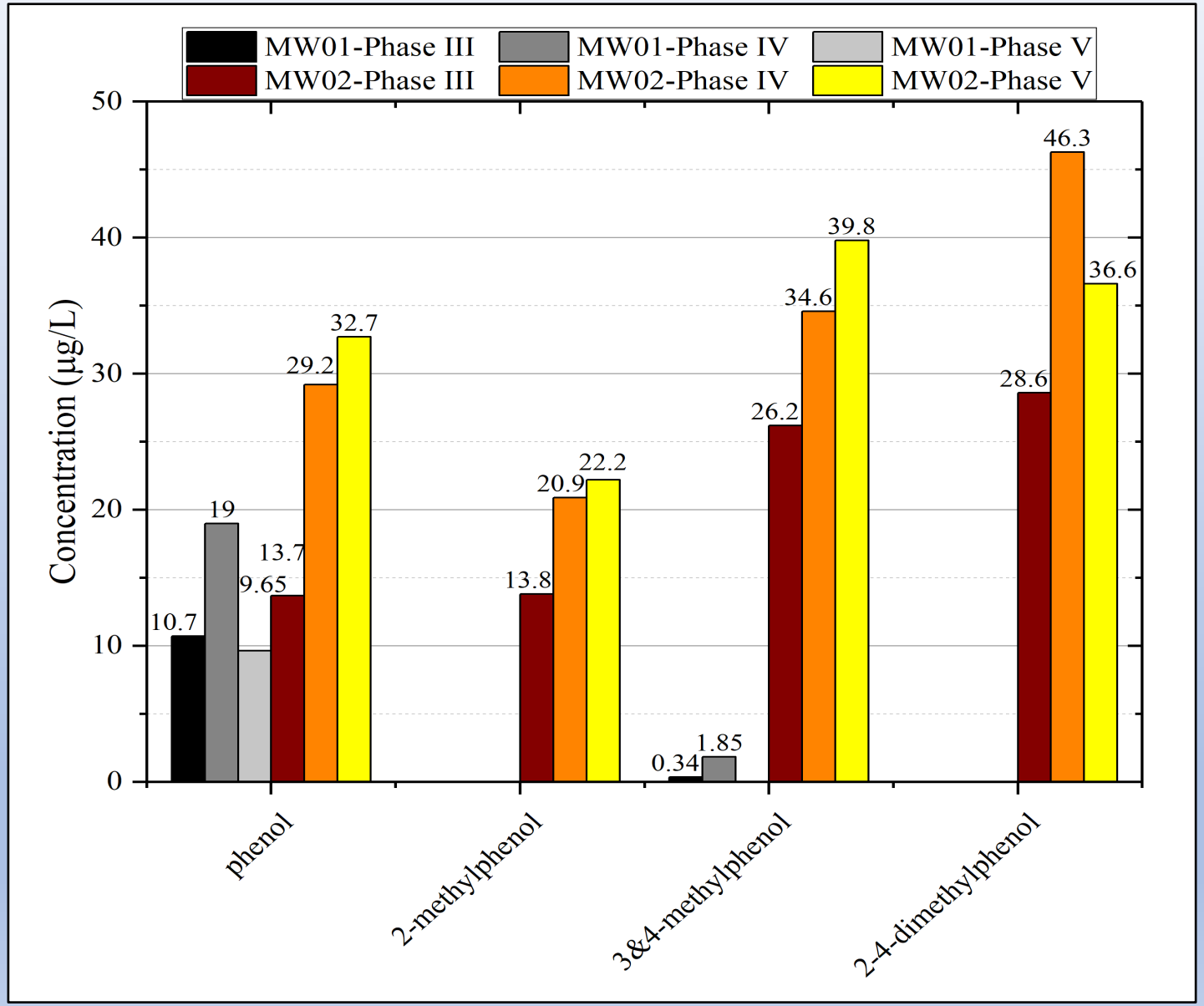
Detection of Degradation Products



Detection of Degradation Products



Detection of Degradation Products



Conclusions

- Criteria for protected groundwater in states are ambiguous and in many cases do not protect brackish groundwater to the standard of an USDW.
- As demonstrated by data from the Pavillion, WY Field, hydraulic fracturing into USDWs is occurring.
- As demonstrated by data from the Pavillion, WY Field, impact to USDWs is occurring.

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