
UCA
Underground Construction Association
A Division of SME
NAT2026
NORTH AMERICAN TUNNELING CONFERENCE
JUNE 15-18, 2026
ANAHEIM, CA

Empirical Method for Prediction of Adverse Ground Behavior in Carbonate Reefs

Prepared for
North American Tunneling Conference 2026

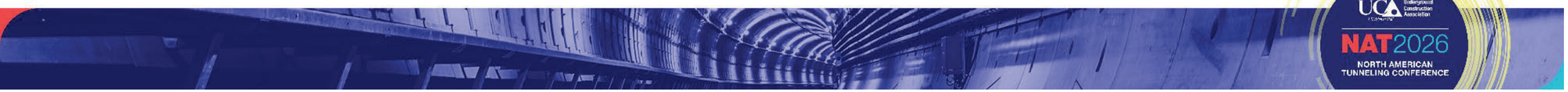
Presented by Ike Isaacson, CEG, GE, PG, PE

BRIERLEY ASSOCIATES
Creating Space Underground

Prepared by:
Ike Isaacson and
Jarek Trela

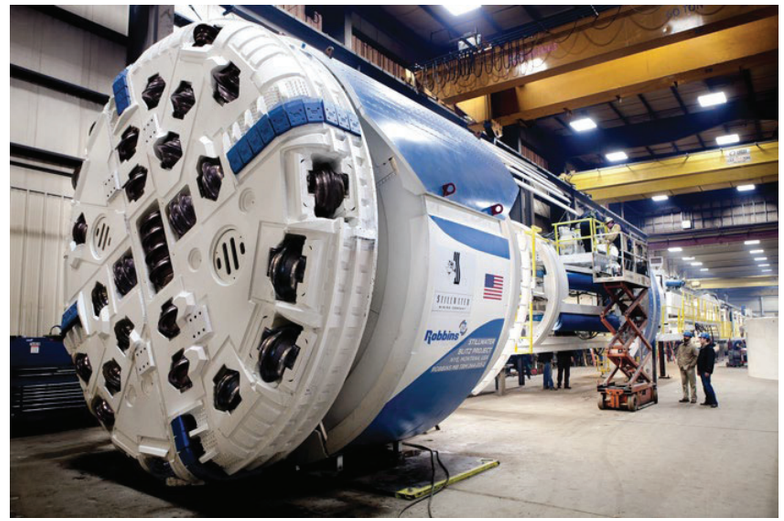
In association with
citizens energy group™

Michael Miller, PE
Citizens Energy Group
Indianapolis, Indiana



Presentation Outline

- Reef Structures and Locations
- Risks & Impacts to Underground Construction
- Geologic Review
- Reef Characterization
- Supplemental Data Since 2024
- Empirical Method
- Suggestion for Future Study
- Conclusions
- Acknowledgements
- Questions and Discussion

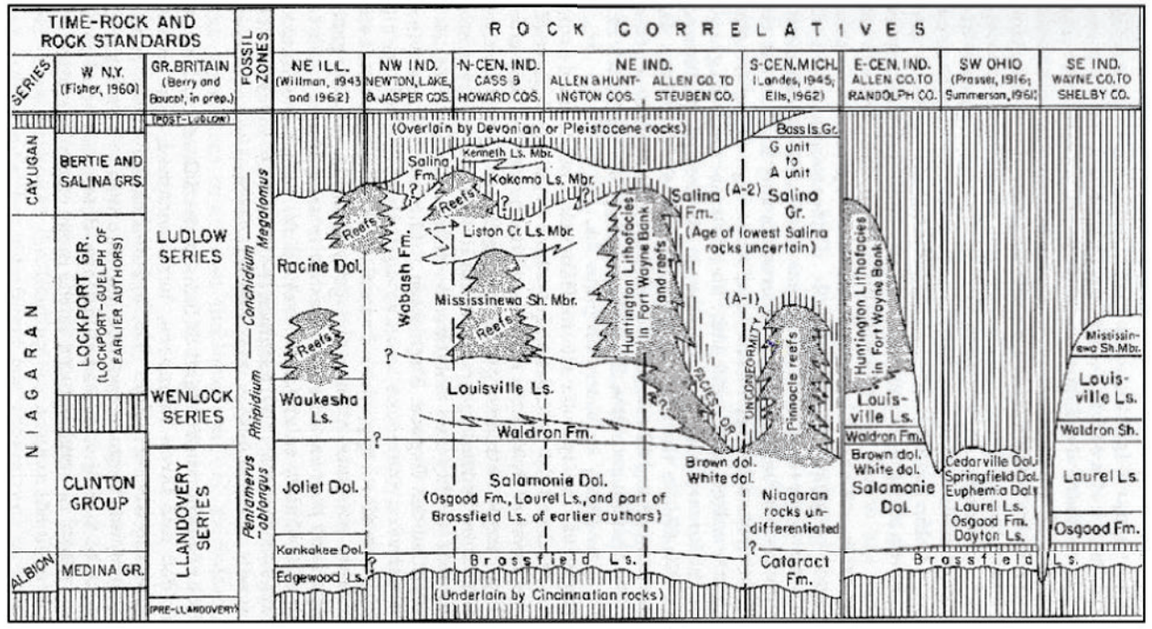


Reef Structures and Locations

Reef Formations

- Pinnacle reefs
- Silurian age (450 Mya) and younger
- Greenland-Texas & Great Lakes
- Multiple states in Midwest
- Well documented in academic literature
- Age correlations across region

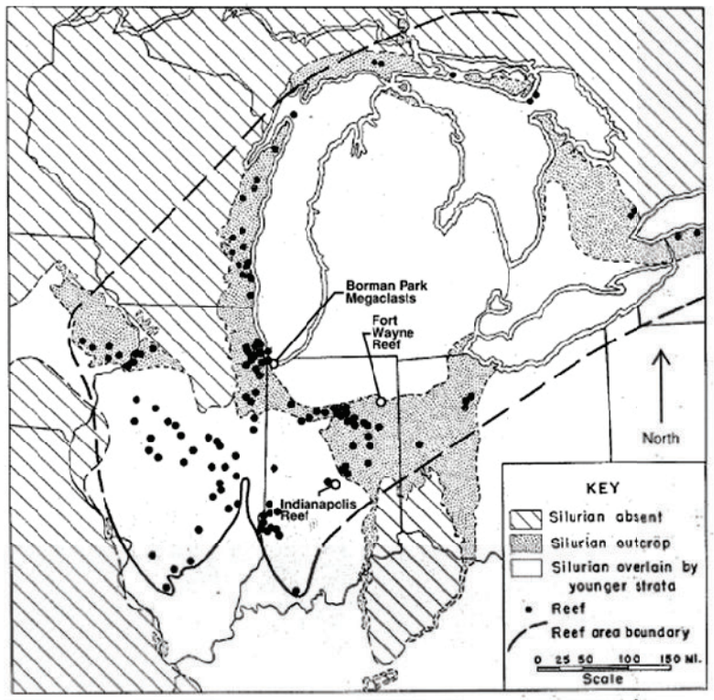
Pinsak and Shaver, 1964



No, not this

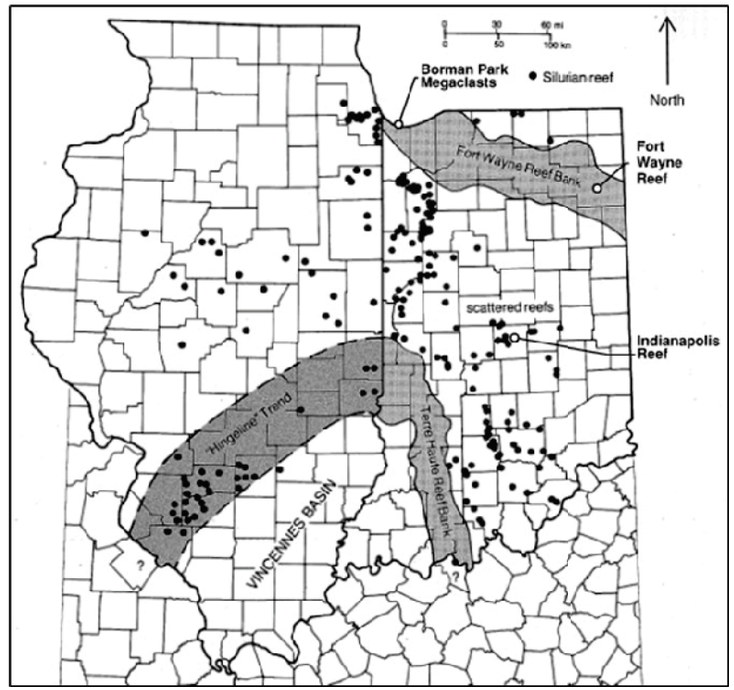
Modern Reefs - Courtesy of National Geographic

Reef Formations in the Midwest



Lowenstam, 1949

- WI, IL, IN, MI, OH
- Aggregate and oil production sources
- Specific locations unpredictable
- Patterns have been identified
- Reefs discovered continues to expand

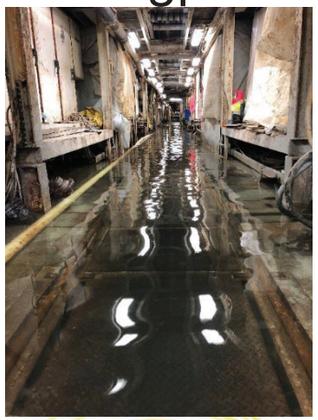


Whitaker, 1988

Risks & Impacts to Underground Construction

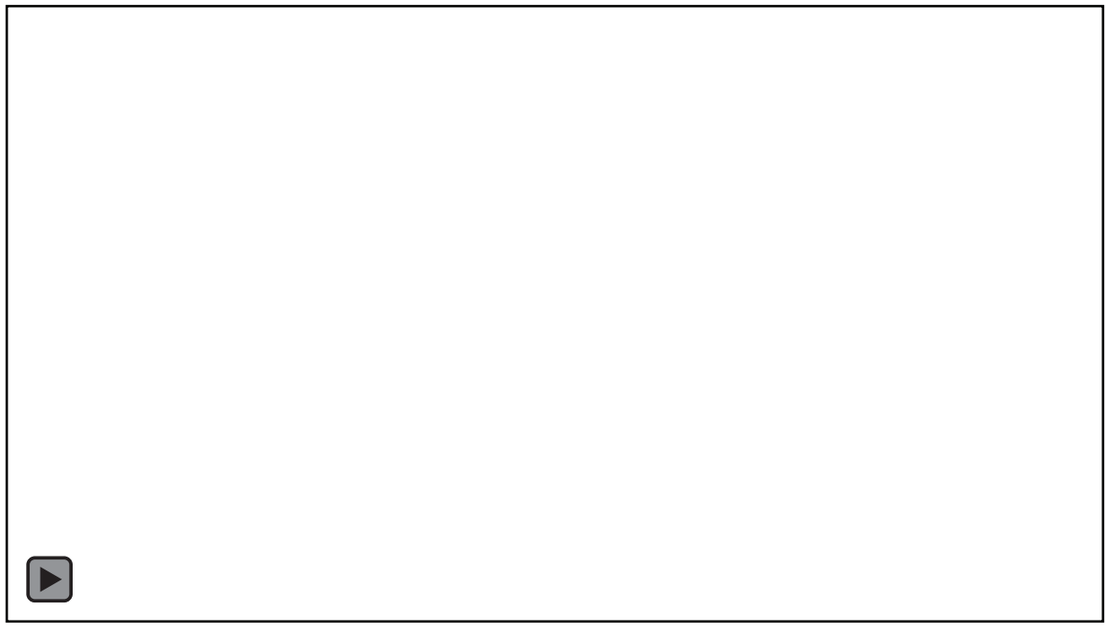
Groundwater Impacts

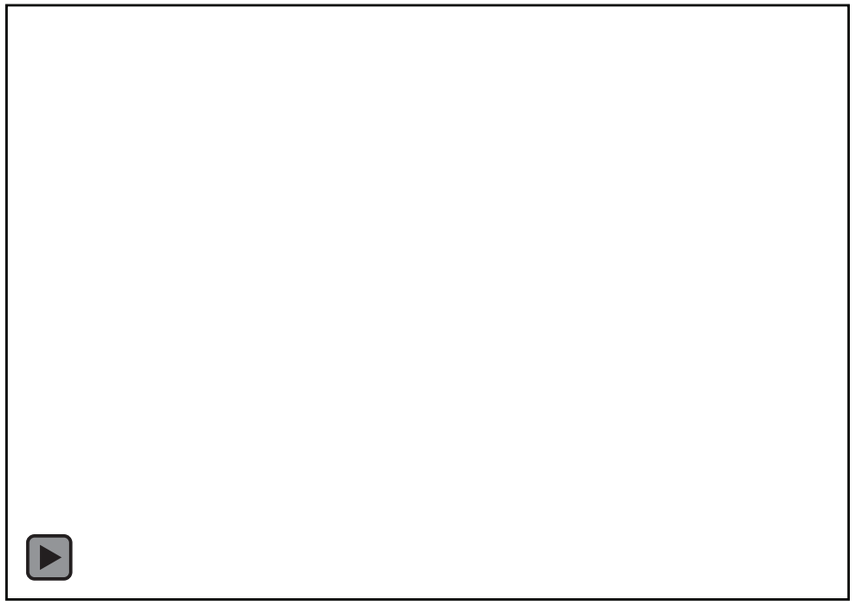
- Diffuse Groundwater Inflow
- Source pores not discontinuities
- Increased pumping and treatment
- Pre-excavation grouting largely ineffective
- CIP Lining Washout
- DigIndy Adverse flows 1 to 2 gpm/LF tunnel
- Ft Wayne Shaft Inflow ~2000 gpm



Production Impacts:

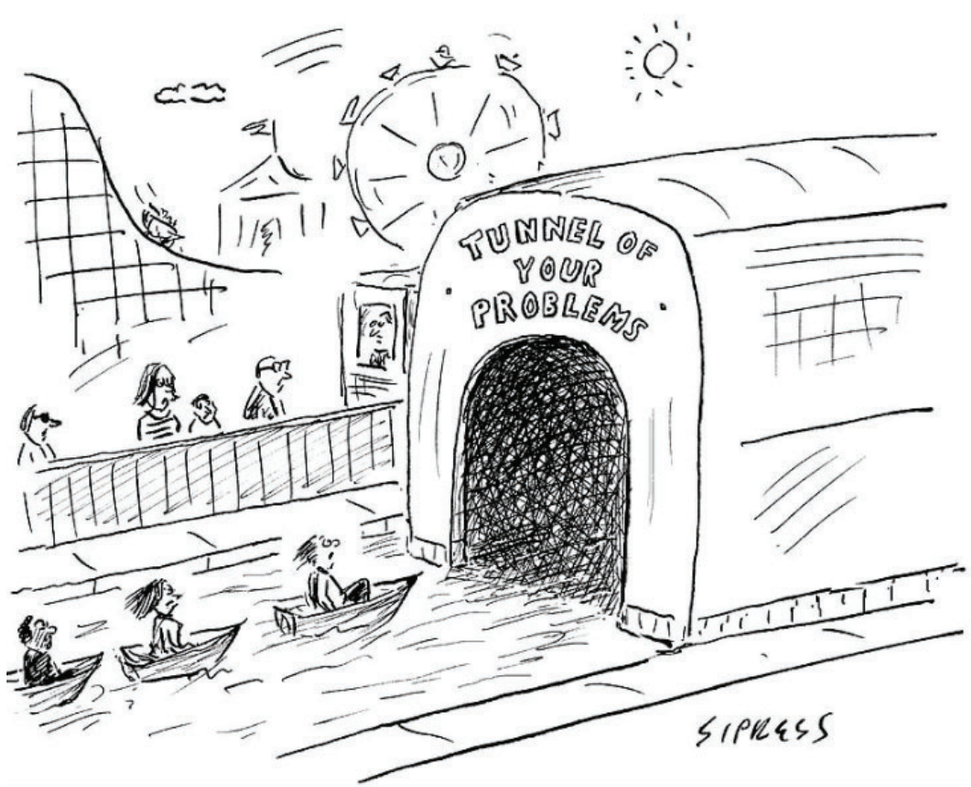
- Crushing during excavation
- Release of porewater
- Slurry-ized Muck
- Advance rates reduced
- Hand mucking
- Grout dilution





Other Potential Construction Impacts

- Hazardous gas release
- Hydrocarbon contamination
- Adverse widespread GW drawdown
  - Its Own Set of Problems
- Above GW, dusty and dangerous
- Potential regulatory issues with effluent discharge (TSS)
- Abrasivity (yes, in carbonate rocks!)

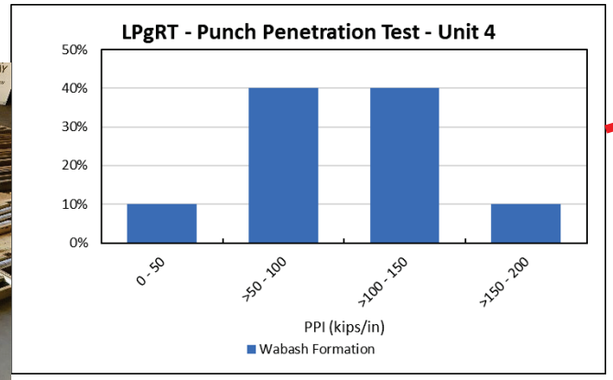


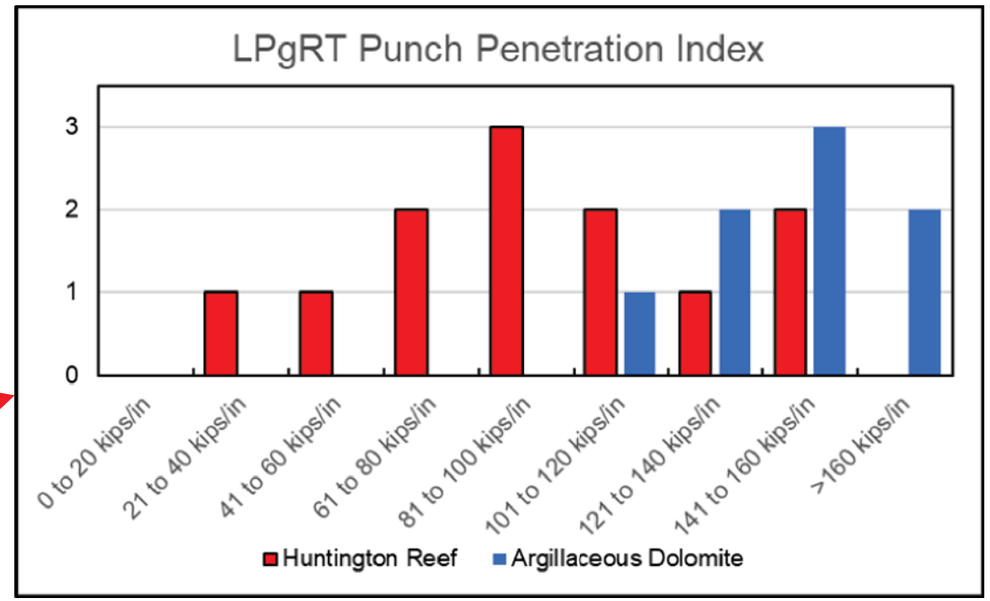
Courtesy David Sipress

Geologic Review

Reef Identification / Differentiation

- Desk study => could it be present?
- Visual identification is critical – LOOK AT CORES
- Reef may be only small fraction of samples
- Delineate top/base of reef facies in logs
- Use delineation to segregate test data
- When segregated, characteristics are pronounced





Identify the Reef

- Reef “telltales”
- During drilling:
  - Drill fluid losses
  - Increased drilling rate
- Pitted TBM rock chips
- Core characteristics:
  - Change in core texture
  - Swaling in cores (wavy)
  - Palpably lighter weight

Pitted rock chips

“Wavy” Pitted Cores

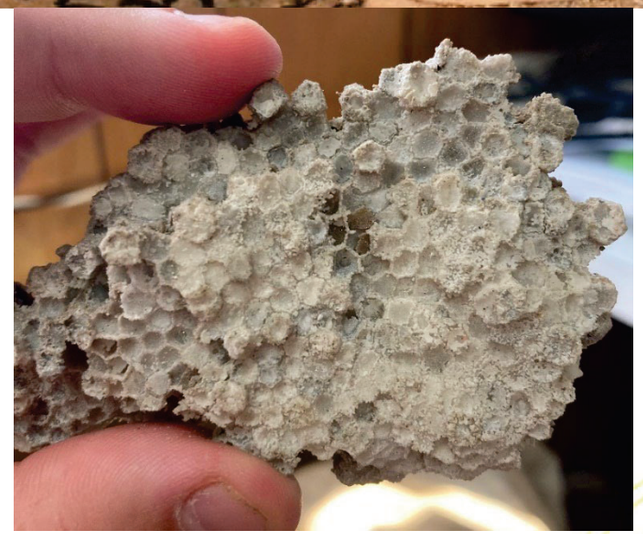
Identify the Reef

- Core characteristics:
  - Appearance of fossils
  - Pitted, spongy texture
  - Moderately/Heavily Pitted
  - Vugs > 1/8”
  - Sometimes localized steep bedding

“Wavy” Pitted Cores

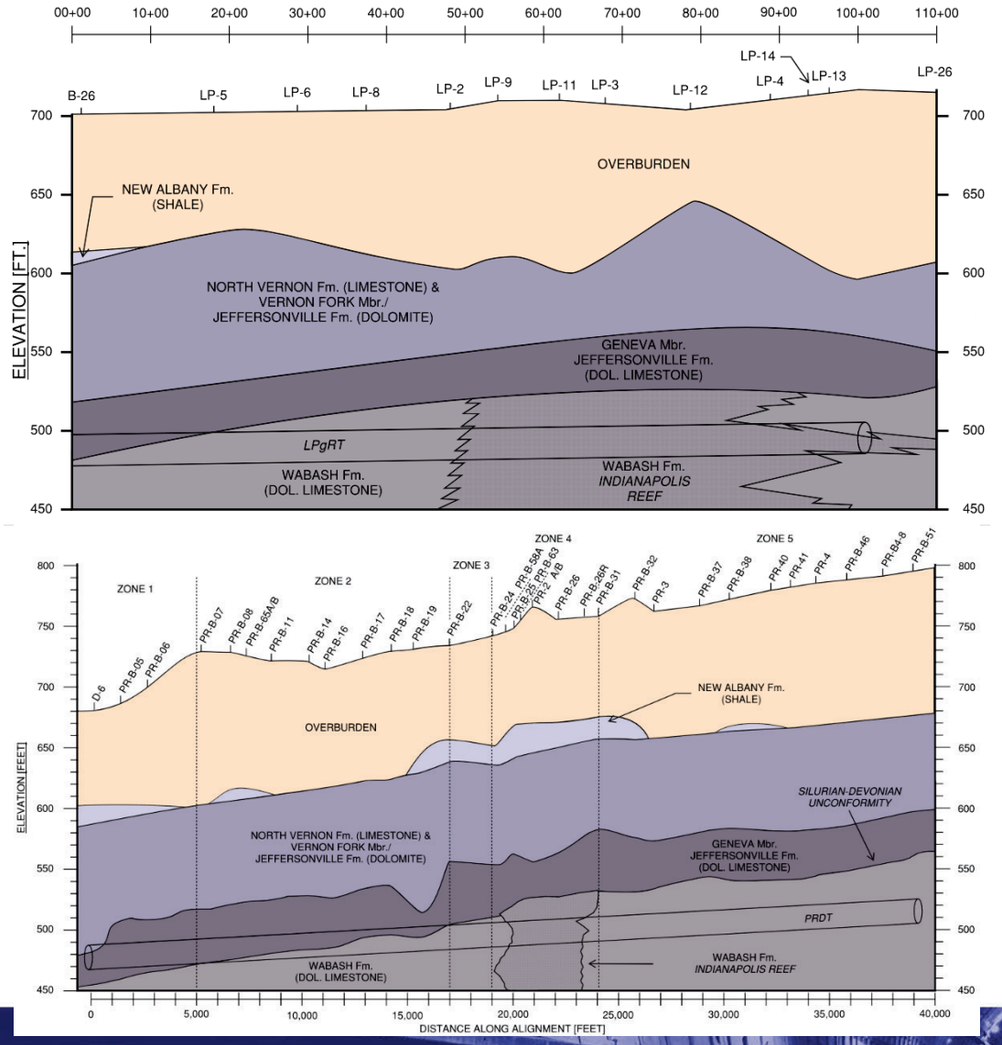
Brach. or Bivalve fossil

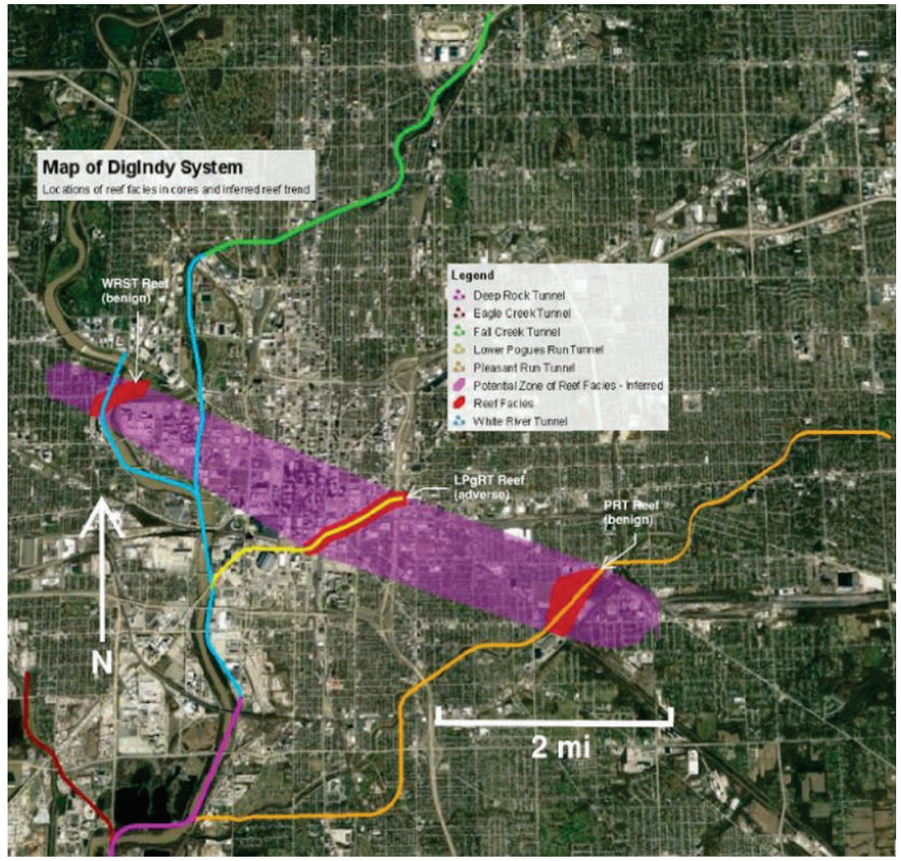
Coral fossil



Favosites “Honeycomb Coral”

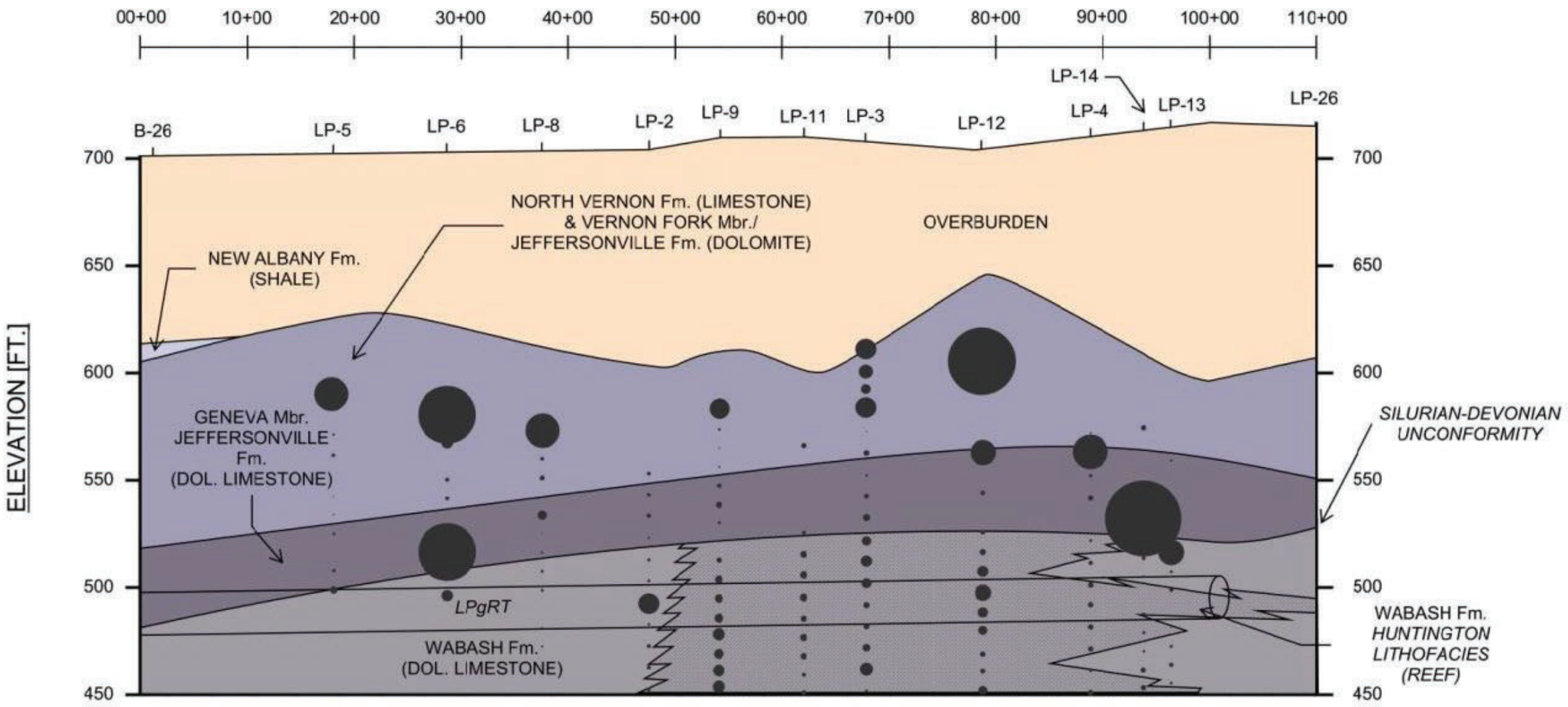
Identify in Profile





- Officially named the "**Indianapolis Reef**" in GSA 2023 publication

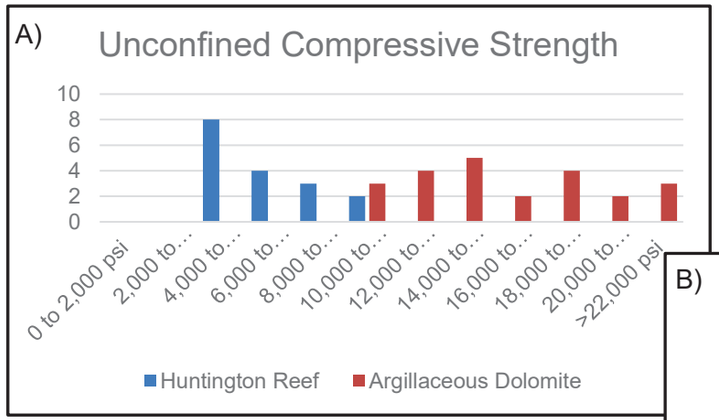
Packer Test Bubble Plots Superimposed

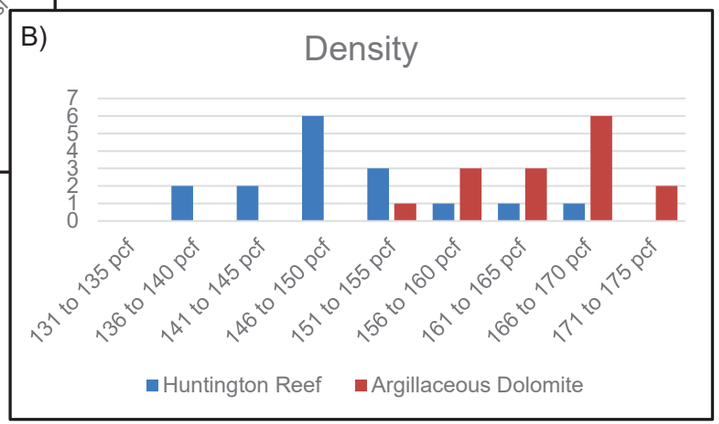


Reef Characterization

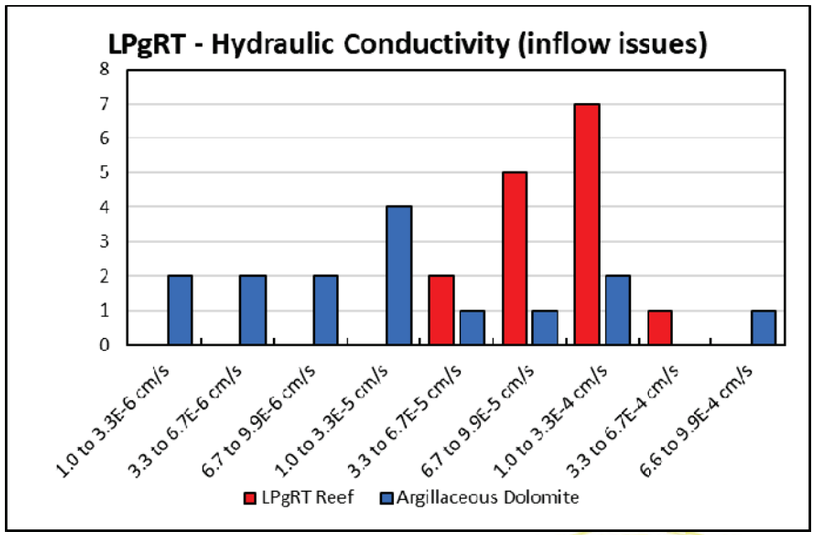
Marker Tests That Identify Reefs

- Laboratory Tests
  - Bulk Density and UCS
    - ASTM D2938-13 and D7012-14



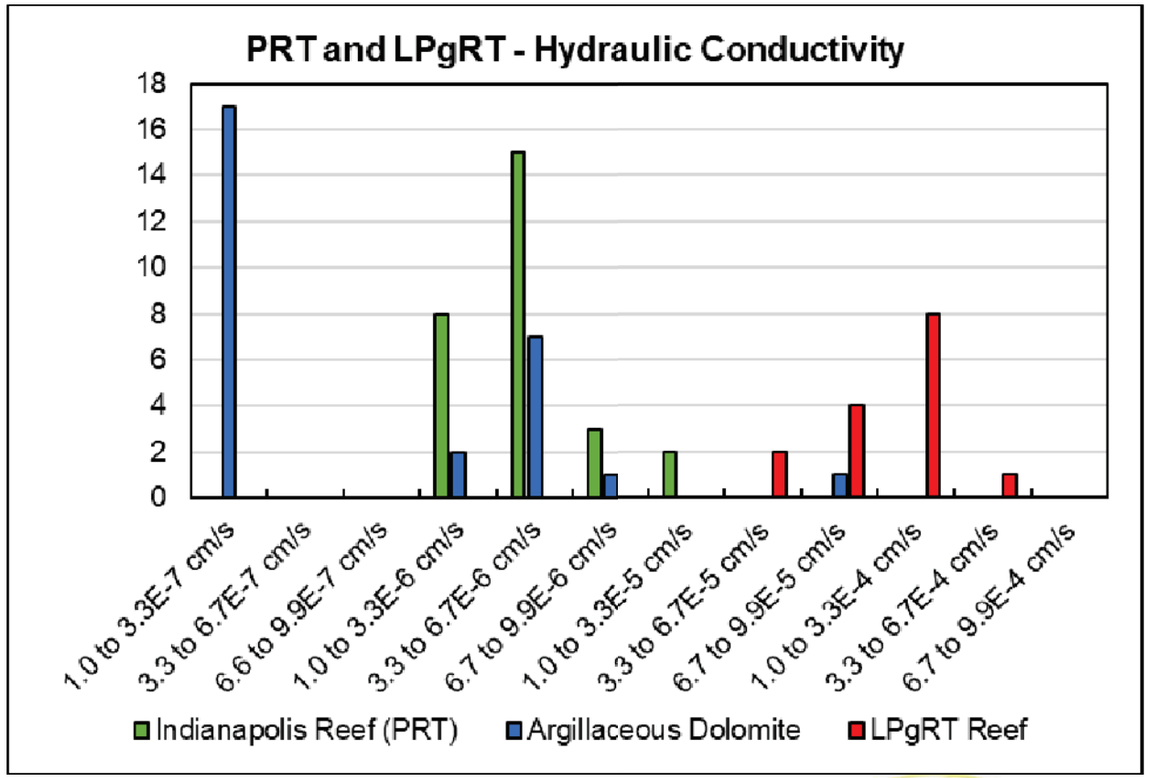


- In-Situ Tests
  - Packer Testing ASTM D4630-96 and USBR, 1989

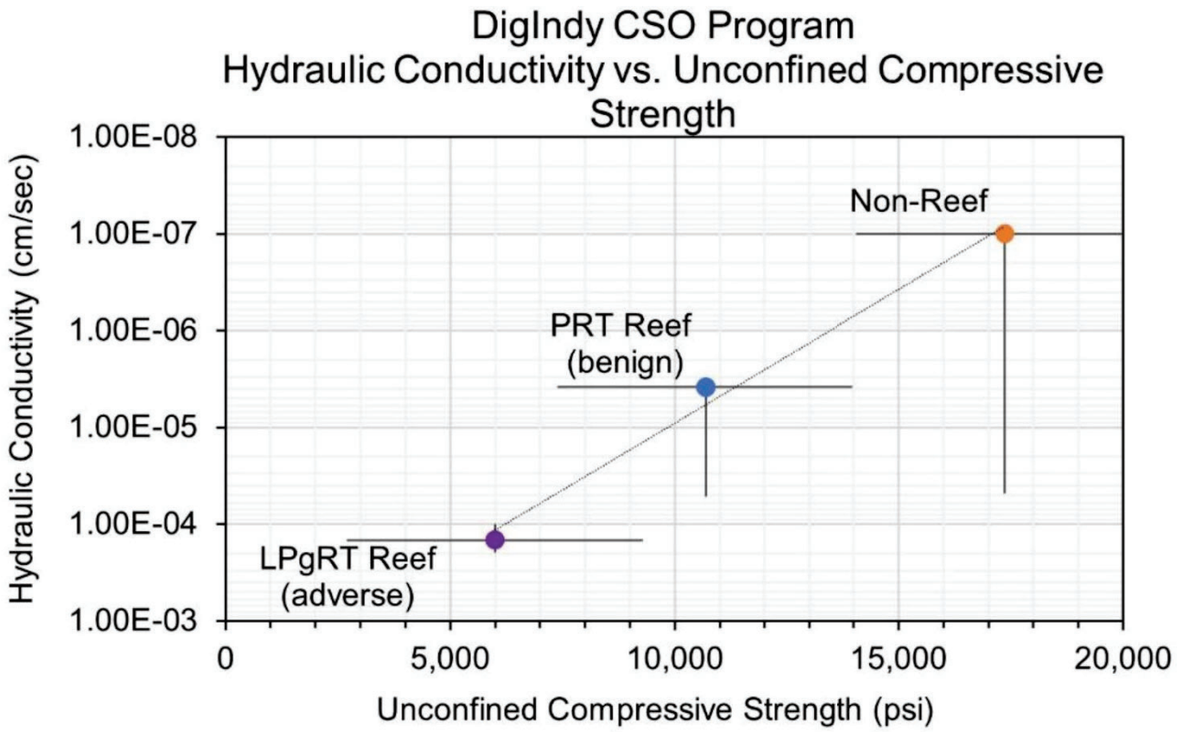


Comparing Indy Reefs – Adverse vs. Benign

- BUT not all reef is adverse (red)
- Already constructed in reef without issue (green)
- Test data corresponding to observed construction behavior
- Benign reef plotted differently
- Was it possible to predict when reef was going to be adverse?



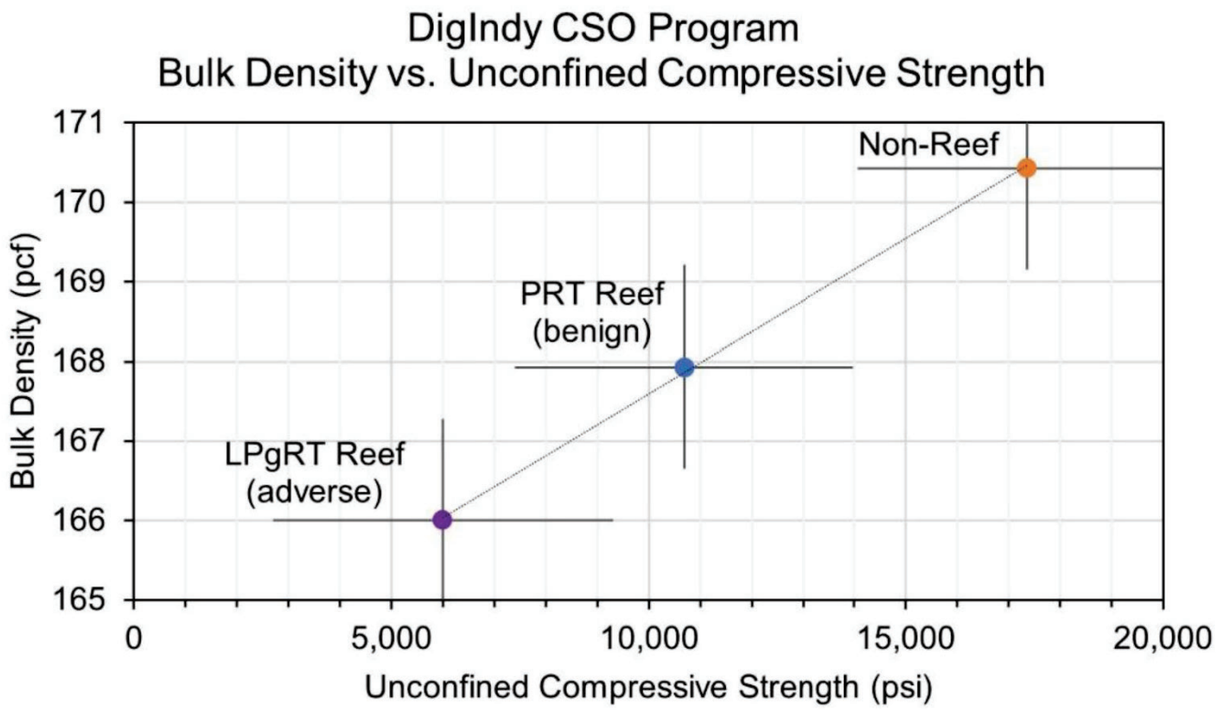
Potential Behavioral Correlation – Packer Testing



Source: Isaacson et al, NAT 2024

- **Plot of Packer Tests vs. UCS**
  - Typical Values Plotted
  - LPgRT (Pinnacle) Reef
    - Adverse behavior
      - Diffuse Inflow 1 – 2 gpm/LF
      - Crushing and poor production
  - PRT (Pinnacle) Reef
    - Relatively benign behavior
  - Non-Reef
    - Favorable conditions
    - Discrete inflows and Typical TBM performance
  - Inverse correlation between K and UCS
    - controlled by porosity and pore connectivity
  - Packer test data trend is robust (despite pore contamination)

Potential Behavioral Correlations – Bulk Density



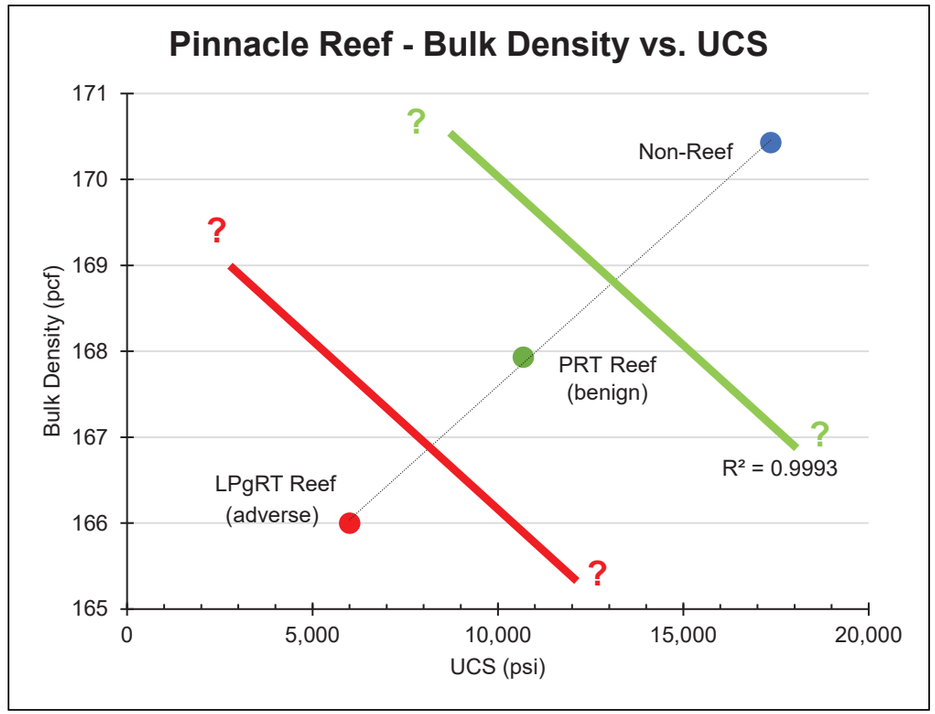
Source: Isaacson et al, NAT 2024

Plot of Bulk Density vs. UCS

- Typical Values Plotted
- LPgRT (Pinnacle) Reef:
  - Adverse behavior
    - Diffuse Inflow 1 – 2 gpm/LF
    - Crushing and poor production
- PRT (Pinnacle) Reef:
  - Relatively benign behavior
- Non-Reef: standard TBM performance
  - Favorable conditions
  - Discrete inflows and Typical TBM performance
- Roughly linear trend between behaviors

Need for More Data to Test Correlation

- Plots hinted at behavioral correlation
  - UCS vs Bulk Density and Packer K
  - Additional datasets to test correlation
  - Dataset requirements
    - Same zone UCS and K values data
    - Same sample UCS and bulk densities
  - During construction, correlate with zones of
    - Adverse reef behavior
    - Benign reef behavior
    - Typical non-reef behavior
  - Goal
    - Predictive chart to evaluate potential issues of pinnacle reefs for tunnel projects



Supplemental Data Since 2024

Supplemental Data Sources

Additional DigIndy Program Data

- Completed Pleasant Run Tunnel (PRT) data from DigIndy
- PRDT reef observed to have benign behavior

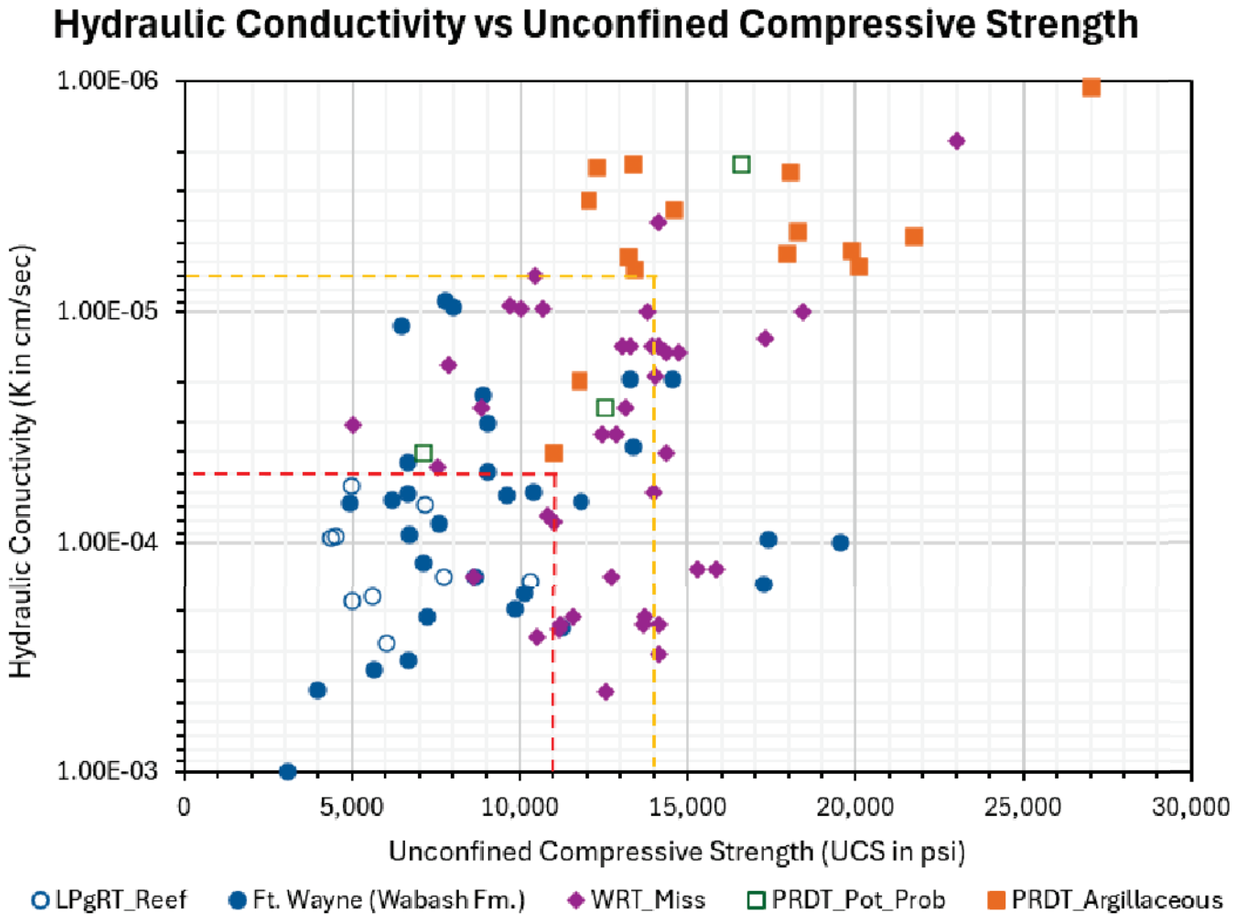
Supplemental Data from Another Program

- Three Rivers Protection and Overflow Reduction Project (3RPORT), Ft. Wayne, IN
- Direct behavioral observation limited to shaft excavations
- Tunnel constructed with a pressurized face TBM
- Adverse Ft. Wayne reef plots similarly to DigIndy Adverse

Dataset scatter reflects reef heterogeneity against control

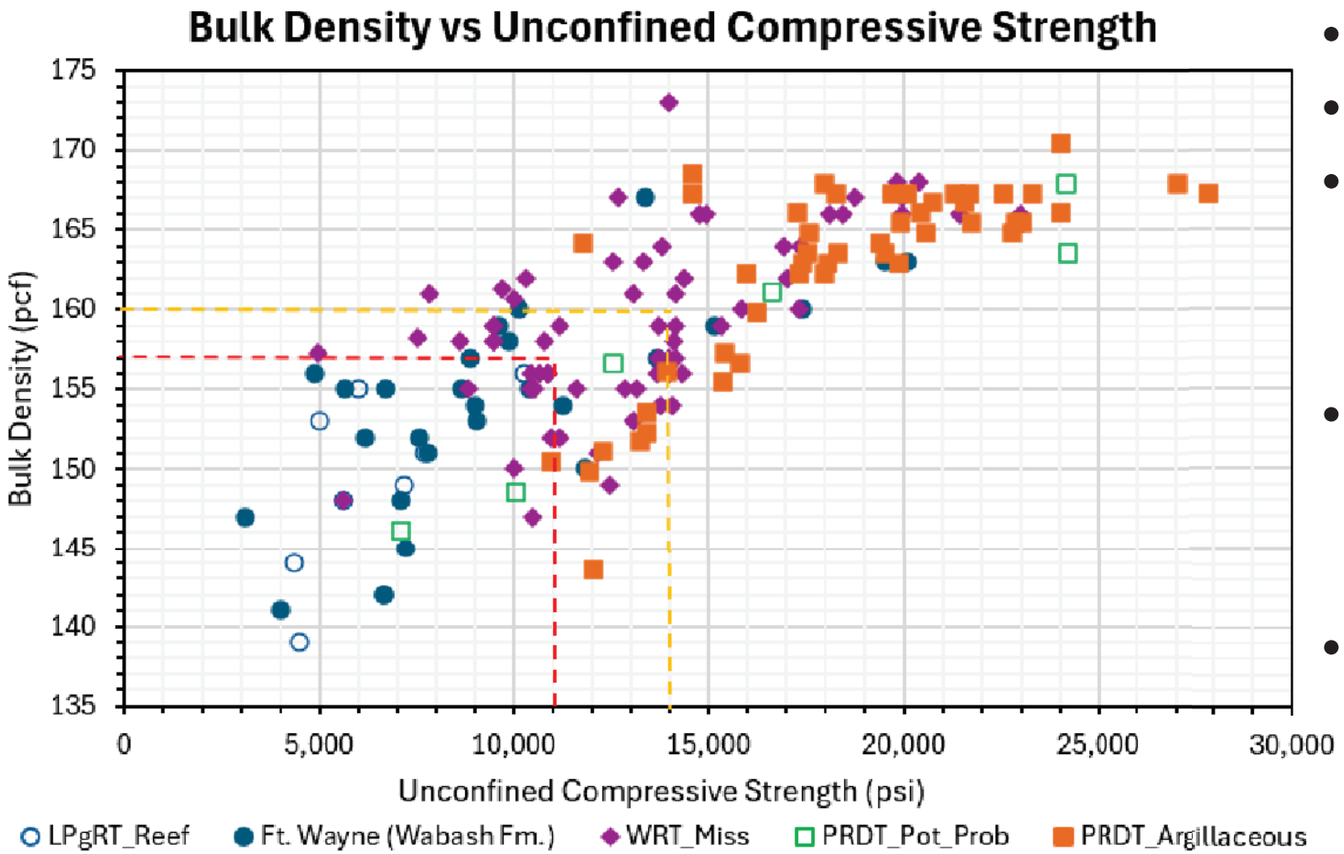
- Multiple reef facies represented: Ft. Wayne (Wabash Fm.), White River Tunnel (WRT_Miss), and Pleasant Run Tunnel (PRDT_Pot_Prob)
- Control (non-adverse): Previous DigIndy Non-Reef, PRDT_Argillaceous

Multi-Project Test of Packer K vs UCS



- Data Scatter Relatively Uniform
- Attempt to Segregate Data
- Adverse Behavior Reef
  - Diffuse & High GW Inflow
  - LPgRT_Reef
  - Much of Ft. Wayne (Wabash Fm.)
- Relatively Benign Behavior
  - Discrete GW Inflow dominated
  - WRT_Miss (reef)
  - PRDT_Pot_Prob (reef)
- Typical Behavior
  - Discrete Inflow from Discontinities
  - PRDT_Argillaceous (non-reef)

Multi-Project Test of Density vs UCS

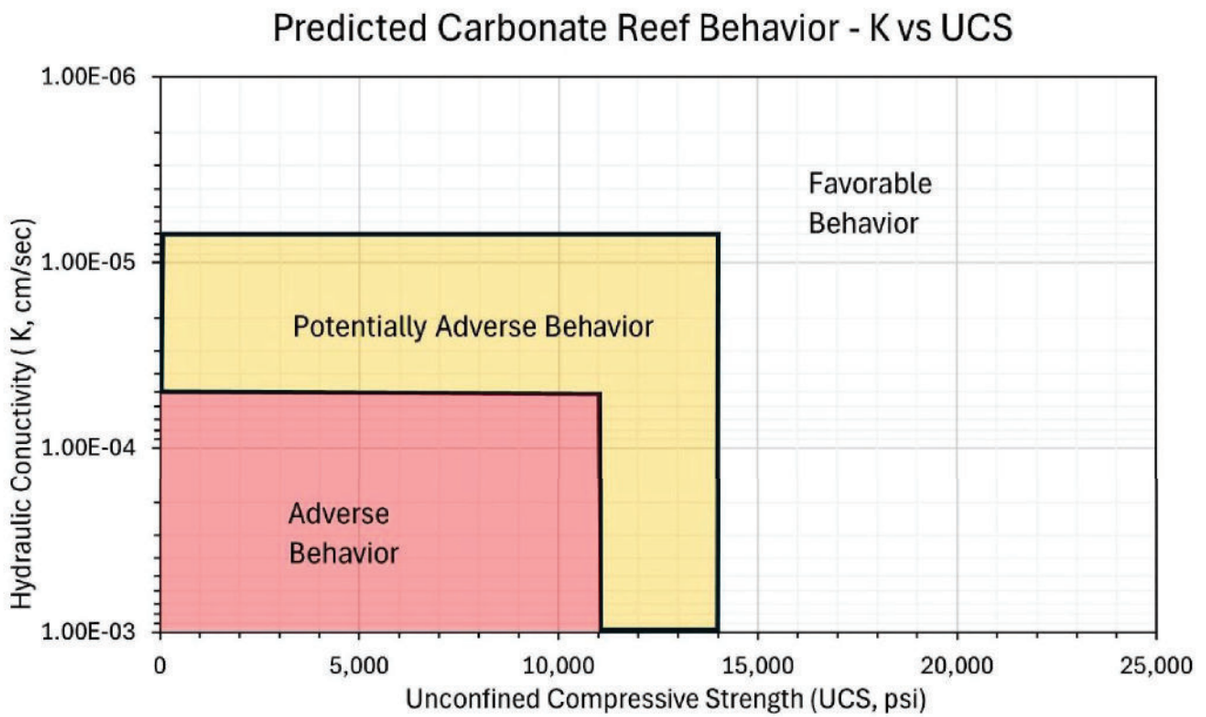


- Higher scatter in adverse region
- Attempt to Segregate Data
- Adverse Behavior Reef
  - Diffuse & High GW Inflow
  - LPgRT_Reef
  - Much of Ft. Wayne (Wabash Fm.)
- Relatively Benign Behavior
  - Discrete GW Inflow dominated
  - WRT_Miss (reef)
  - PRDT_Pot_Prob (reef)
- Typical Behavior
  - Discrete Inflow from Discontinities
  - PRDT_Argillaceous (non-reef)

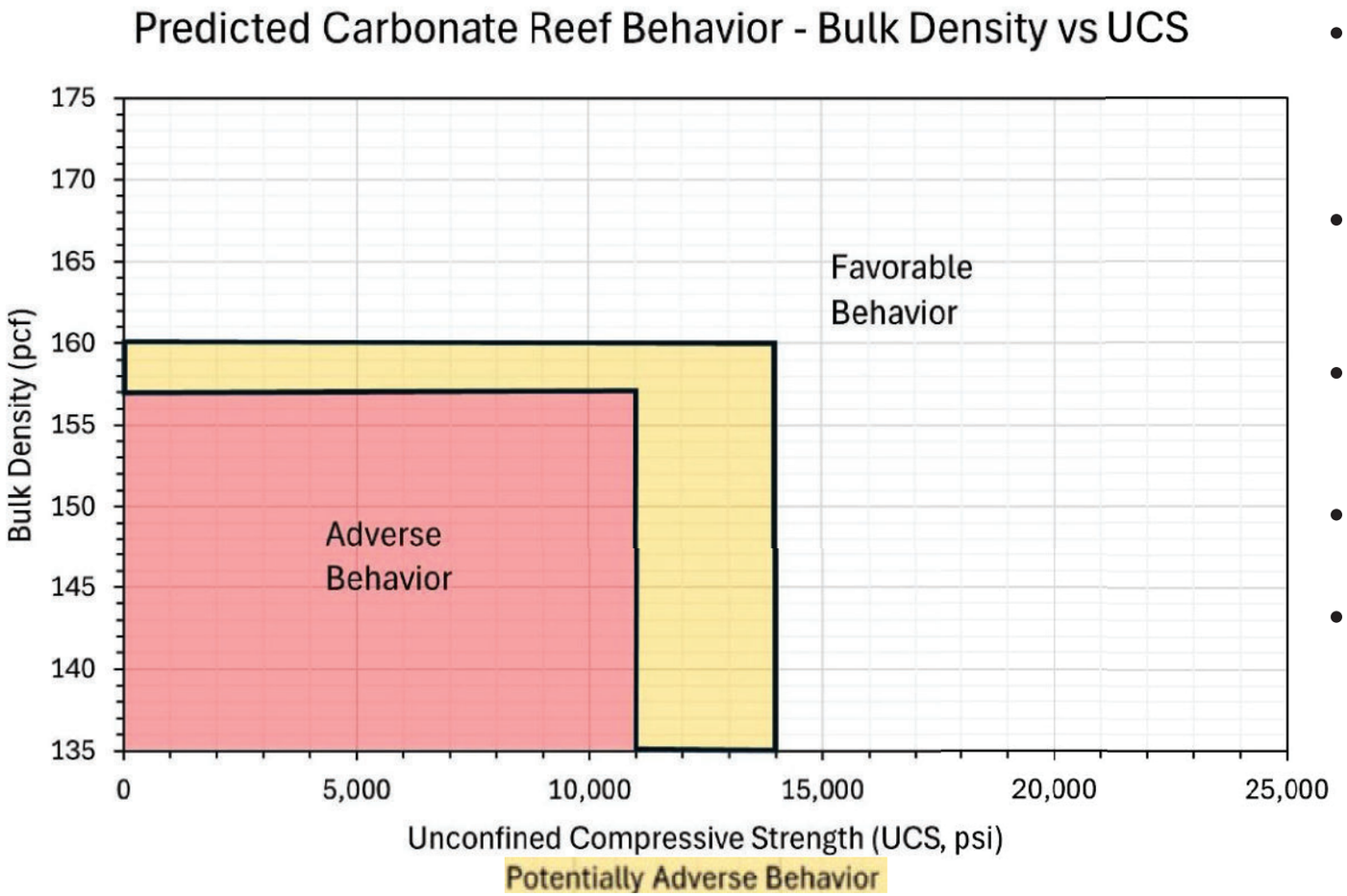
Empirical Method

Empirical Method - K vs UCS Plot

- Adverse behavior region
  - High conductivities K > 6×10^{-4} cm/sec
  - Low UCS < 11,000 psi
- Favorable behavior region
  - Low conductivities K < 4×10^{-5} cm/sec
  - High UCS > 14,000 psi
- Potentially adverse behavior region represents transition space where conditions are less predictable
- Inverse relationship—both controlled by primary porosity and pore connectivity
- Requires Coordinated Lab and Field-based testing

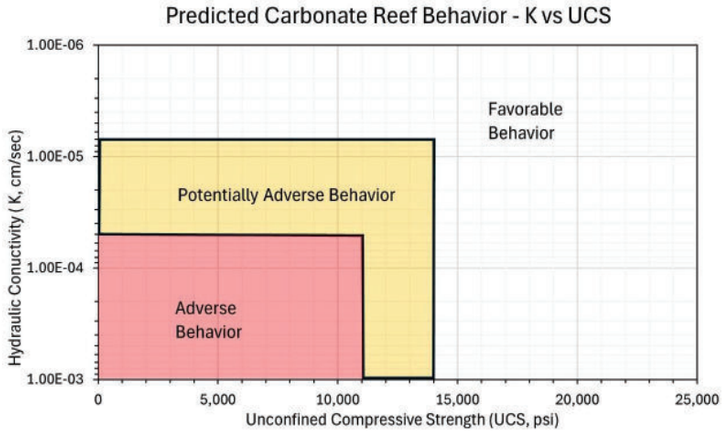


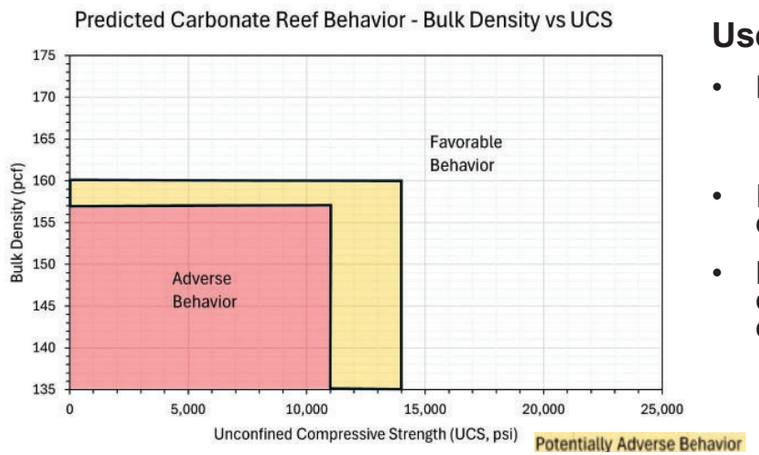
Empirical Method – Bulk Density vs UCS Plot



- Adverse behavior region:
  - Low bulk densities < 157 pcf
  - Low UCS < 11,000 psi (primary porosity control)
- Favorable behavior region:
  - High bulk densities >160 pcf
  - High UCS >14,000 psi
- Transition zone exists between adverse and favorable conditions with intermediate characteristics
- Bulk density AND UCS both decrease in adverse reef conditions
- Lab-based assessment when both tests conducted on same rock core samples

Empirical Method – Use



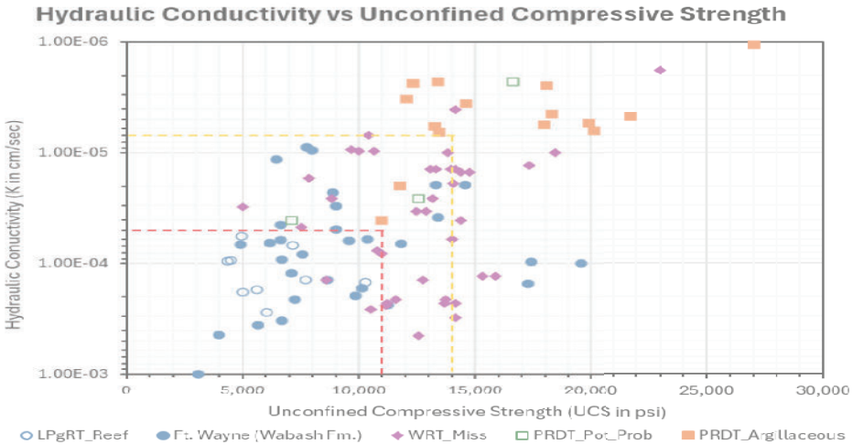


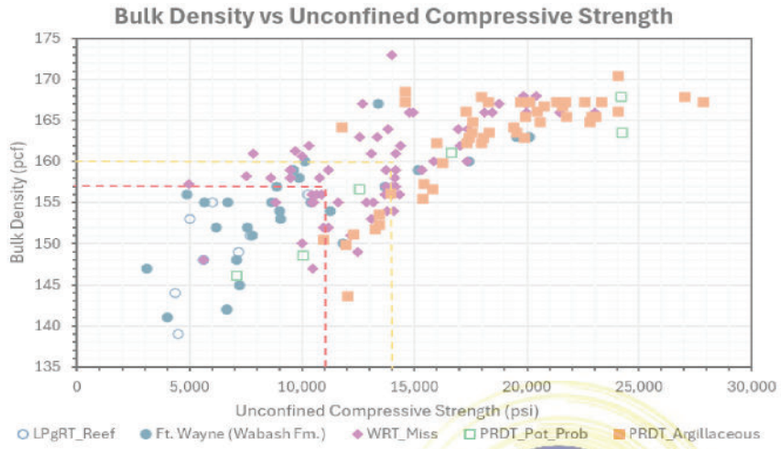
Prior To Geotechnical Investigations

- Know of possible reef prior to investigation
- Train staff to identify reef
- Logs should call out reef facies
- Geotechnical program with targeted and coordinated reef zone bulk density, UCS, and packer testing

Use of Empirical Method

- For Single Plot Use:
  - Bulk Density vs UCS recommended due to reduced scatter
- If test data permits, use both plots for higher confidence
- Reef cores plotting in adverse region of both charts Pressurized face methods should be considered to mitigate risk





Future Study

Request of Future Projects to Contribute

- Awareness, Training, Planning
  - Desk Studies **must** identify potential of reef facies
  - Field personnel **must** be trained to identify and log occurrence of reef in cores
  - Geotech programs should include and target UCS, bulk density, and packer testing in reef rock
  - Bulk Density and UCS on same samples
  - Segregate “reef” test data from other surrounding rock
- Additional Datasets
  - Include coordinated bulk density, UCS, and packer testing on same reef samples/intervals
  - Construction Observation of reef behavior during excavation
    - Diffuse inflows observed
    - Excavation difficulties (crushing)
    - Approximate rate of inflows
    - Stations/elevations of inflows/crushing relative to test data
  - Construction observations required to assess adversity
  - Reach out if you have reef data!

Additional Data or Inquiries: iisaacson@brierleyassociates.com

Conclusions

Conclusions

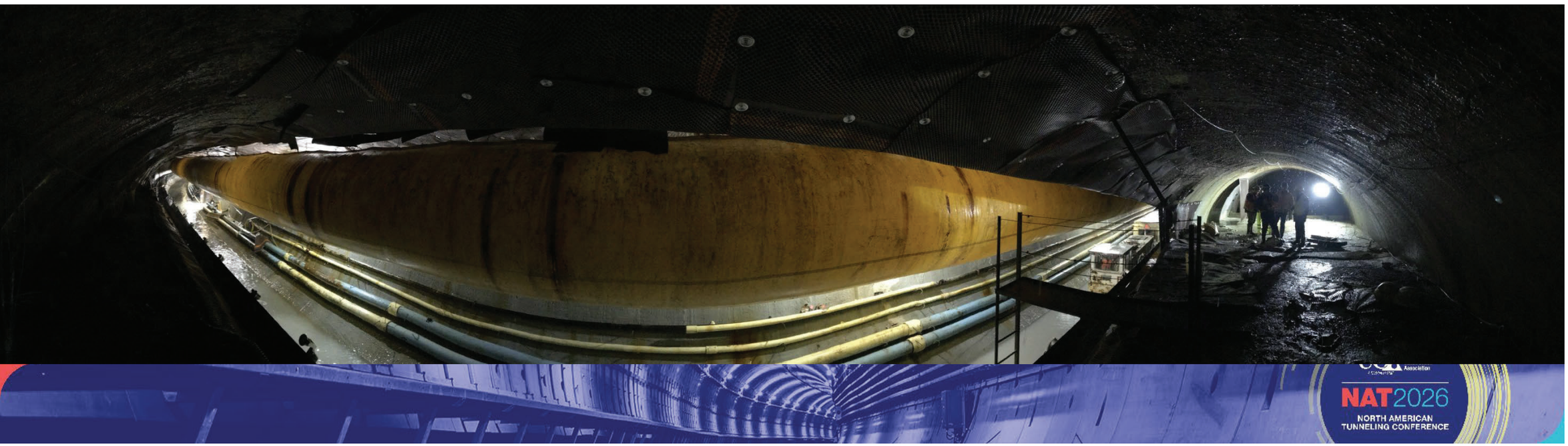
- Empirical method enables ground characterization and risk assessment
- Characteristics of adverse reef behavior and risk
  - $K > 6 \times 10^{-4}$ cm/sec
  - UCS < 11,000 psi
  - bulk density < 157 pcf
- Transition zone - potential adversity / heightened risk
- Risk increases with number of adjacent locations plotting as “adverse”
- Aid to industry enhanced by future data
- Limited effectiveness of pre-excavation grouting to mitigate adverse reef inflow
- Adverse reef behavior’s influence on excavation methodology
  - Open TBM present higher risk of inflow and crushing
  - Slurry TBM reduced inflow risk at 3RPORT despite adverse reef
  - Cutterhead design should consider reduced strength in adverse reef

Acknowledgements

- Coauthors
  - Jarek Trela, Brierley Associates
  - Mike Miller, Citizens Energy Group
- DigIndy CSO Program, Indianapolis, IN
  - Citizens Energy Group, Owner
  - JF Shea Construction, Tunnel Contractor
  - AECOM, Construction Administrator
  - Black & Veatch Corporation, Designer
- Three Rivers Protection and Overflow Reduction Project (3RPORT), Ft. Wayne, IN
  - City of Ft. Wayne, Owner
  - Black & Veatch Corporation, Designer

Questions and Discussion

Additional Data or Inquiries: iisaacson@brierleyassociates.com



Additional Data or Inquiries:
Ike Isaacson, CEG, GE, PG, PE
iisaacson@brierleyassociates.com