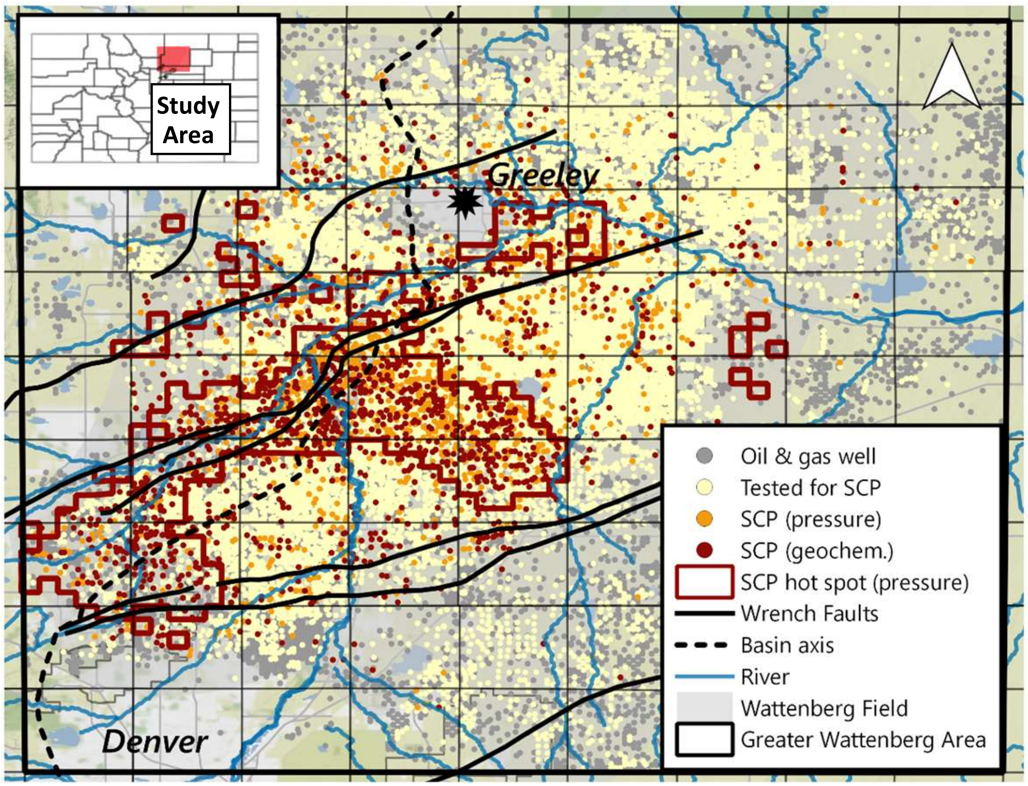
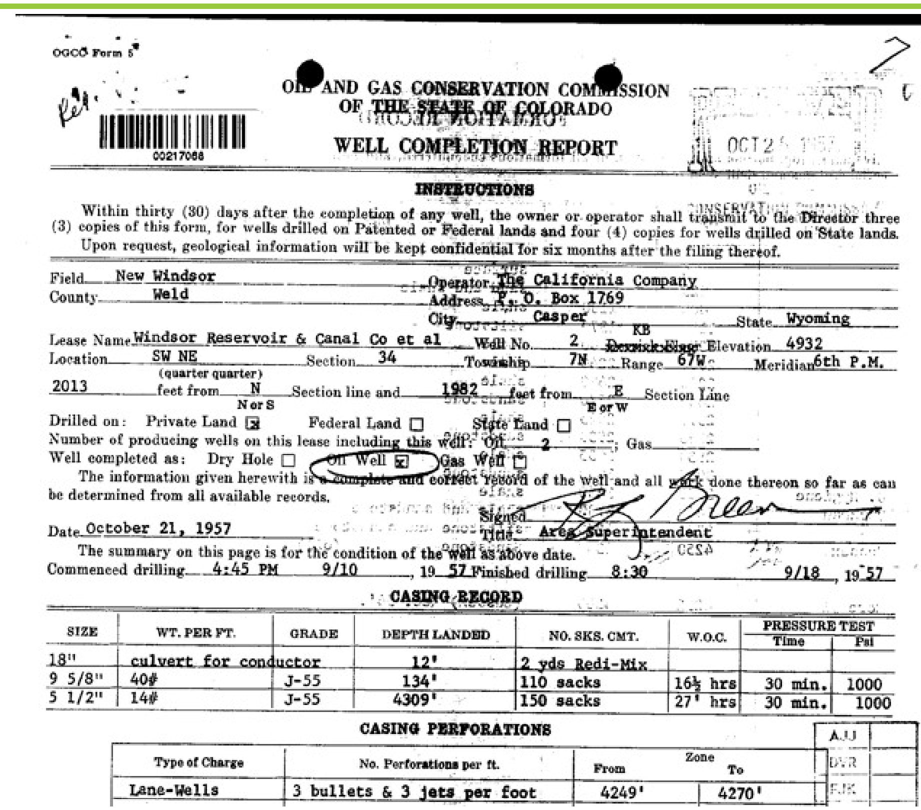
Data Driven Approaches for Understanding Well Integrity

2023 FECM/NETL Carbon Management Research Project Review Meeting

August 28, 2023

Greg Lackey
Research Engineer, NETL





OGCC Form 5

00217066

OIL AND GAS CONSERVATION COMMISSION
OF THE STATE OF COLORADO

WELL COMPLETION REPORT

OCT 2

INSTRUCTIONS

Within thirty (30) days after the completion of any well, the owner or operator shall transmit to the Director three (3) copies of this form, for wells drilled on Patented or Federal lands and four (4) copies for wells drilled on State lands. Upon request, geological information will be kept confidential for six months after the filing thereof.

Field New Windsor — Operator The California Company
County Weld — Address P. O. Box 1769
City Casper — State Wyoming

Lease Name Windsor Reservoir & Canal Co et al — Well No. 2 — KB Elevation 4932
Location SW NE (quarter quarter) — Section 34 — Township 7N — Range 67W — Meridian 6th P.M.
2013 feet from N (N or S) Section line and 1982 feet from E (E or W) Section Line

Drilled on: Private Land ☒ Federal Land ☐ State Land ☐
Number of producing wells on this lease including this well: Oil 2; Gas
Well completed as: Dry Hole ☐ Oil Well ☒ Gas Well ☐

The information given herewith is a complete and correct record of the well and all work done thereon so far as can be determined from all available records.

Signed
Date October 21, 1957 — Title Area Superintendent

The summary on this page is for the condition of the well as above date.
Commenced drilling 4:45 PM 9/10, 19 57 Finished drilling 8:30 9/18, 19 57

CASING RECORD

SIZE	WT. PER FT.	GRADE	DEPTH LANDED	NO. SKS. CMT.	W.O.C.	PRESSURE TEST Time	PRESSURE TEST Psi
18"	culvert for conductor		12'	2 yds Redi-Mix			
9 5/8"	40#	J-55	134'	110 sacks	16½ hrs	30 min.	1000
5 1/2"	14#	J-55	4309'	150 sacks	27' hrs	30 min.	1000

CASING PERFORATIONS

Type of Charge	No. Perforations per ft.	Zone From	Zone To
Lane-Wells	3 bullets & 3 jets per foot	4249'	4270'

Disclaimer

This project was funded by the U.S. Department of Energy, National Energy Technology Laboratory, in part, through a site support contract. Neither the United States Government nor any agency thereof, nor any of their employees, nor the support contractor, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Authors and Contact Information

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[2]*National Energy Technology Laboratory, 1450 Queen Avenue SW, Albany, OR 97321, USA*

[3]*NETL Support Contractor, 1450 Queen Avenue SW, Albany, OR 97321, USA*

[4]*National Energy Technology Laboratory, 3610 Collins Ferry Road, Morgantown, WV 26505, USA*

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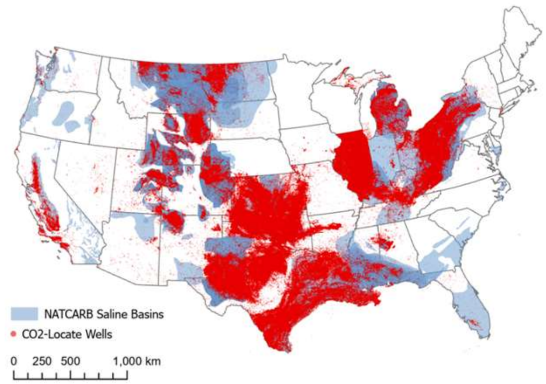
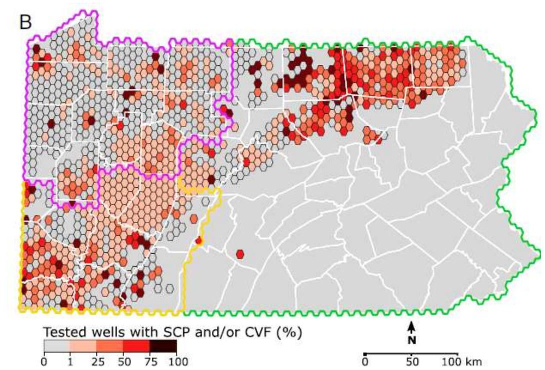
Motivation

- Millions of active and abandoned wells in the United States
- Historic overlap between drilling and valuable formations for GCS
- Well integrity is a potential leakage risk that varies spatially among well types, configurations, and construction
- Generally poor documentation of well construction, use, and integrity history

Need to understand drivers of well integrity issues to better characterize leakage risks



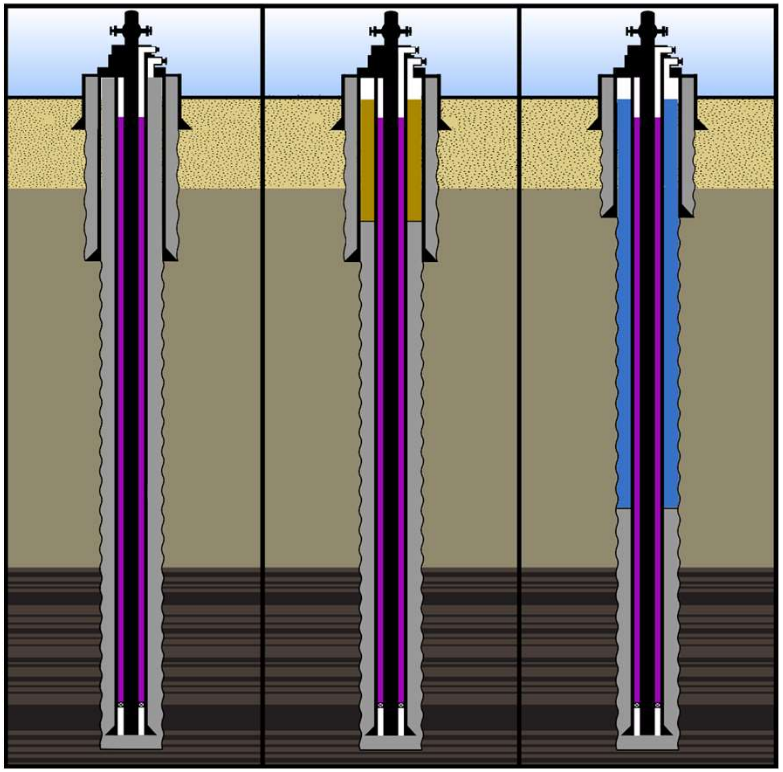
(Romeo et al., 2023)



(Lackey et al., 2021)

Potential Well Leakage Pathways

- **Well integrity**
  - Controlled production/injection of fluids
  - Isolate formation fluids along depth



Potential Well Leakage Pathways

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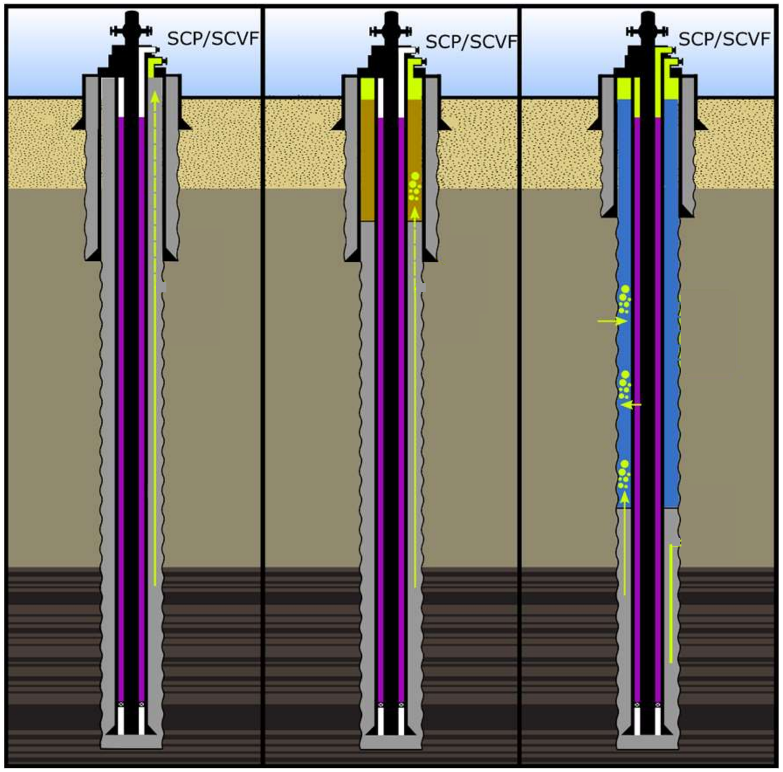
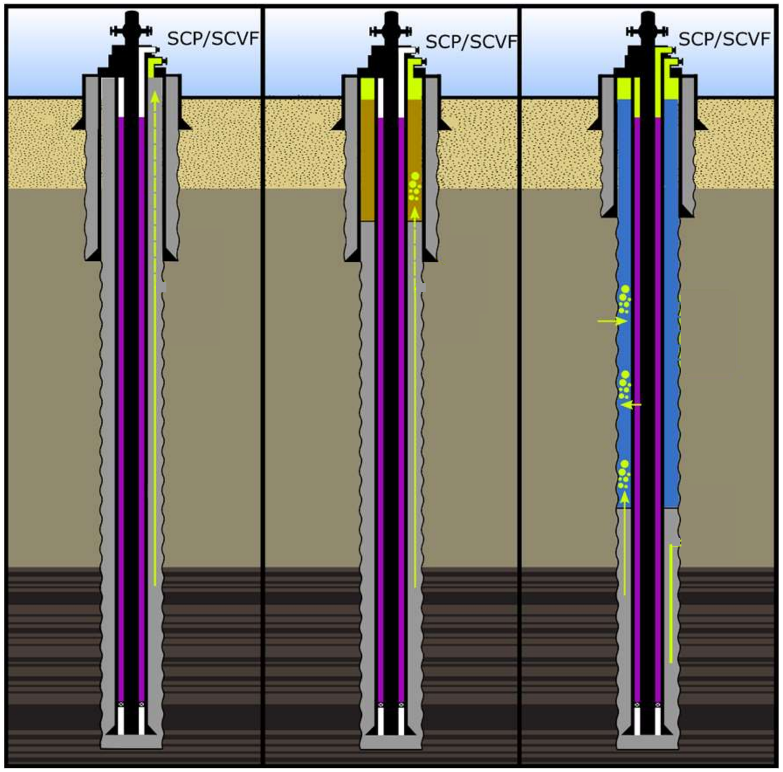
  - Improper cement seal
  - Faulty steel casing
  - Fluid invasion from an intermediate



Potential Well Leakage Pathways

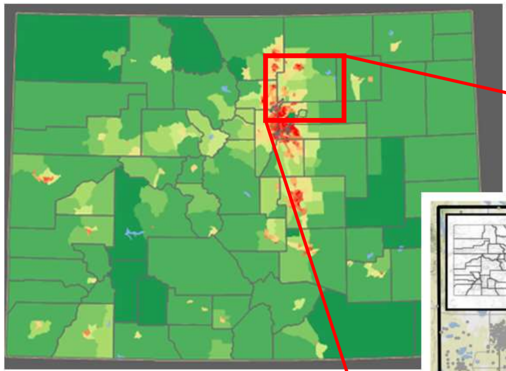
- **Well integrity**
  - Controlled production/injection of fluids
  - Isolate formation fluids along depth
- **Integrity issues:**
  - Improper cement seal
  - Faulty steel casing
  - Fluid invasion from an intermediate
- **Integrity testing methods:**
  - Sustained casing pressure (SCP)/casing-vent flow (CVF)
  - Annular geochemical sampling
  - Temperature log, noise log, bond log, pressure fall off tests (SAPT)



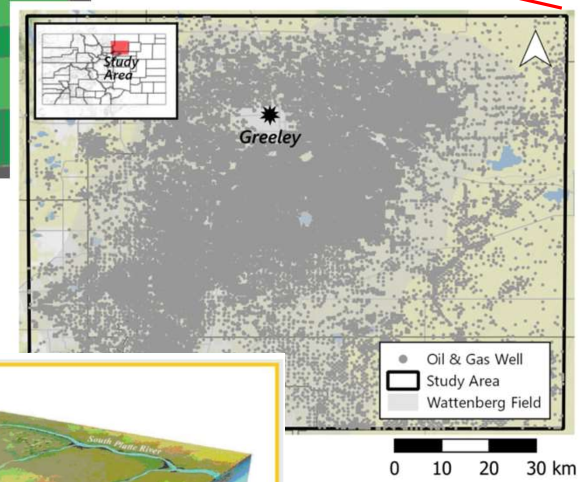
Study Area - The Wattenberg Field

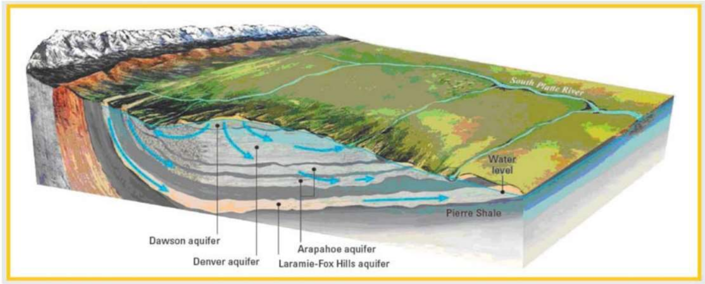
- Regional well integrity monitoring since 2010
- CO Energy & Carbon Management Commission (ECMC) a leader in data availability
- Annular pressure monitoring and geochemical sampling
- Relatively high frequency of integrity issues

Data availability and integrity challenges make the Wattenberg Field an ideal case study



(Wikimedia Commons, 2022)

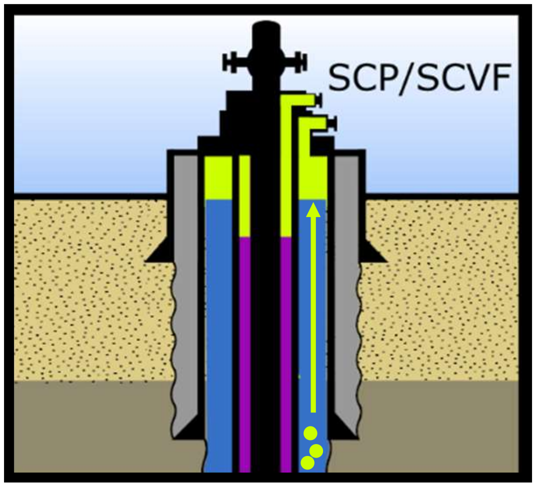




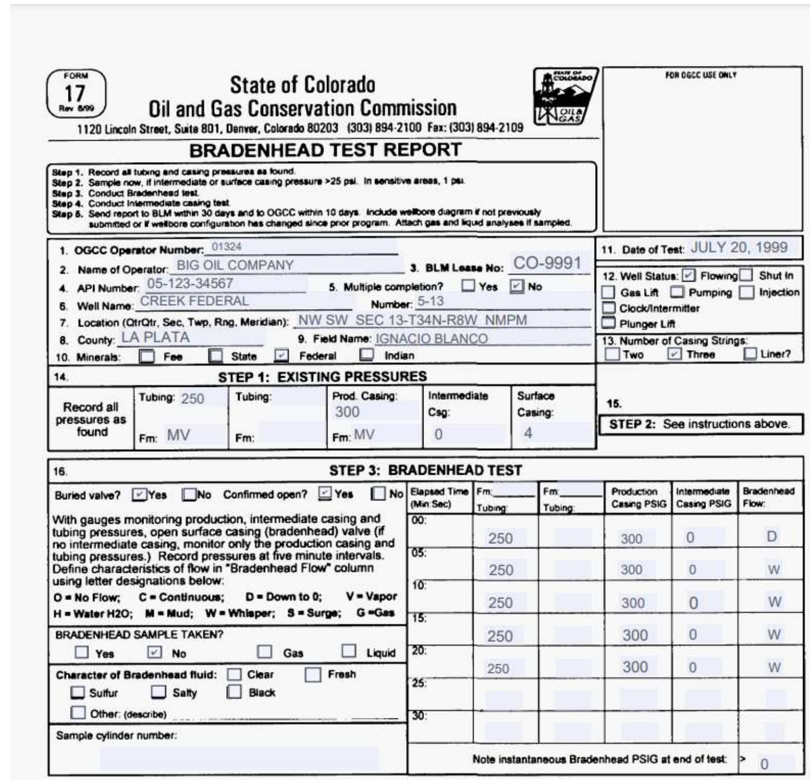
(Paschke et al., 2011)

Integrity Testing Requirements

NATIONAL ENERGY TECHNOLOGY LABORATORY



- Routine inspections for Sustained Casing Pressure (SCP)
  - Began in 2010; expanded in 2019
- Pressure check and 30 min bleed-off
- Fluids collected if produced during test



FORM 17 Rev 6/99

State of Colorado
Oil and Gas Conservation Commission
1120 Lincoln Street, Suite 801, Denver, Colorado 80203 (303) 894-2100 Fax: (303) 894-2109

FOR OGCC USE ONLY

BRADENHEAD TEST REPORT

Step 1. Record all tubing and casing pressures as found.
Step 2. Sample now, if intermediate or surface casing pressure >25 psi. In sensitive areas, 1 psi.
Step 3. Conduct Bradenhead test.
Step 4. Conduct Intermediate casing test.
Step 5. Send report to BLM within 30 days and to OGCC within 10 days. Include wellbore diagram if not previously submitted or if wellbore configuration has changed since prior program. Attach gas and liquid analyses if sampled.

1. OGCC Operator Number: 01324
2. Name of Operator: BIG OIL COMPANY
3. BLM Lease No: CO-9991
4. API Number: 05-123-34567
5. Multiple completion? ☐ Yes ☑ No
6. Well Name: CREEK FEDERAL Number: 5-13
7. Location (QtrQtr, Sec, Twp, Rng, Meridian): NW SW SEC 13-T34N-R8W NMPM
8. County: LA PLATA
9. Field Name: IGNACIO BLANCO
10. Minerals: ☐ Fee ☐ State ☑ Federal ☐ Indian
11. Date of Test: JULY 20, 1999
12. Well Status: ☑ Flowing ☐ Shut In ☐ Gas Lift ☐ Pumping ☐ Injection ☐ Clock/Intermitter ☐ Plunger Lift
13. Number of Casing Strings: ☐ Two ☑ Three ☐ Liner?

14. STEP 1: EXISTING PRESSURES

Record all pressures as found	Tubing: 250	Tubing:	Prod. Casing: 300	Intermediate Csg:	Surface Casing:
	Fm: MV	Fm:	Fm: MV	0	4

15. STEP 2: See instructions above.

16. STEP 3: BRADENHEAD TEST

Buried valve? ☑ Yes ☐ No Confirmed open? ☑ Yes ☐ No

With gauges monitoring production, intermediate casing and tubing pressures, open surface casing (bradenhead) valve (if no intermediate casing, monitor only the production casing and tubing pressures.) Record pressures at five minute intervals. Define characteristics of flow in "Bradenhead Flow" column using letter designations below:

O = No Flow; C = Continuous; D = Down to 0; V = Vapor
H = Water H2O; M = Mud; W = Whisper; S = Surge; G = Gas

BRADENHEAD SAMPLE TAKEN? ☐ Yes ☑ No ☐ Gas ☐ Liquid

Character of Bradenhead fluid: ☐ Clear ☐ Fresh ☐ Sulfur ☐ Salty ☐ Black ☐ Other: (describe)

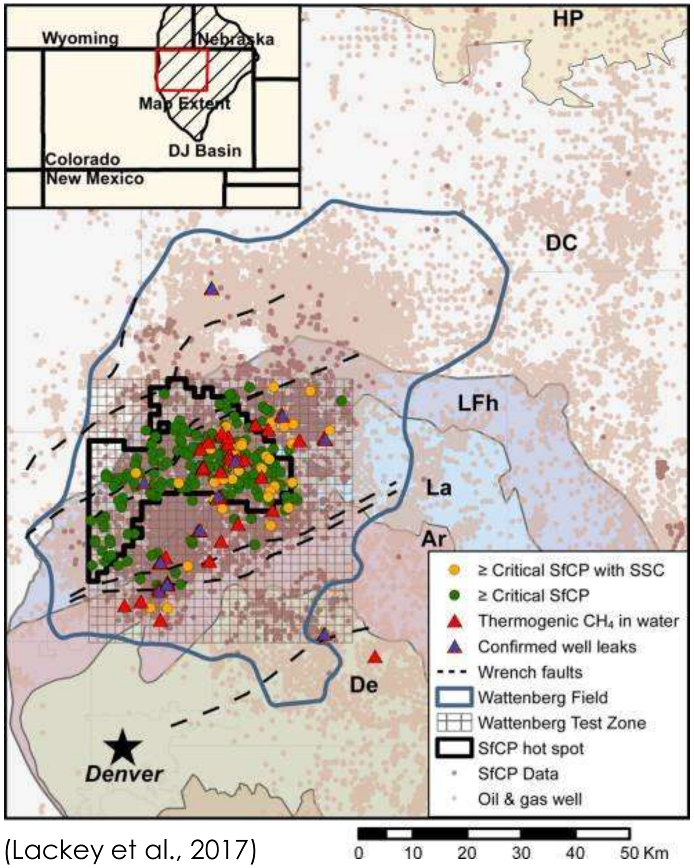
Sample cylinder number:

Elapsed Time (Min:Sec)	Fm: ___ Tubing	Fm: ___ Tubing	Production Casing PSIG	Intermediate Casing PSIG	Bradenhead Flow:
00:	250		300	0	D
05:	250		300	0	W
10:	250		300	0	W
15:	250		300	0	W
20:	250		300	0	W
25:					
30:					

Note instantaneous Bradenhead PSIG at end of test: > 0

Previous Work

- **<u>2017:</u>** Analysis of SCP occurrence and well construction prior to 2016
  - SCP in 13.8% of 3,923 wells tested
  - Logistic regression model (poor performance)



(Lackey et al., 2017)

Previous Work

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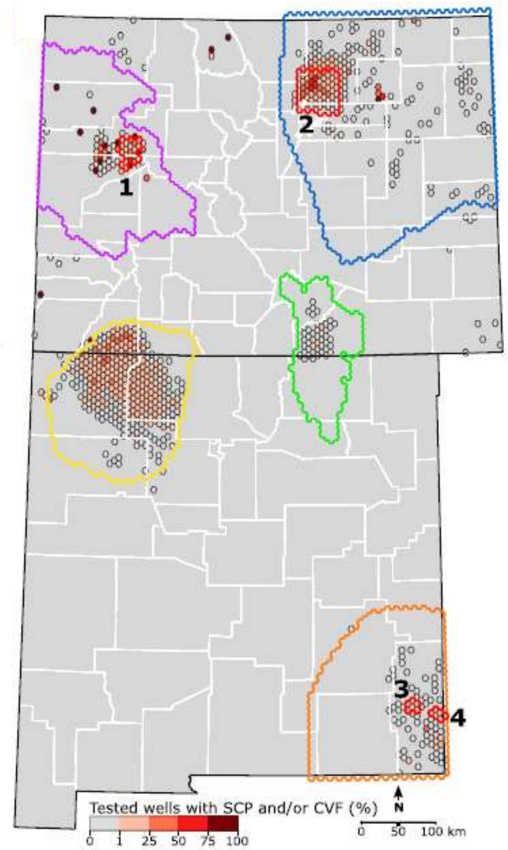
- **<u>2021:</u>** Analysis of SCP occurrence prior to 2018 across multiple states
  - SCP in 26.5% of 11,394 wells tested



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Previous Work

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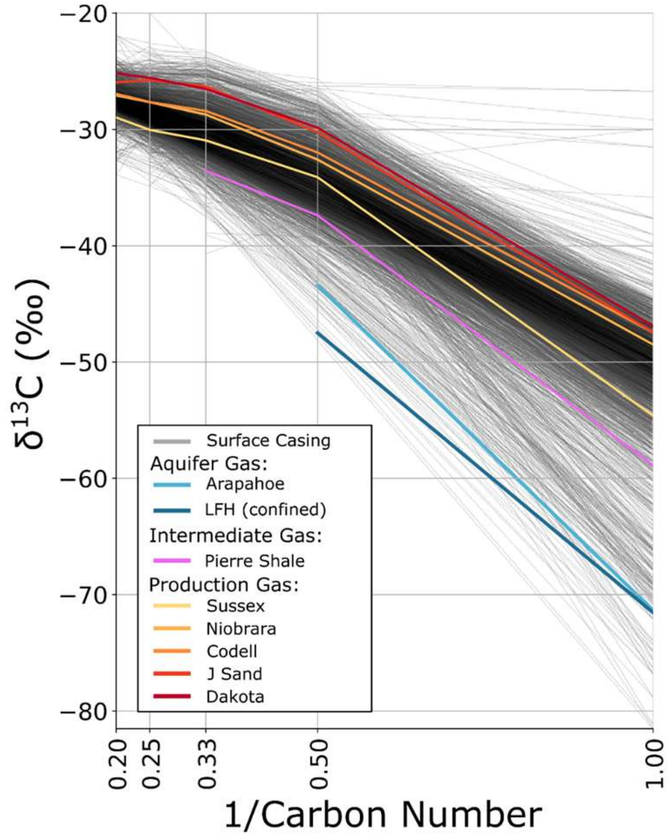
- **2021:** Analysis of SCP occurrence prior to 2018 across multiple states
  - SCP in 26.5% of 11,394 wells tested
- **2022:** Analysis of geochemical samples collected from well annuli with respect to well construction
  - Thermogenic gas in 96.2% of 2,148 wells
  - Gas from below cement top in 73.3% of 1,803 wells

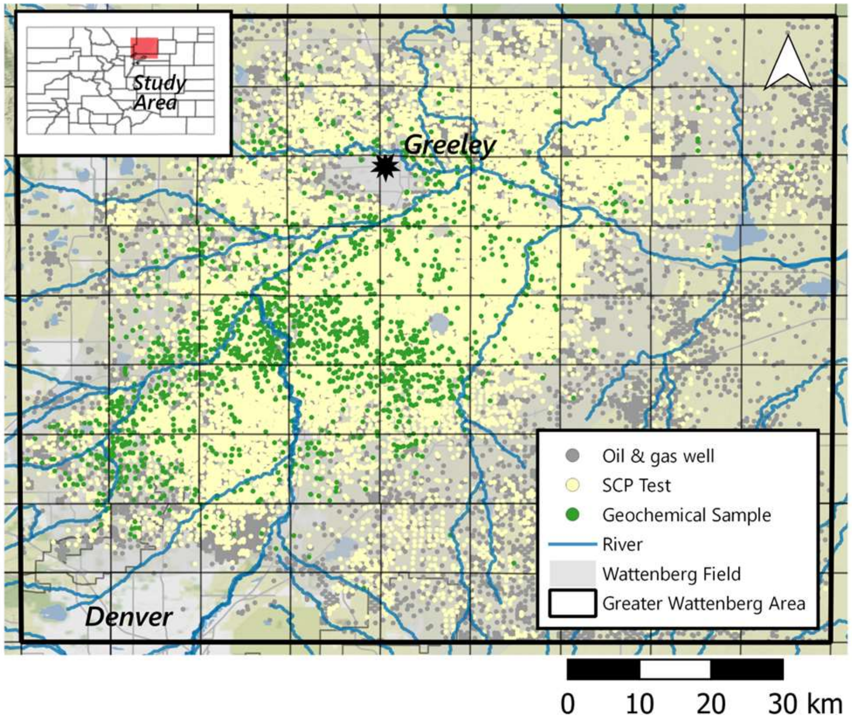
Well integrity issues are common in Wattenberg Field and primarily due to barrier failure



(Lackey et al., 2022)

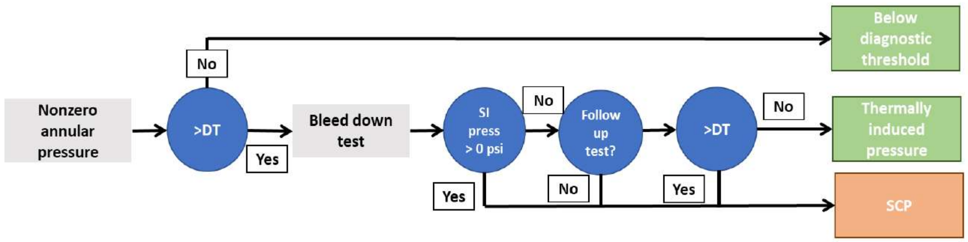
Expanded Integrity Testing Dataset

- ECMC records gathered through end of 2019
- Dataset expanded:
  - SCP tests from 26,375 wells
  - Geochemical samples from 2,148 wells
- Complementary records gathered from proprietary sources (Enverus)
- 106 attributes that describe:
  - Location, underlying geology, construction, operation, and production history

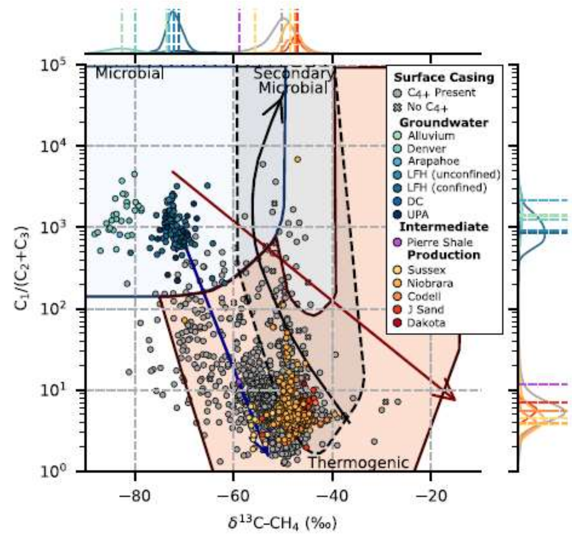


Well Integrity Evaluation

- SCP (Pressure)
  - API RP 90-2
  - 345 kPa (50 psi) diagnostic threshold
  - Pressure did not bleed to zero
  - Bled to zero but multiple tests above threshold
- SCP (Geochem.)
  - Presence of thermogenic gas (C_{4+}) hydrocarbons



(Lackey et al., 2021)



(Lackey et al., 2022)

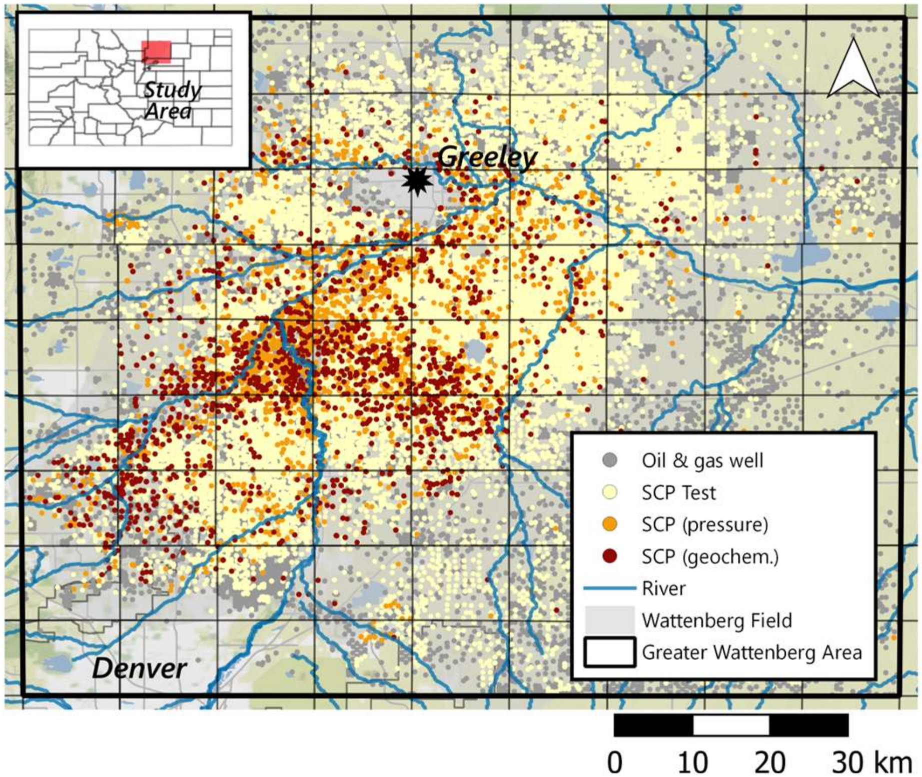
Integrity Issue Occurrence

NATIONAL ENERGY TECHNOLOGY LABORATORY

- SCP testing expanded to all active wells
- 26.5% (2021) to 17.1%
- 8.2% of wells with thermogenic gas

Category	All Wells (%)
Tested	26,332
SCP (Pressure)	4,490 (17.1%)
SCP (Geochem.)	2,159 (8.2%)

New data has decreased estimates of percentage of wells with integrity issues

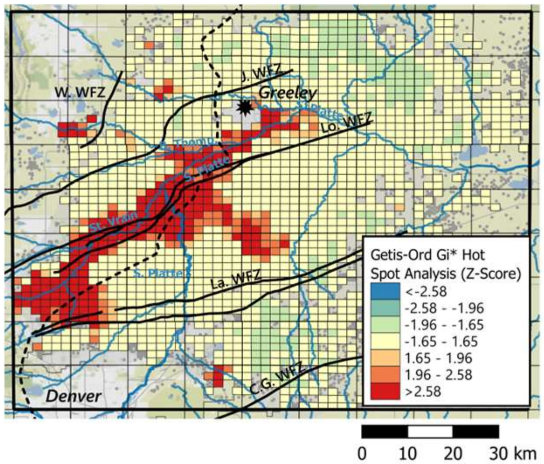


Spatiotemporal Analysis

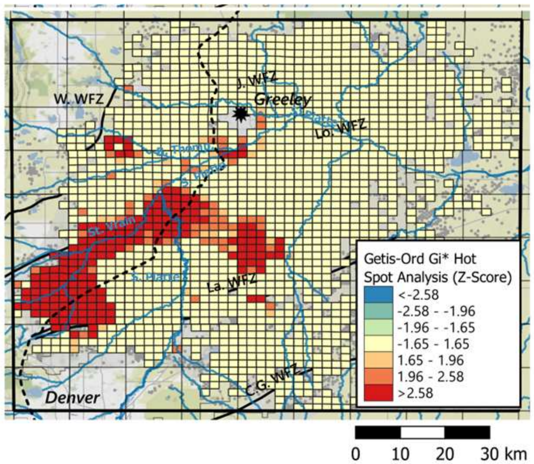
- Getis-Ord GI* hotspot analysis on percentage of wells in each section
- Yearly percentage of wells that exceed diagnostic threshold

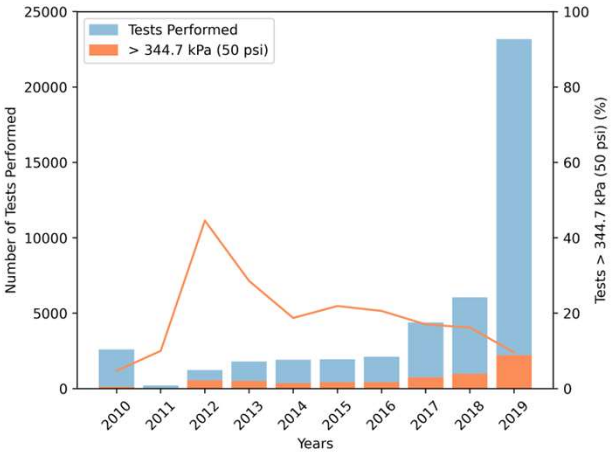
Statistically significant hotspot of well integrity issue occurrence. No significant temporal trend.

SCP Pressure



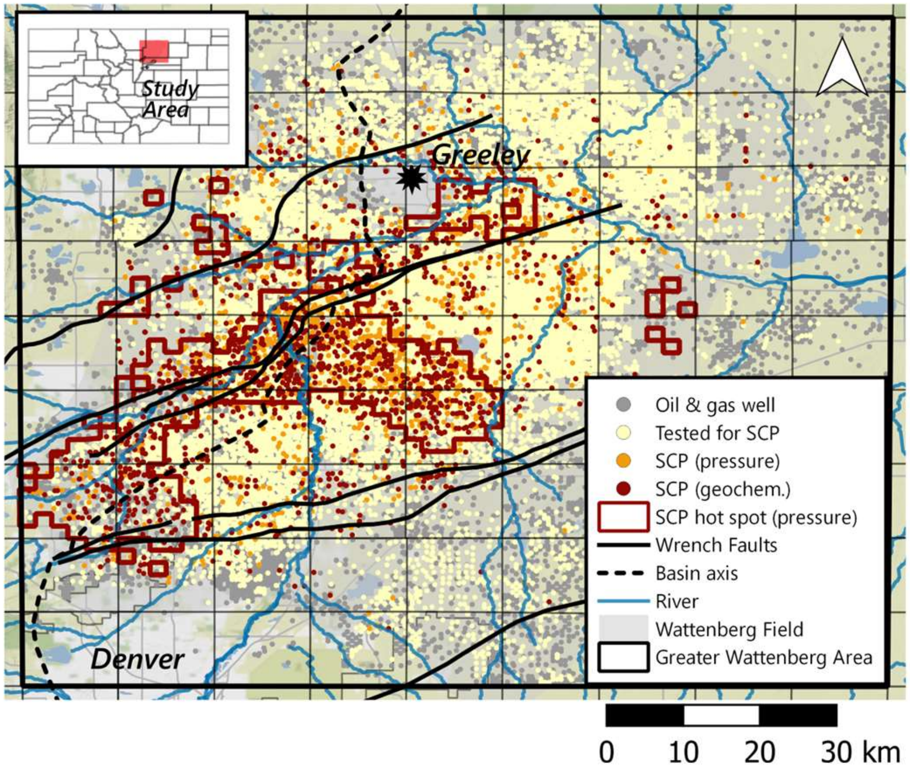
SCP Geochem





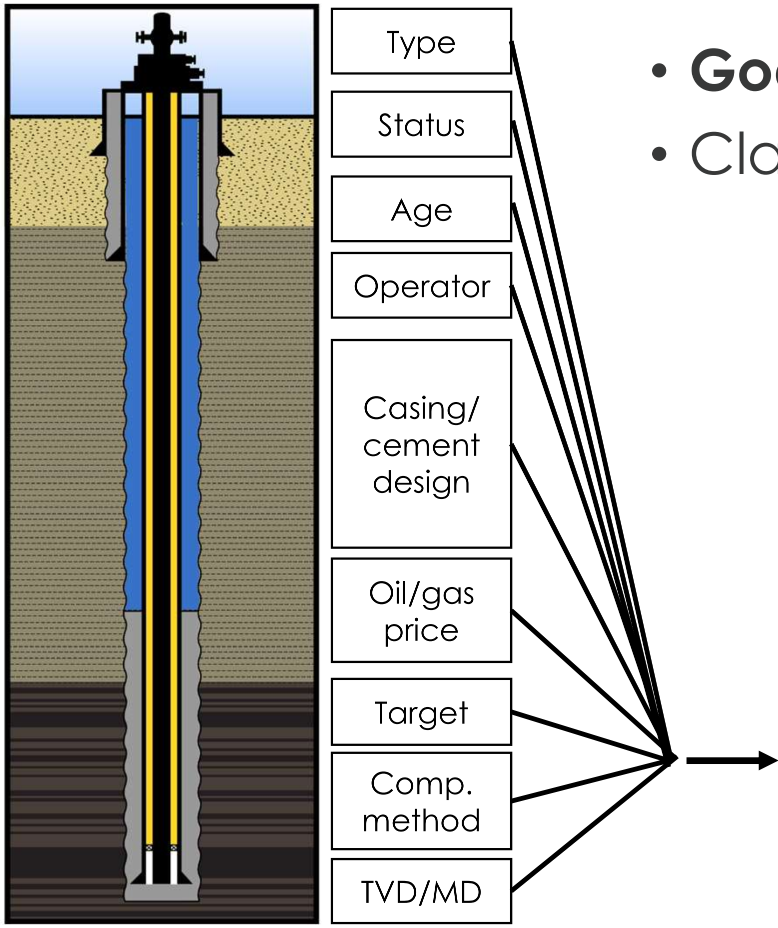
Impact of Hot Spot

Category	All (%)	Vert. (%)	Dev. (%)	Horiz. (%)
Inside Hot Spot				
Tested	6,914	3,453	1,792	1,627
SCP (pressure)	2,614 (37.8%)	1,193 (34.5%)	816 (45.5%)	589 (36.2%)
SCP (geochem.)	1,329 (19.2%)	557 (16.1%)	490 (27.3%)	267 (16.4%)
Outside Hot Spot				
Tested	19,418	10,437	2,984	5,919
SCP (pressure)	1,876 (9.7%)	692 (6.6%)	434 (14.5%)	740 (12.5%)
SCP (geochem.)	830 (4.3%)	317 (3.0%)	239 (8.0%)	263 (4.4%)



Greater than three-fold increase in percent of wells with SCP inside the hotspot

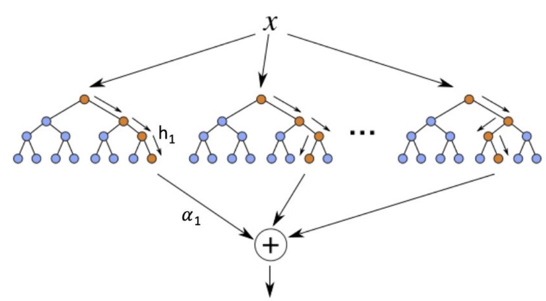
Modeling SCP Occurrence

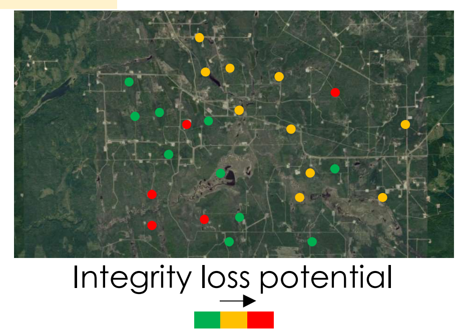


- **Goal:** binary prediction of well integrity
- Classifiers considered:

Model	F1 Score	AUC
Gradient Boosted	0.74	0.82
Random Forest	0.74	0.82
Logistic Regression	0.67	0.77

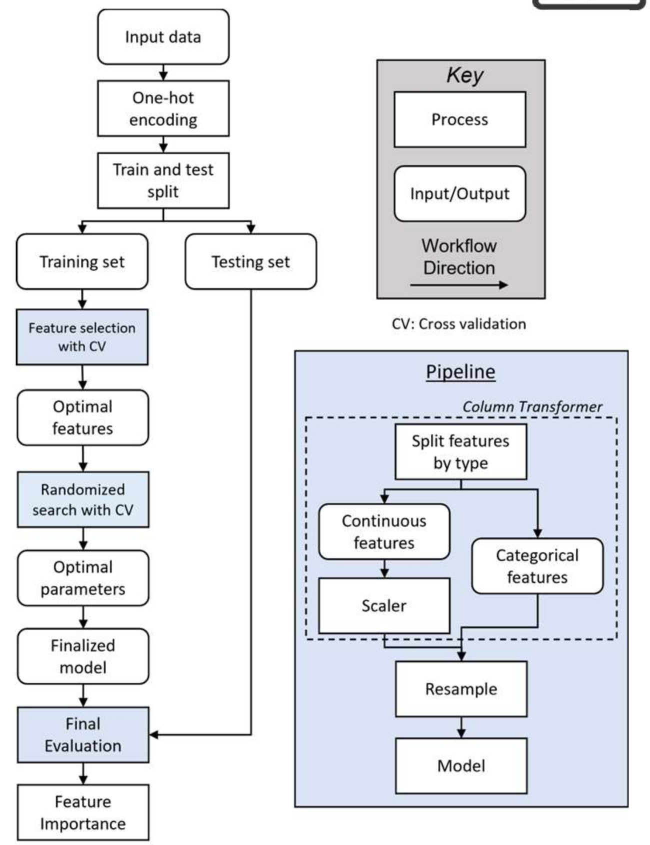
Using XGBoost Gradient Boosted Decision Tree Algorithm





Model Workflow

- Held out 30% for validation
- Under-sample to balance dataset
- KNN imputation (3.7% of dataset)
- 10-fold cross validation
- Recursive feature drop
- Hyper parameter tuning
- Early stopping
- **<u>Target:</u>** SCP (geochem.)

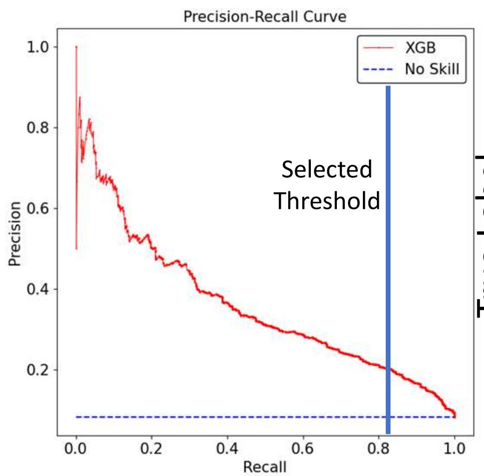


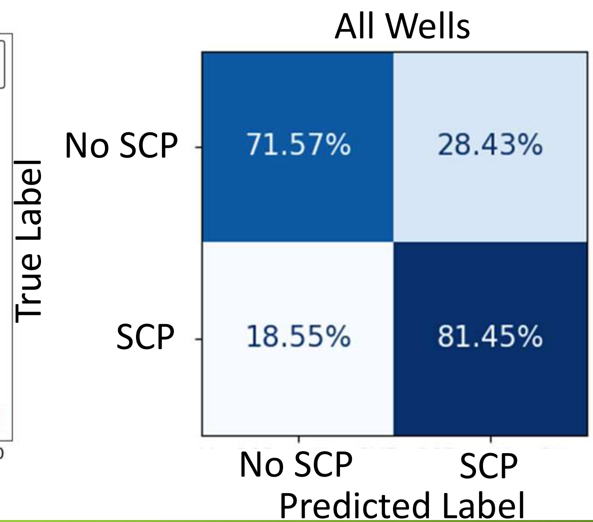
Model Performance – All Wells

- Reasonable classification power
- Held-out set:
  - 7,833 wells; 647 (8.3%) with SCP
  - 527 (81.5%) of 647 identified
  - 120 (18.6%) with SCP misclassified
- Favored precision over recall
  - 2,043 false positives
- Reduces wells considered by 67%
  - 20.5% in selected pool have SCP
  - 2.3% in non selected pool have SCP

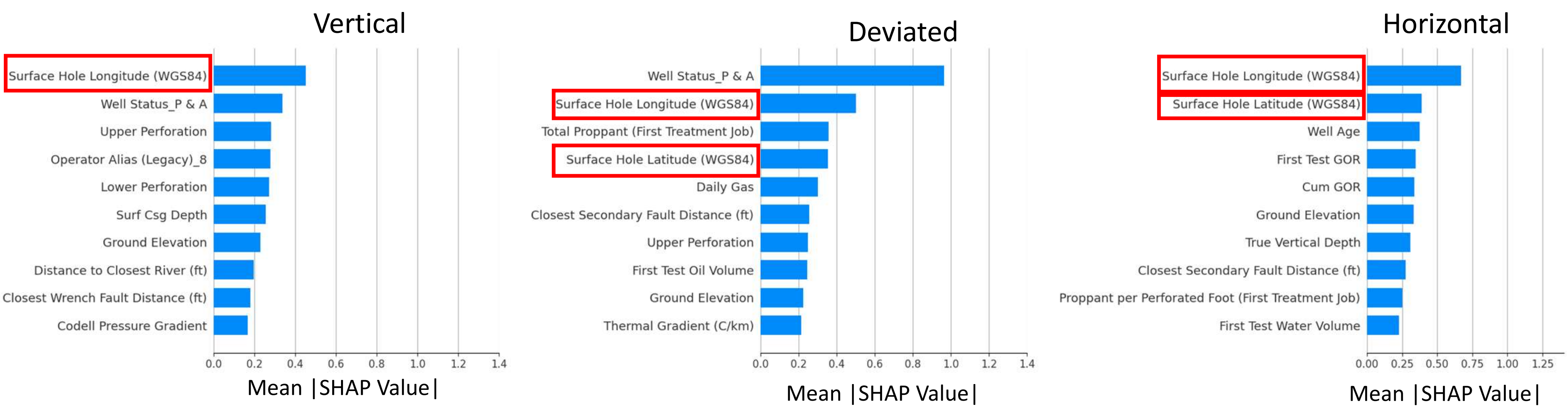
Model Useful for Risk Assessment

Metric	All
AUC	0.84
F1 Score	0.33
Recall	0.81
Precision	0.21





Importance of Location/Geology



- Strong spatial correlation in SCP occurrence among wells

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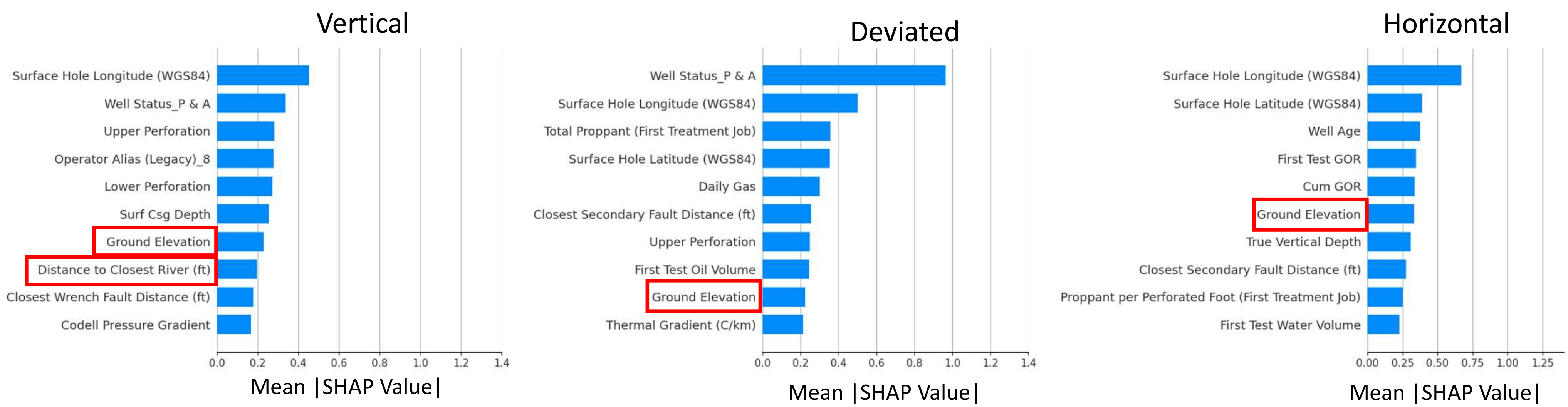

- Strong spatial correlation in SCP occurrence among wells
- Wells located in valleys are more likely to exhibit SCP

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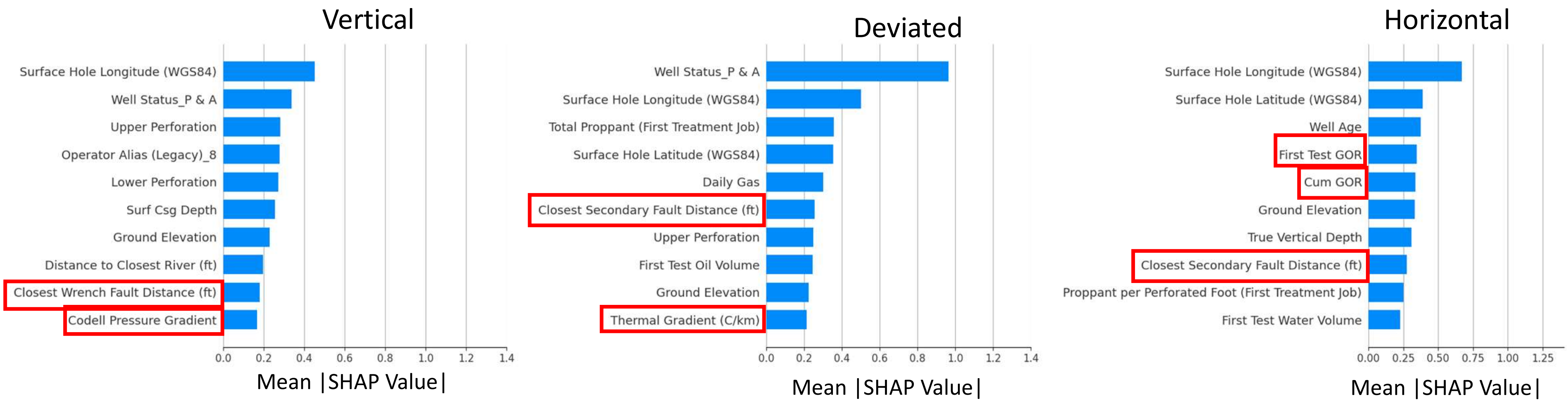
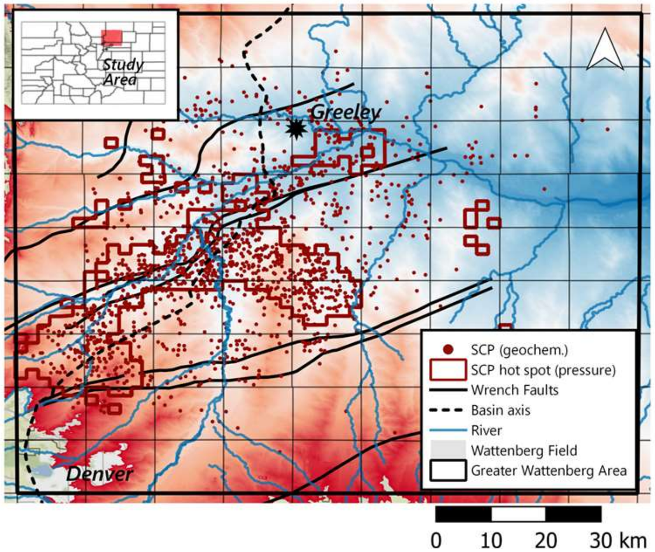
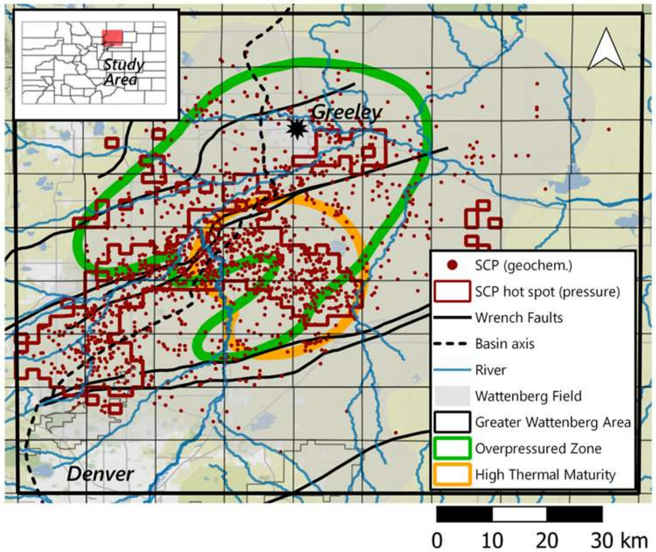


- Strong spatial correlation in SCP occurrence among wells
- Wells located in valleys are more likely to exhibit SCP
- Location with respect to faulting, over pressured zones, and thermal maturity also important

Feature Importance – Location/Geology

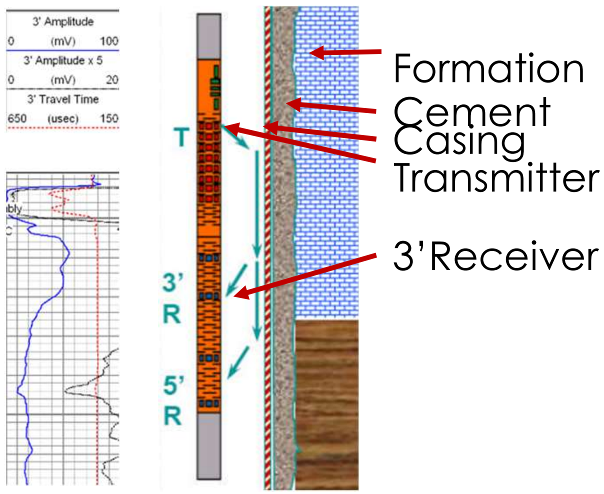
- Highly complex geology – nexus of basin axis and wrench fault system
- Aligns with path of St. Vrain Creek, South Platte River, and Longmont Wrench Fault
- Extension overlies region where source rocks have highest thermal maturity

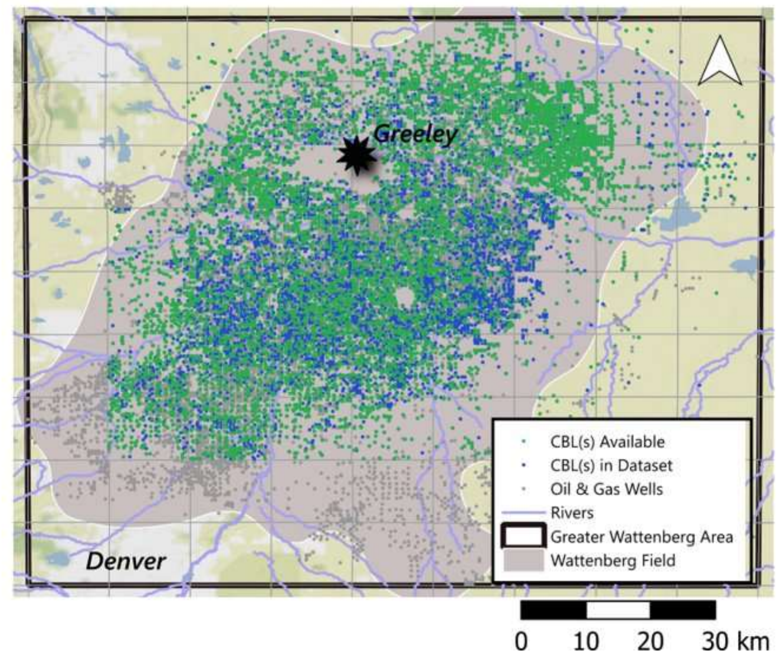




Incorporating Cement Quality

- Cement bond logs (CBLs) industry standard for interpreting quality of cement seal between casing and formation
- CBLs available for 18,639 tested wells in the Wattenberg Field

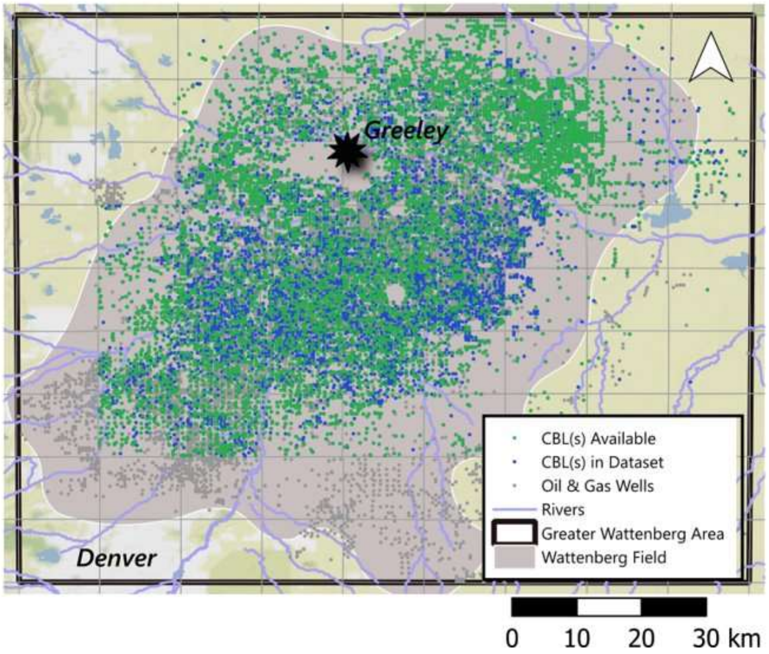




Incorporating Cement Quality

- Cement bond logs (CBLs) industry standard for interpreting quality of cement seal between casing and formation
- CBLs available for 18,639 tested wells in the Wattenberg Field
- CBLs downloaded for 13,464 wells

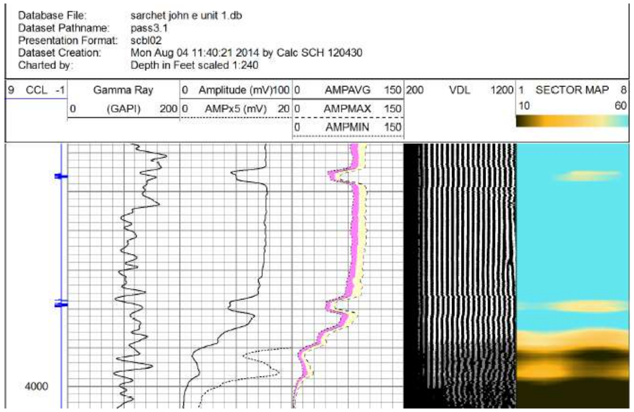
Sufficiently large dataset to identify relationships between cement quality and well integrity issues

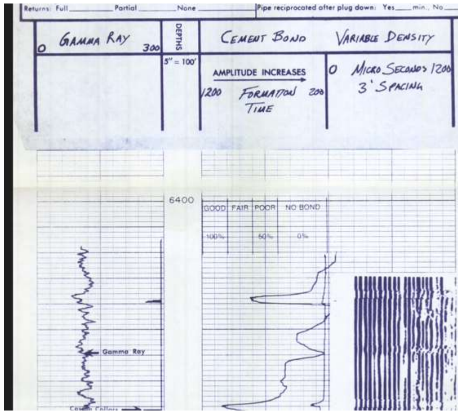


Bond Log Data

- **.LAS Files**
  - Amplitude
  - CCL
  - Gamma Ray
- **PDF files:**
  - Amplitude:
  - VDL
  - Gamma Ray
  - Collar Location
  - Sector Maps
  - Pressure

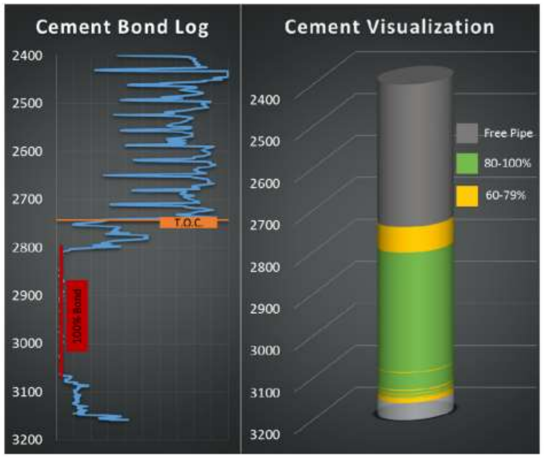

```
~Version Information
VERS.                          2.0: CWLS Log ASCII Standard - VERSION 2.0
WRAP.                           NO: One line per depth step
~Well Information Block
STRT.FT               1645.5000:
STOP.FT               7238.0000:
STEP.FT                  0.2500:
NULL.                 -999.2500:
COMP.          Noble Energy Inc.: COMPANY
WELL.          Dietrich C07-27DX: WELL
FLD.                Wattenberg: FIELD
LOC.           SHL: 200' FNL & 1305' FEL NENE--BHL: 99' FSL & 1366' FEL SWSE-- sec-7, twp-4N, rge-64W: LOCATION
CNTY.                     Weld: COUNTY
SRVC.          Superior well Services: SERVICE COMPANY
DATE.          Thu Oct 02 11-48-05 2008: LOG DATE
UWI.           05-123-27159-00: UNIQUE WELL ID
STAT.                     Colo: STATE
PROV.                         :
CTRY.                         :
~Curve Information Block
DEPT.FT              0 000 00 00: Depth
AMP3FT.mV                     : AMP3FT Amplitude
CCL.                          : Casing Collar Locator
GR_cbl.GAPI                   : Gamma Ray
~Parameter Information Block
~A  Depth      AMP3FT       CCL         GR_cbl
  1645.5000   -999.2500   -999.2500   -999.2500
  1645.7500   -999.2500      0.1157   -999.2500
  1646.0000   -999.2500     -0.0630   -999.2500
  1646.2500   -999.2500      0.0341   -999.2500
  1646.5000   -999.2500      0.0586   -999.2500
```



Bond Index Calculation

- Gather amplitude data from .las files
- Identify cement top
- Identify amplitude for 100% and 0% bond
- Calculate the bond index (BI) score
  - Good: 0.8-1
  - Mid: 0.6-0.79
  - Poor: 0.4-0.59
  - Worst: 0.0-0.4
- Derive cement quality parameters



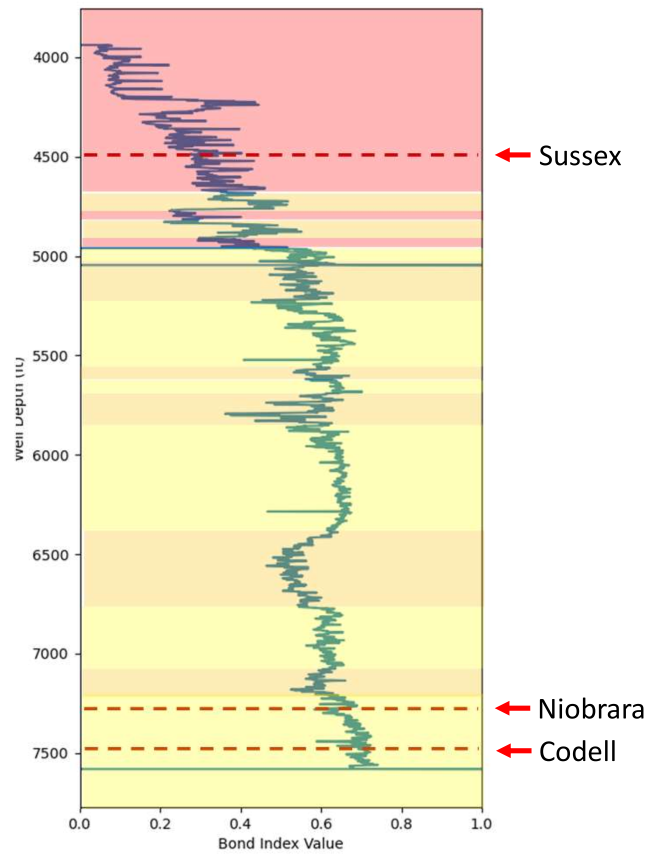
(Haagsma et al., 2015)

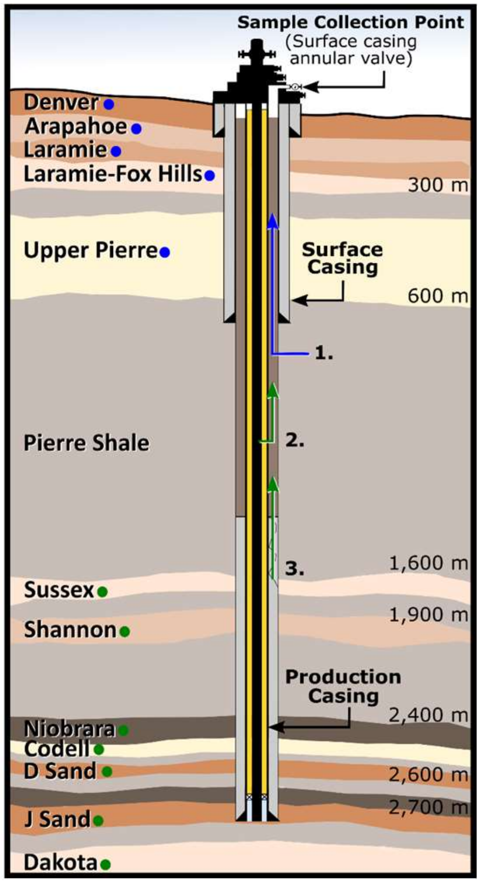
$$BI = \frac{Attenuation\ Measured\ Bond\ Index}{Maximum\ Attenuation}$$

(Bigelow, 1990)

CBL Model Parameters

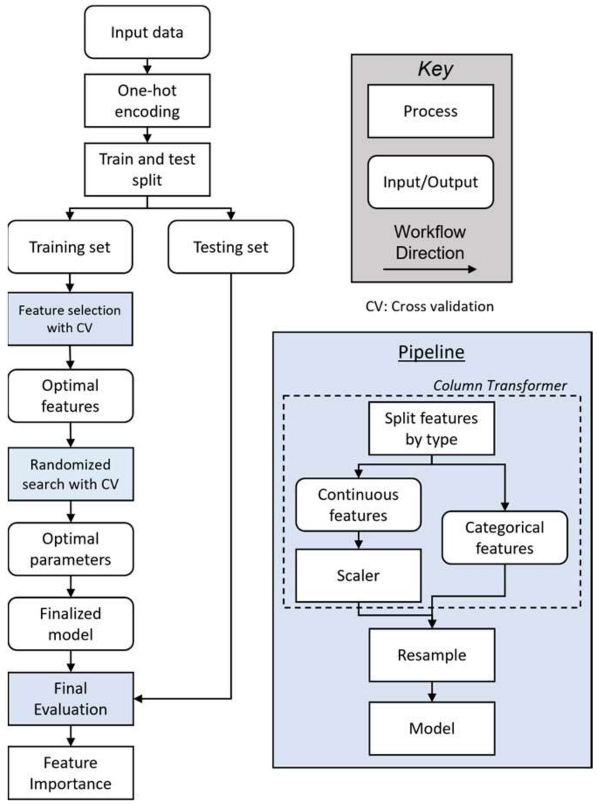
Model Parameters
Min. BI
Max BI
Total Average BI
Good Footage
Mid Footage
Poor Footage
Worst Footage
Top Third Avg.
Mid Third Avg.
Bottom Third Avg.
Sussex Avg.
Niobrara Avg.
Codell Avg.





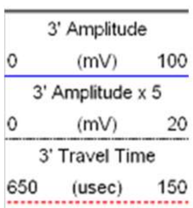
Ensemble Decision Tree Approach

- Ensemble decision tree model
- CBL data only model & combined model
- Confounding variables
  - Pressure applied during CBL
  - Eccentricity
  - Expert judgement

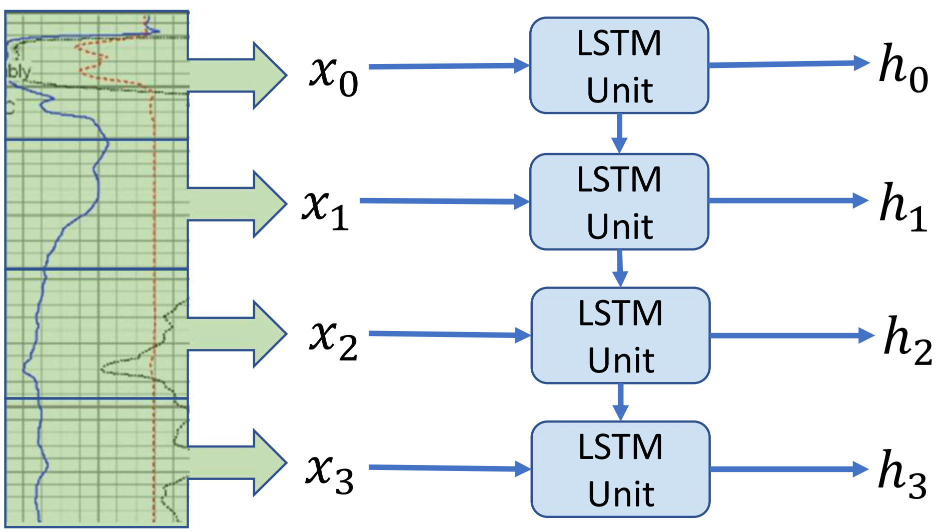


Alternative Modeling Approaches

Long Short-Term Memory Networks



The current state of the LSTM unit and "outputs" (hidden state) are used as inputs for the next interval of data



- Recurrent neural networks
- Architecture designed for sequential data (speech, text, sensor, financial)
- Sequential data processing preserves the order of the data
- Challenges:
  - long sequences
  - variable length
  - variable resolution (0.5' vs 1' intervals)

Model Application for GCS

GCS in the Denver Basin

- The Denver Basin contains 70% of all CO_2 storage capacity in Colorado
- 82 screened candidate oil and gas reservoirs in 31 fields have a total estimated capacity of 505 MMT and an average of 6.2 MMT per field (McPherson, 2006)

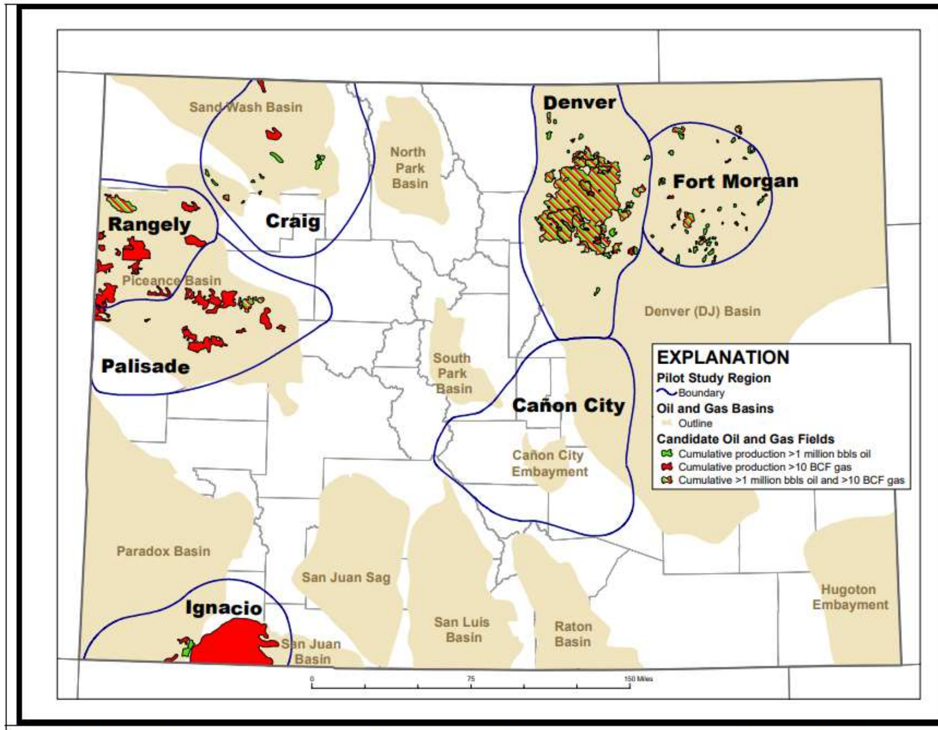


Fig. 4. Oil and gas reservoirs included in carbon storage estimates for Colorado (bbls = barrels; BCF = Billion Cubic Feet).

(McPherson, 2006)

Model Application for GCS

GCS in the Denver Basin

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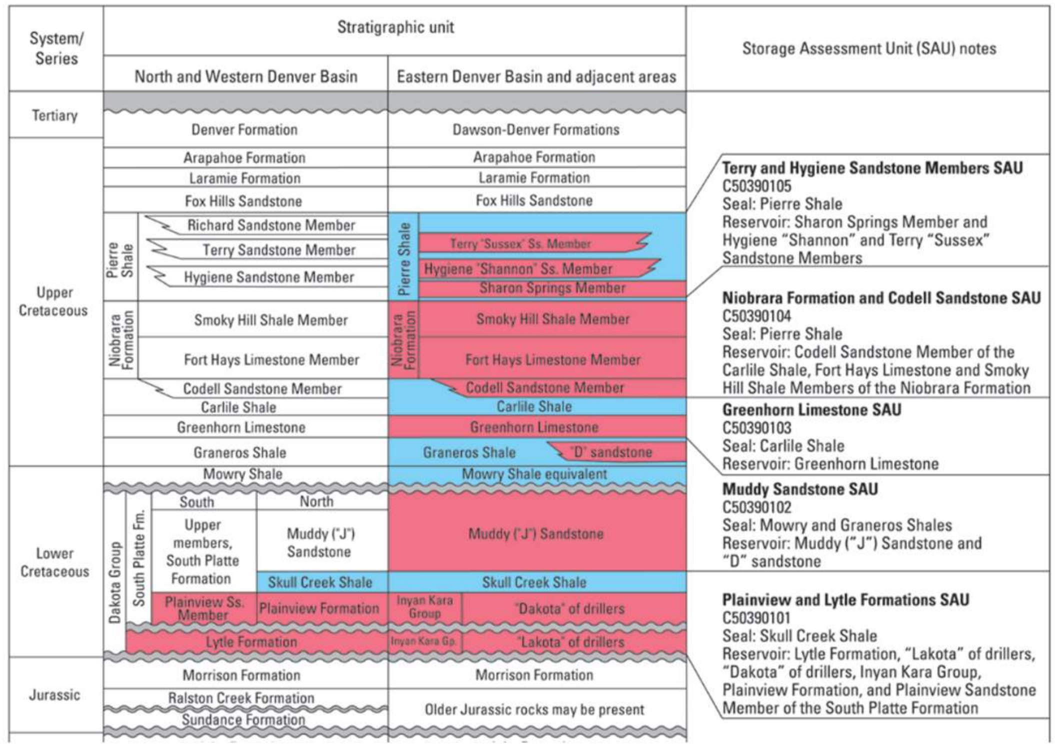
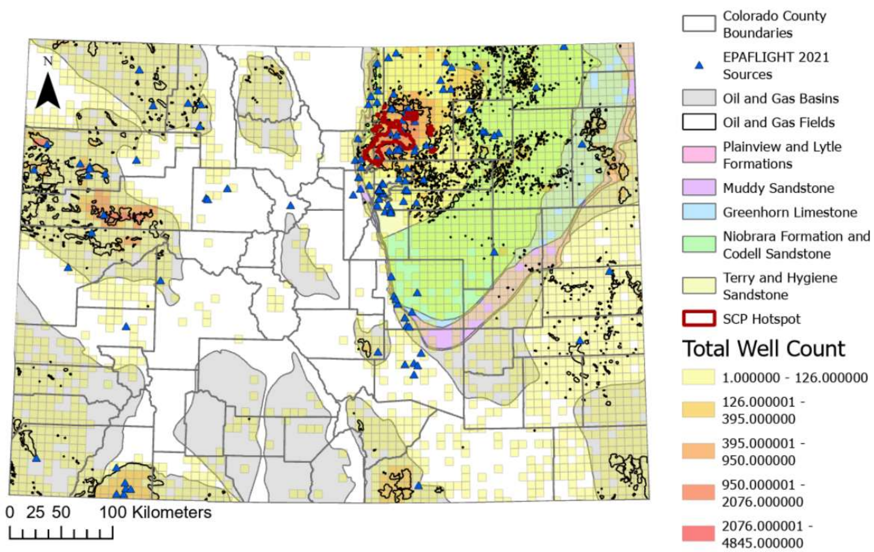
- 82 screened candidate oil and gas reservoirs in 31 fields have a total estimated capacity of 505 MMT and an average of 6.2 MMT per field (McPherson, 2006)
- Potential formations include Terry and Hygiene Sandstone, Niobrara, Codell, Greenhorn Limestone, Muddy Sandstone, Dakota and Lakota

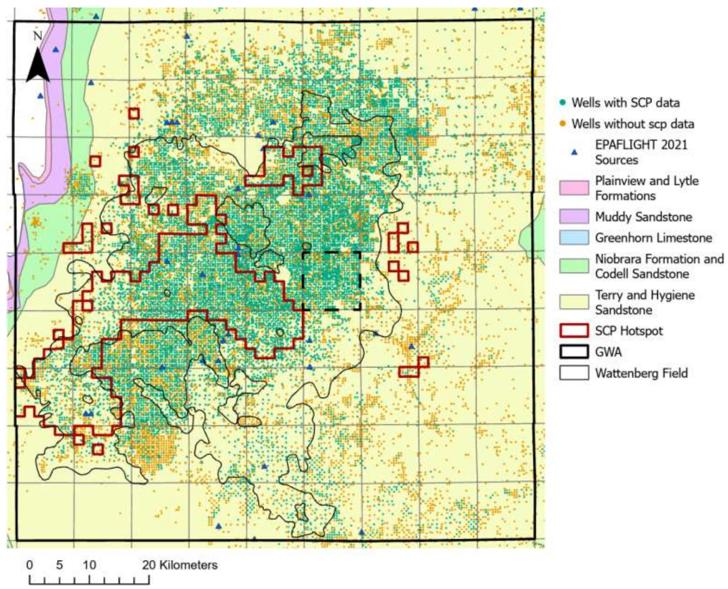


(Drake et al., 2014)

Model Demonstration

Case Study GCS Site Selection





GCS Case Study - Wattenberg

- Wattenberg field provides the largest capacity in the Denver basin at an estimated 352 MMT (Drake et al., 2014) and presence of CO_2 emitters with stacked formations makes it a good candidate for GCS (Ning and Tura, 2022)
- Existing wells in the field create potential leakage pathways
- Regional well integrity monitoring data and predictive models are valuable for site selection and corrective action planning

Conclusions

- Well integrity can be forecasted with regulatory records
- Geology is a primary driver of oil and gas well integrity issues in the Wattenberg Field of Colorado
- SCP monitoring programs help identify regions with a high risk of well integrity issues and provide valuable insight for future GCS operations

Next Steps

- Incorporate CBL data in ensemble decision tree modeling approach
- Explore LSTM approach
- Develop GCS case study in the Wattenberg Field that demonstrates value of regional integrity monitoring data and predictive modeling approach for GCS

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