The Consolidation and Strength Behavior of Mechanically Compressed Fine-Grained Sediments

A Ph.D. Defense

by

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Friday, April 25th 2014

Outline

- Motivation and Objectives
- Resedimentation
- Permeability Results
- Triaxial Equipment and Procedures
- Principle of Effective Stress
- Shear Strength Behavior
- Summary and Conclusions

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- **Motivation and Objectives**
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Motivation

For soils and 'soft' rock, shear strength is complex a function of:

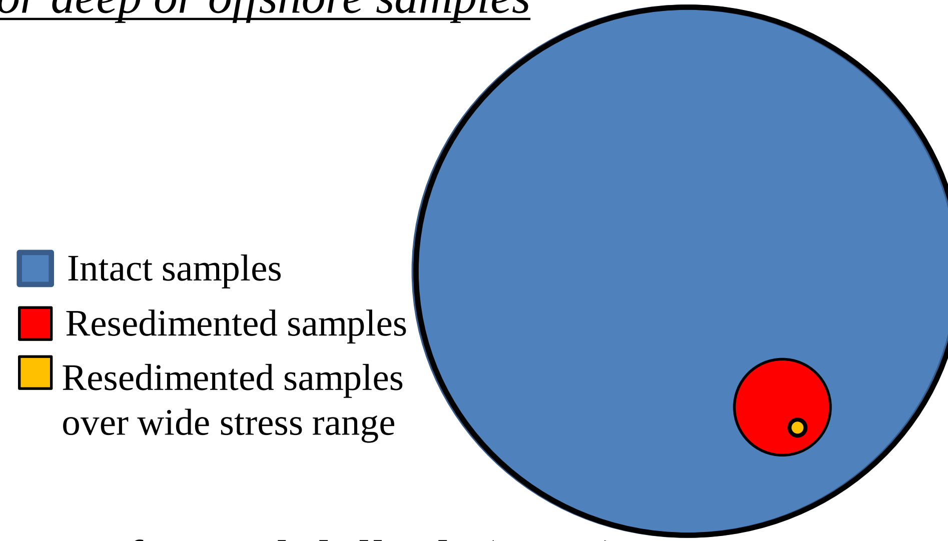
$\tau_{max} = f$

- composition (w_L)
- effective stress (σ')
- stress history (OCR)
- mode of shear (b, α)
- temperature (T)
- strain rate ($\dot{\varepsilon}$)
- water saturation (S_w)
- diagenesis

This work

- Majority of previous studies have involved testing intact samples
  - **cannot isolate and quantify individual factors influencing behavior**
  - disturbance and cost, *particularly for deep or offshore samples*

- Resedimentation
  - Technical necessity!
  - Practical advantages
  - Compares well with intact behavior



- Best data for resedimented clay behavior from Abdulhadi (2009)
  - tested RBBC for stresses from 0.1→ 10 MPa in triaxial compression

- Very limited testing of resedimented soil over a wide stress range
  - Bishop et al. (1975); tested London Clay at Imperial College
  - Yassir (1989); tested mud volcano clay at UCL
  - Nüesch (1991); tested unsaturated Opalinus Shale
  - Berre (1992); tested a kaolinite – Moum clay mixture at NGI
  - William (2007); tested Bringelly Shale at University of Sydney

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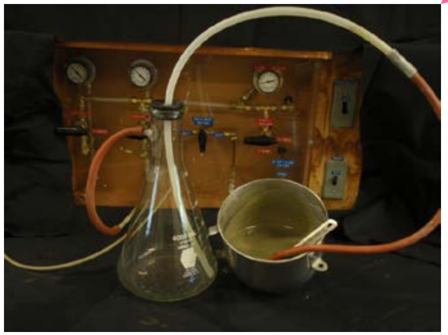
Resedimentation

1. Obtain core material

2. Breakdown into powder and blend

3. Mix dry powder and water into slurry

4. Vacuum the slurry



5. Pour slurry into a consolidometer

<u>Comparisons of resedimented vs. intact behavior:</u>

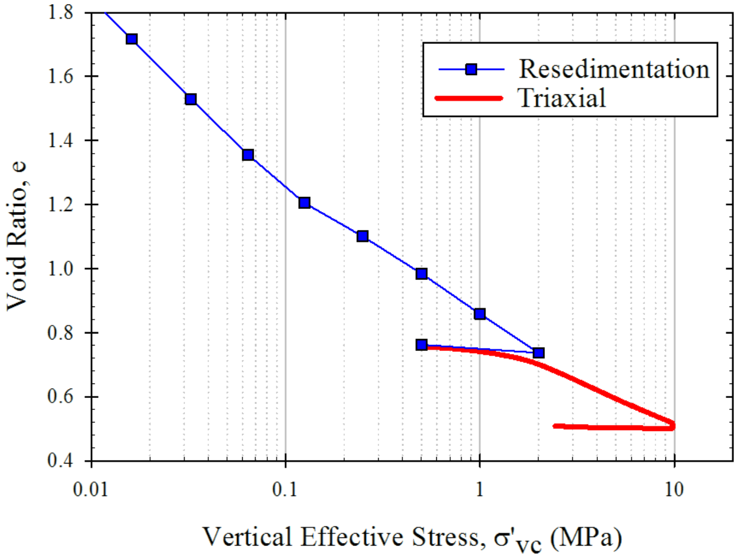
- *Berman 1993 (BBC)*
- *Mazzei 2008 (RGoM Ursa)*
- *Casey 2011 (BBC)*
- *House 2012 (BBC)*
- *Betts 2014 (RGoM Eugene Is.)*

Resedimentation

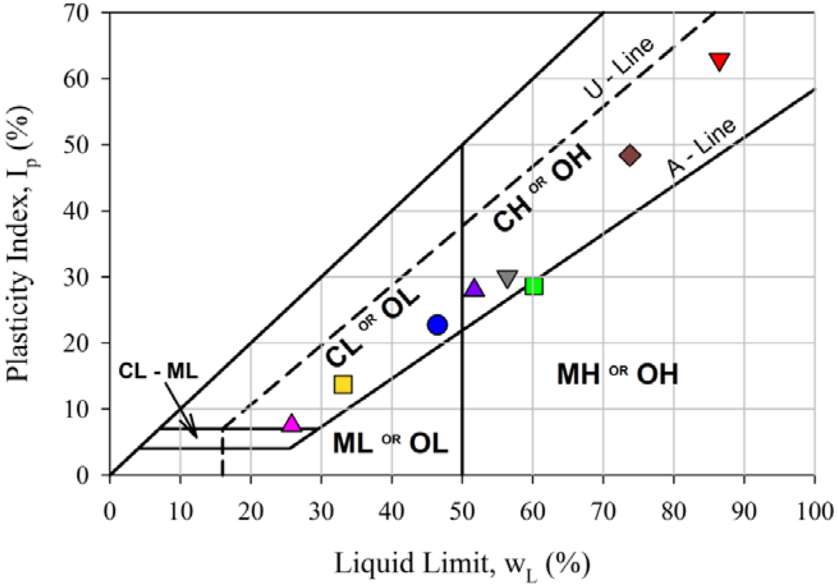
4. Load incrementally
   - Different consolidometers used depending on testing needs
   - Low stress triaxial: σ'_p = 0.1 MPa
   - Medium stress triaxial: σ'_p = 2 MPa
   - High stress triaxial: σ'_p = 10 MPa
   - Time required for resedimentation strongly dependent on soil type (c_v)

5. Swell to OCR = 5

6. Extrude and trim test specimen



What am I dealing with?



	Contributing researchers:
Skibbereen Silt	Grennan (2010)
Presumpscot Clay	
Boston Blue Clay	Abdulhadi (2009), Sheahan (1991)
GoM Ursa Clay	
Ugnu Clay	Jones (2010)
S.F. Bay Mud	Kontopoulos (2012)
London Clay	
GoM Eugene Is. Clay	Betts (2014), Fahy (2014)

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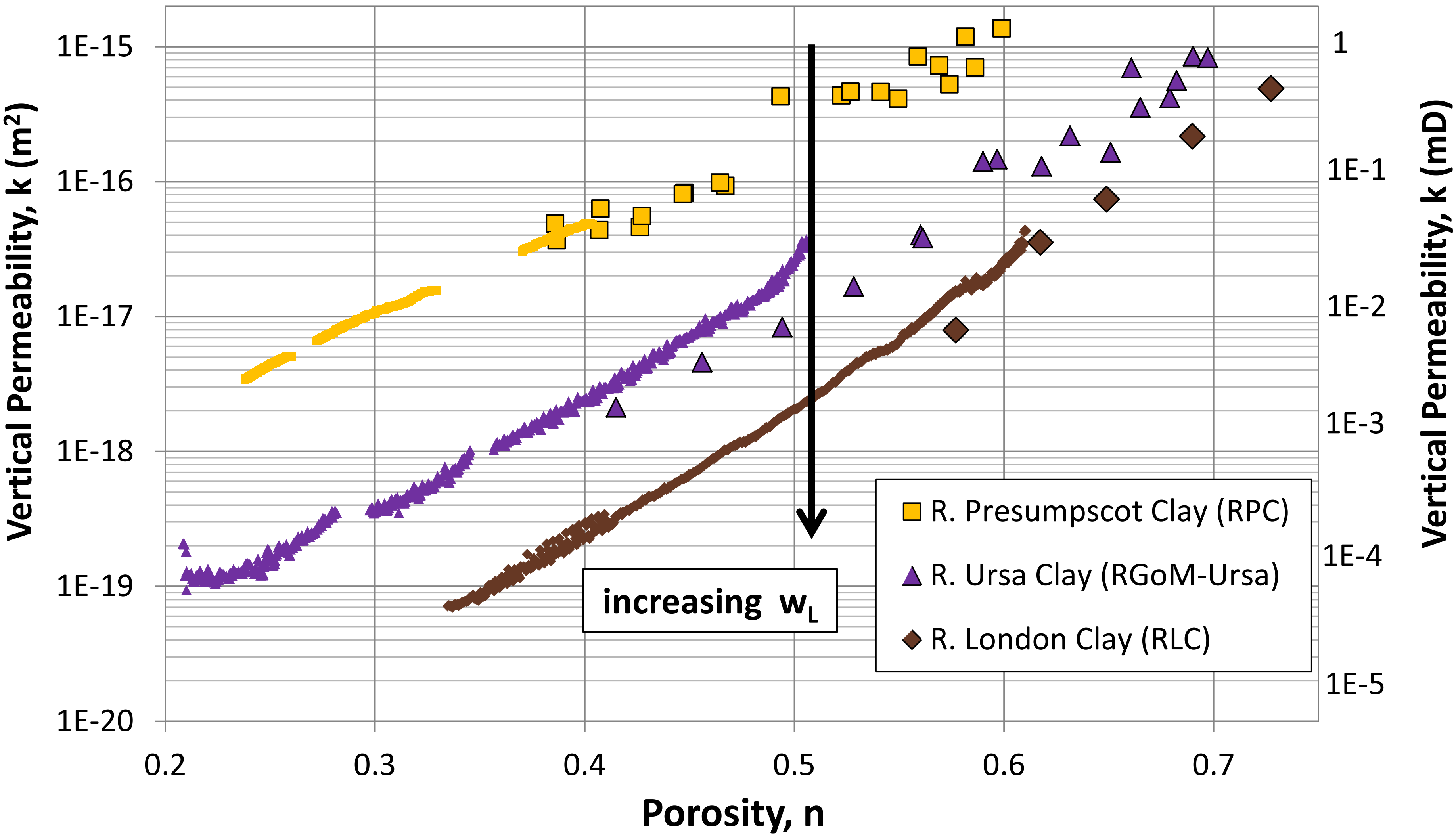
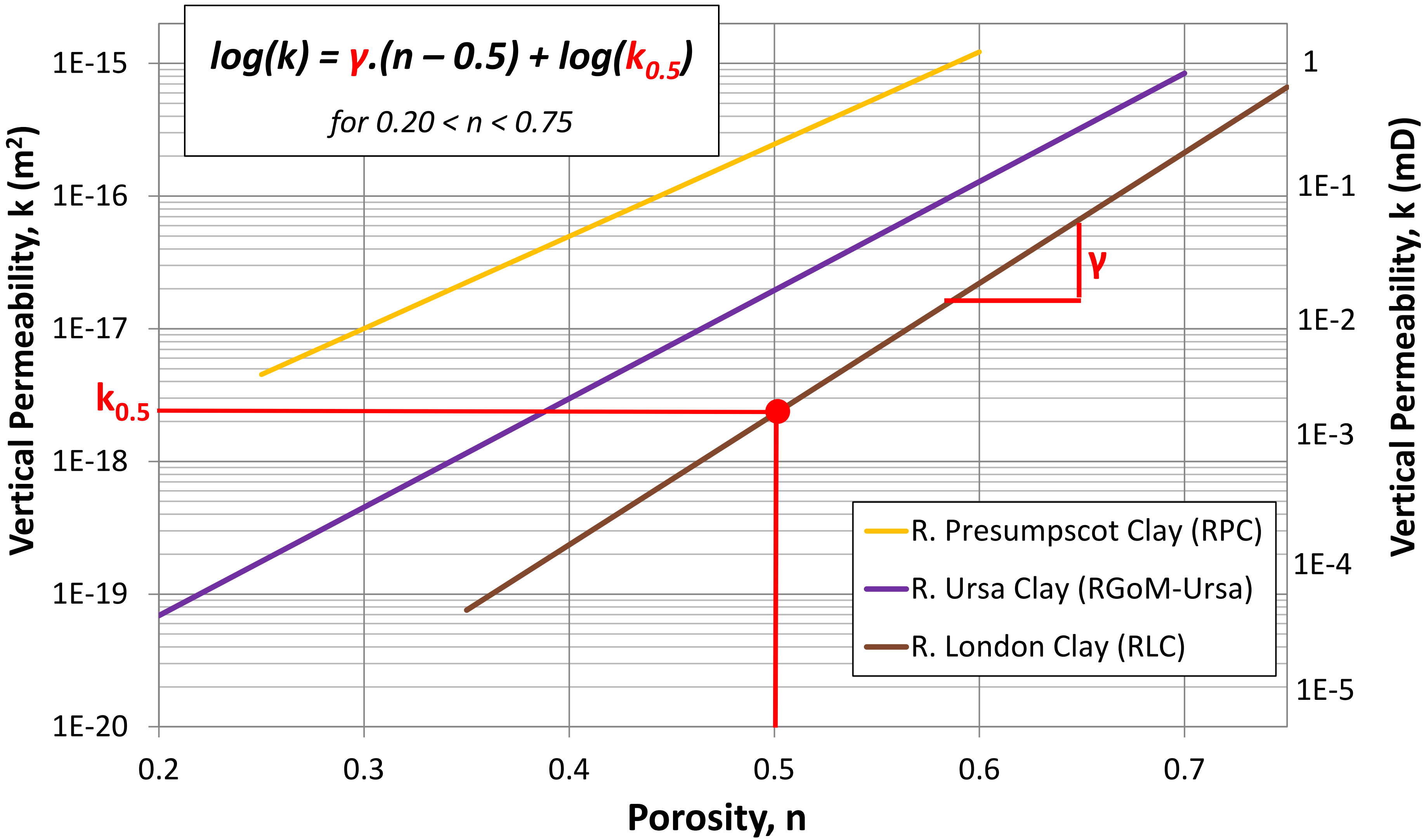
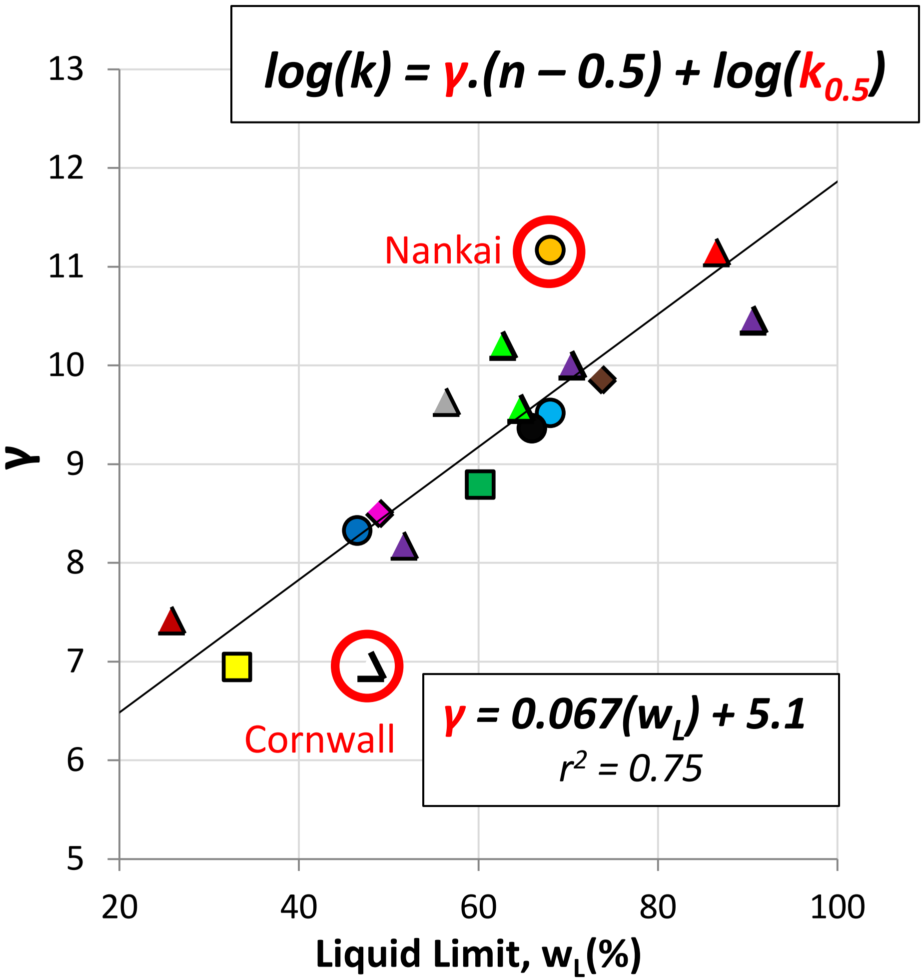
Permeability

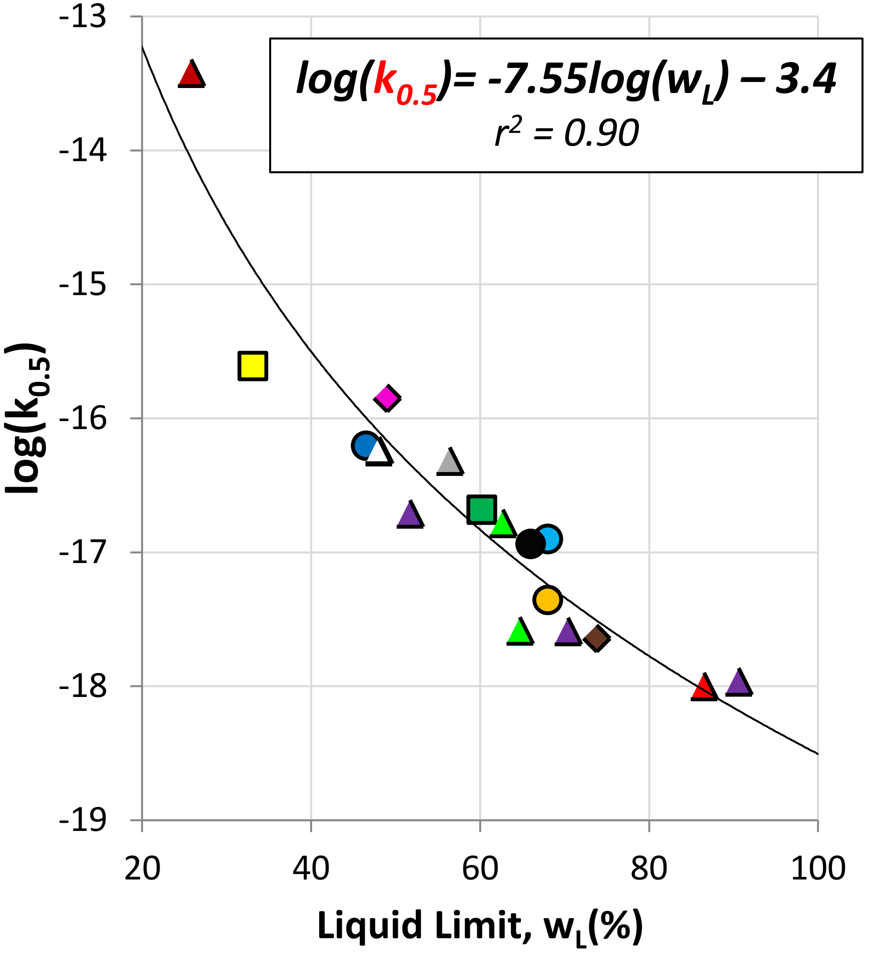


Permeability

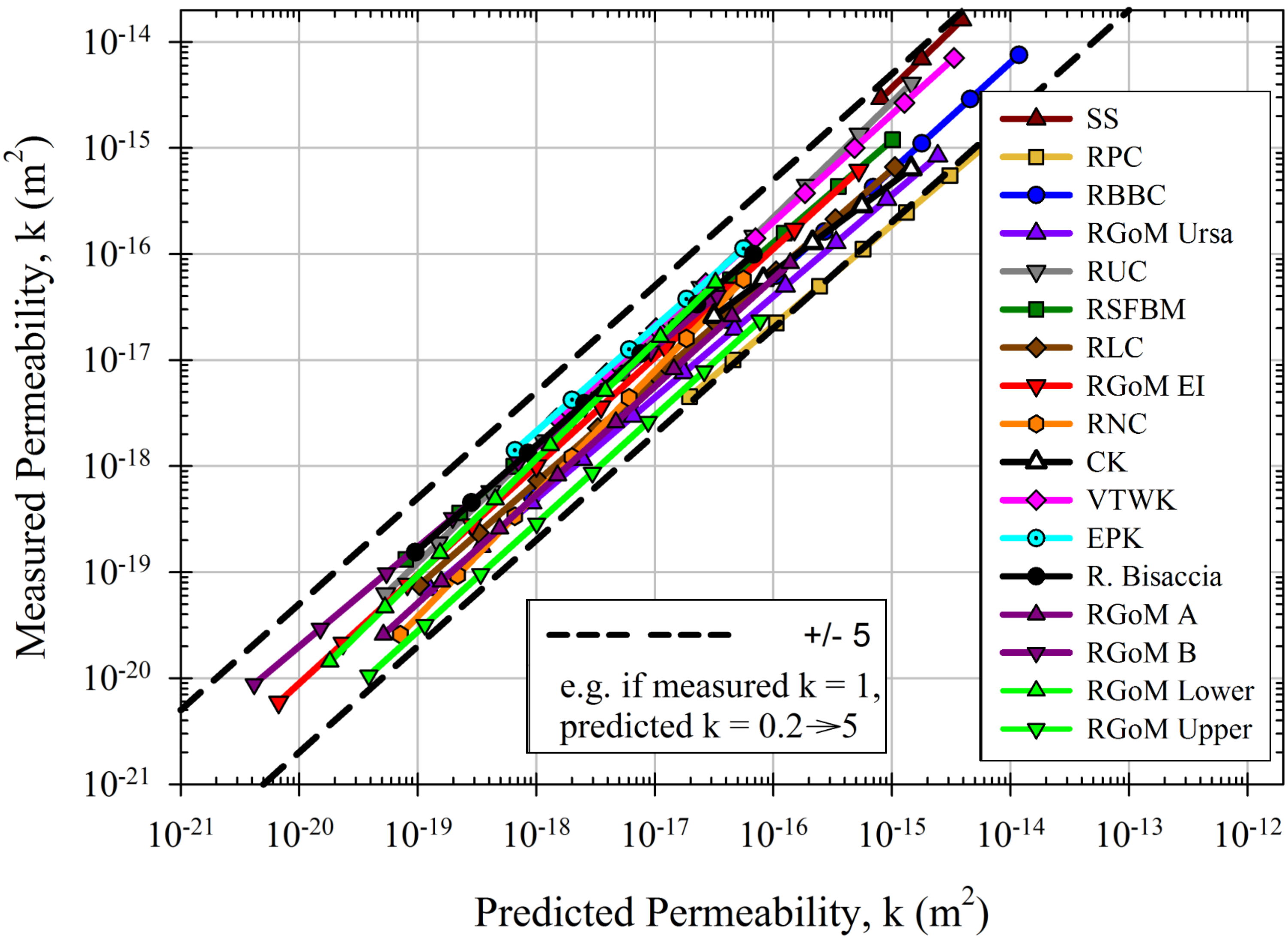


Permeability Correlations

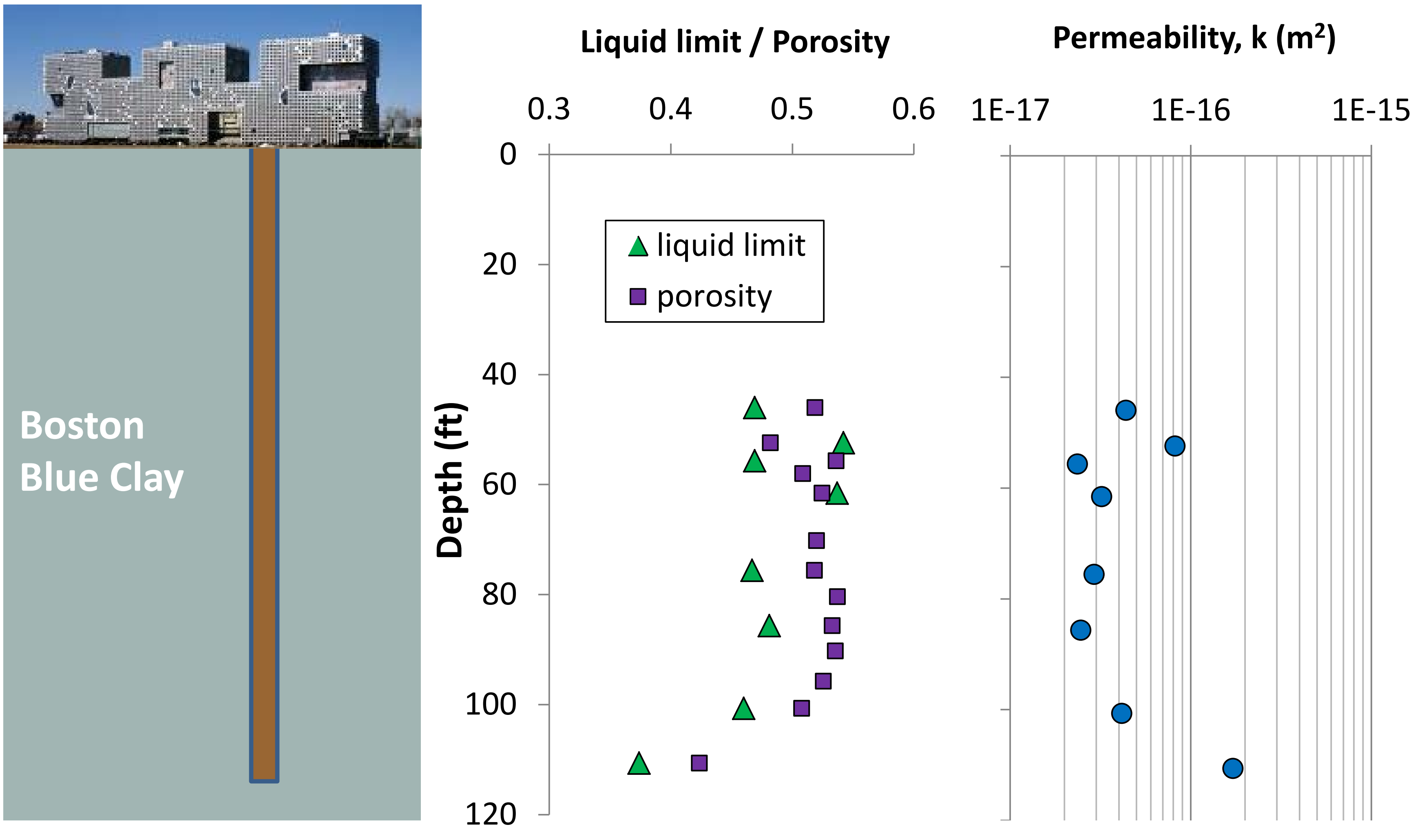




Permeability Model: Error Analysis



Permeability: Predicting In situ Behaviour



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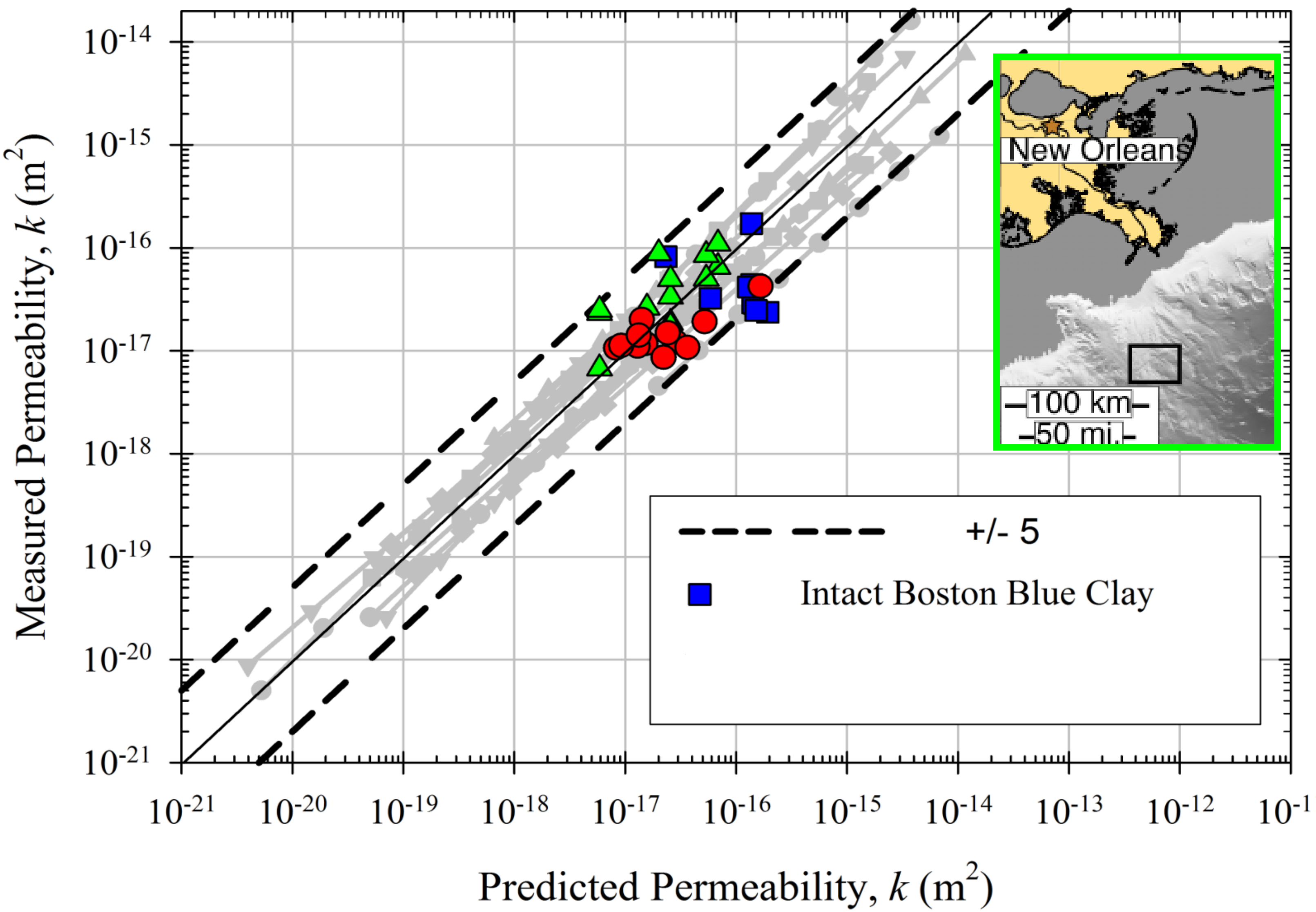

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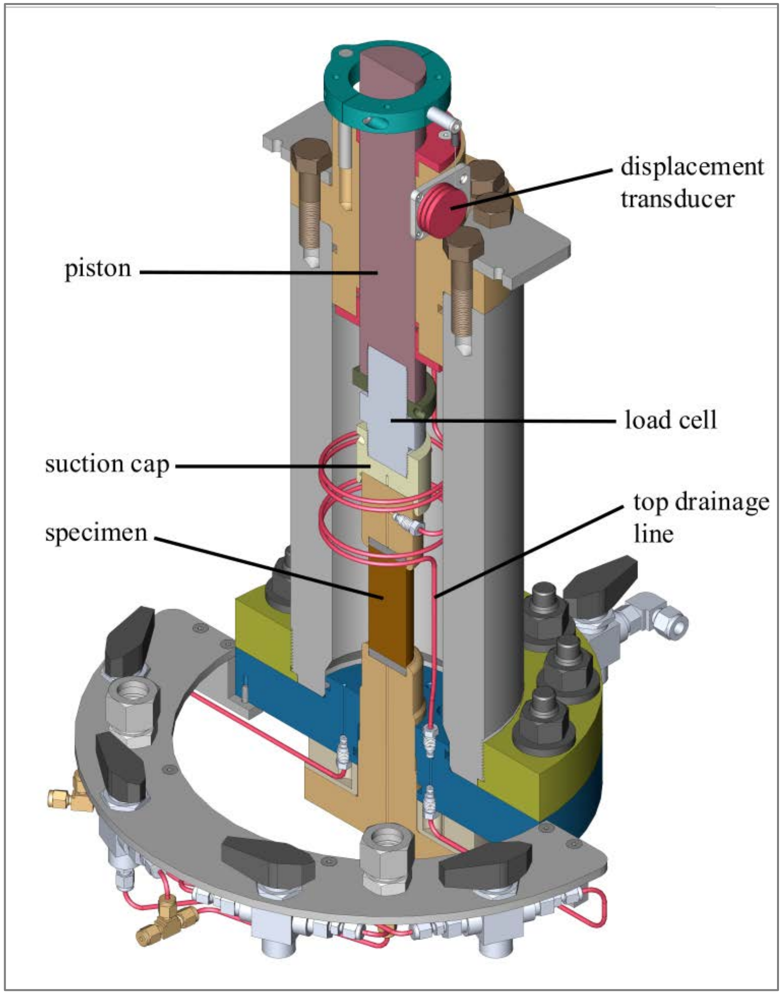
Typical Triaxial Test Procedure

1. Setup and back-pressure saturation *(1 day)*
2. K_O-consolidation of specimens (*3-10 days)*
   - ➢ Important to mimic field conditions
3. Secondary compression/creep *(1 day)*
4. K_O-swelling *(1 – 2 days)*
5. Undrained shear in triaxial compression *(1 day)*



low pressure triaxial
($\sigma'_p < 2$ MPa)

high pressure triaxial
($10 < \sigma'_p < 100$ MPa)

medium pressure triaxial
($2 < \sigma'_p < 10$ MPa)

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Effective Stress

- <u>Effective Stress:</u> *Partial stress which controls changes in deformation and shear resistance of porous materials*

- Conventional Terzaghi (1923) definition for saturated soil:

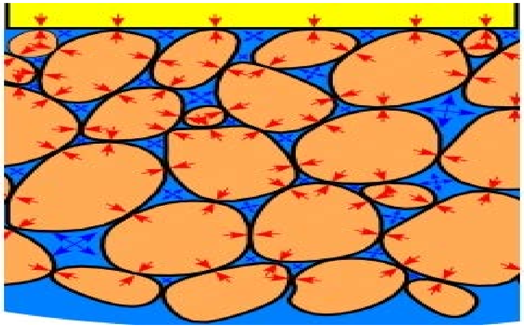
$$\boldsymbol{\sigma' = \sigma - u}$$

  - assumes particles are: 1) incompressible, and 2) have a constant yield strength

- Some have proposed modified definitions, such as:

  - $\sigma' = (\sigma - u) + \boldsymbol{a}u + (R - A)$ 'Intergranular stress'
  - $\sigma' = \sigma - \left(1 - a\dfrac{\tan\psi}{\tan\varphi'}\right)u$ *(Skempton 1960)*

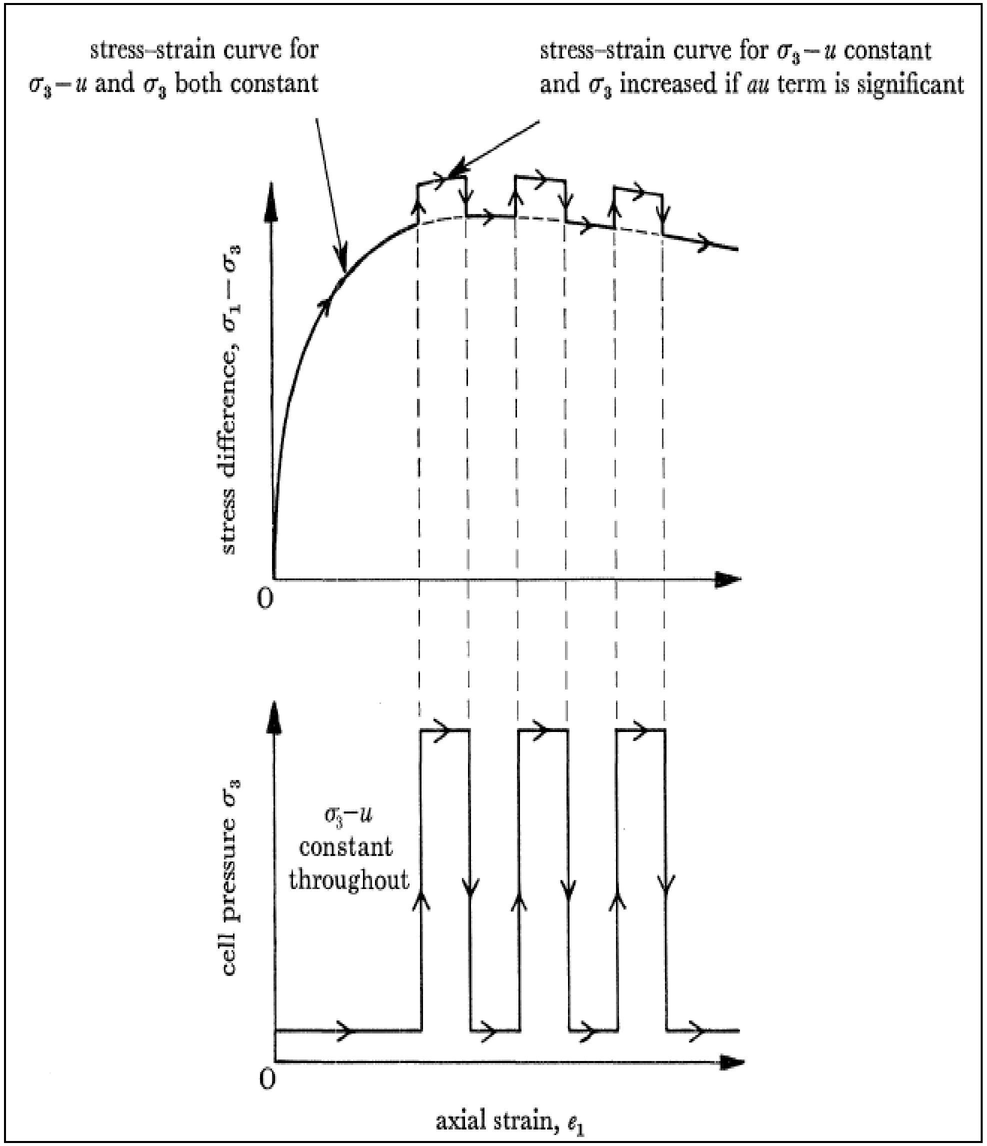
  (**a** = contact area between particles per unit area)



- At high stresses the contact area can become significant; can true effective stress deviate from Terzaghi definition? ...literature typically assumes no

Tests of Bishop and Skinner (1977)

- Most significant testing program to examine effective stress in relation to shear resistance
- Drained triaxial compression tests involving large changes in back-pressure but keeping ($\sigma_3 - u_b$) constant during shearing
- Significance of interparticle contact area determined from discontinuities in shear stress-strain curve
- Tested sand, silt, crushed marble, lead shot for pore pressures up to 40 MPa



Tests of Bishop and Skinner (1977)

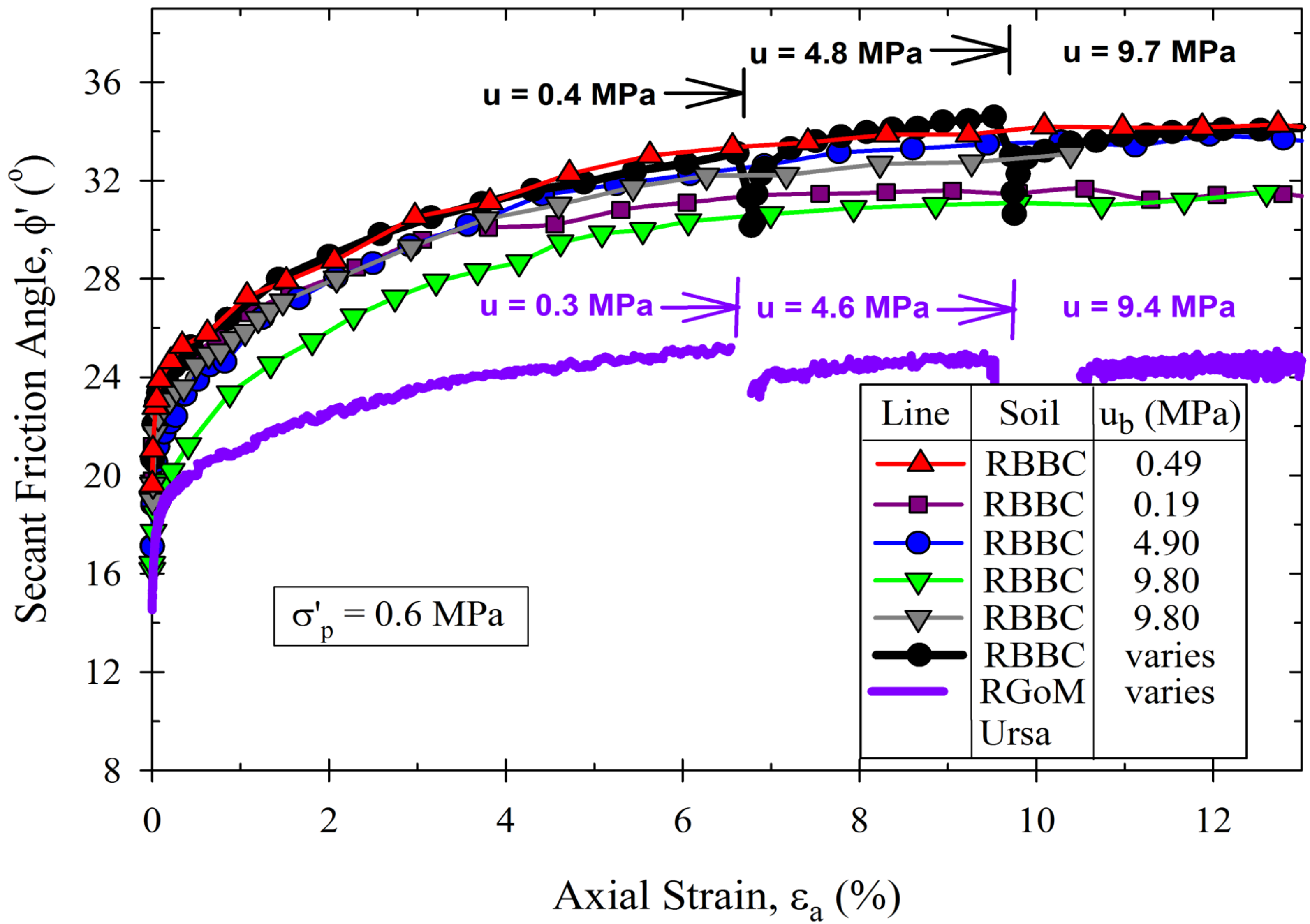
Results and conclusions:

- Terzaghi definition applicable for full range of stresses tested with no observable change in shear resistance
- Intergranular stress equation not valid
- Inconclusive re. Skempton's (1960) equation

However….

- No clays were tested
- Nature of inter-particle contacts is potentially different for clays

Effective Stress Tests



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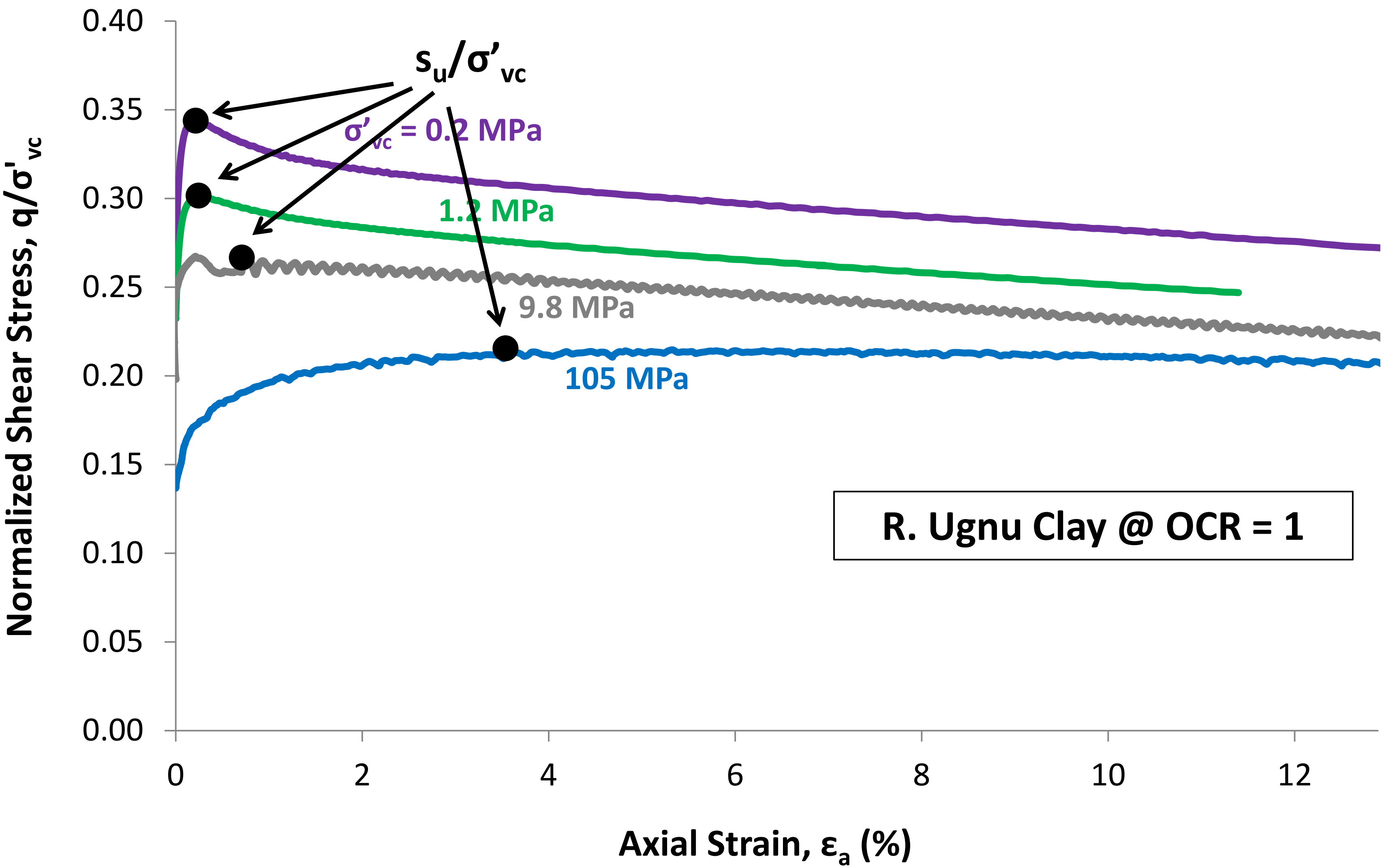
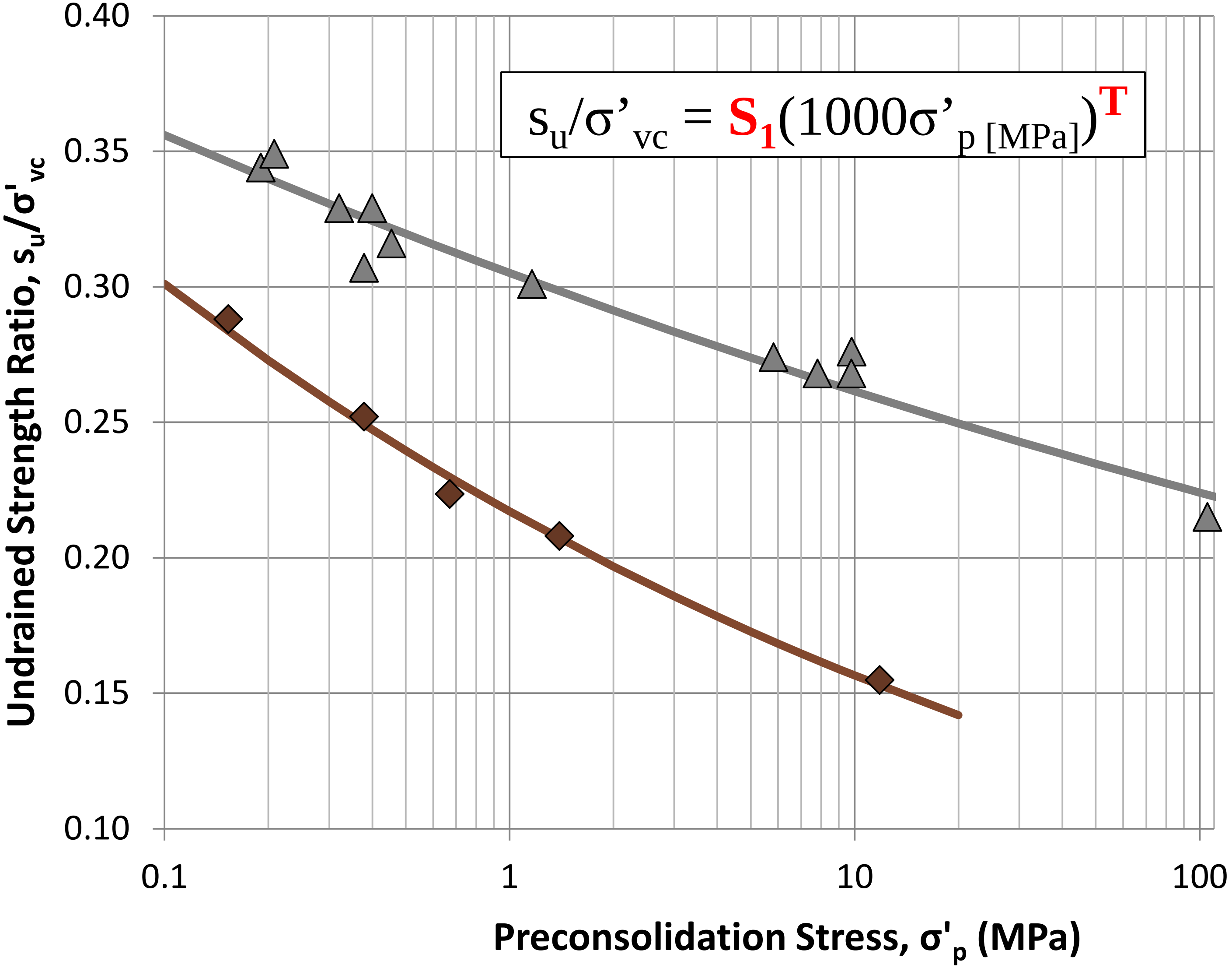
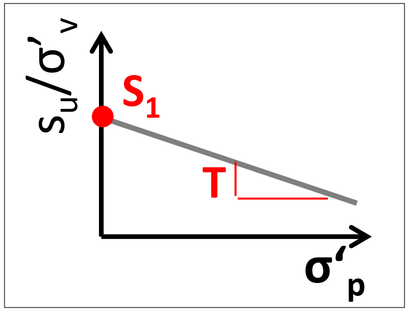
Stress-Strain Response during Shearing



Undrained Strength @ OCR = 1





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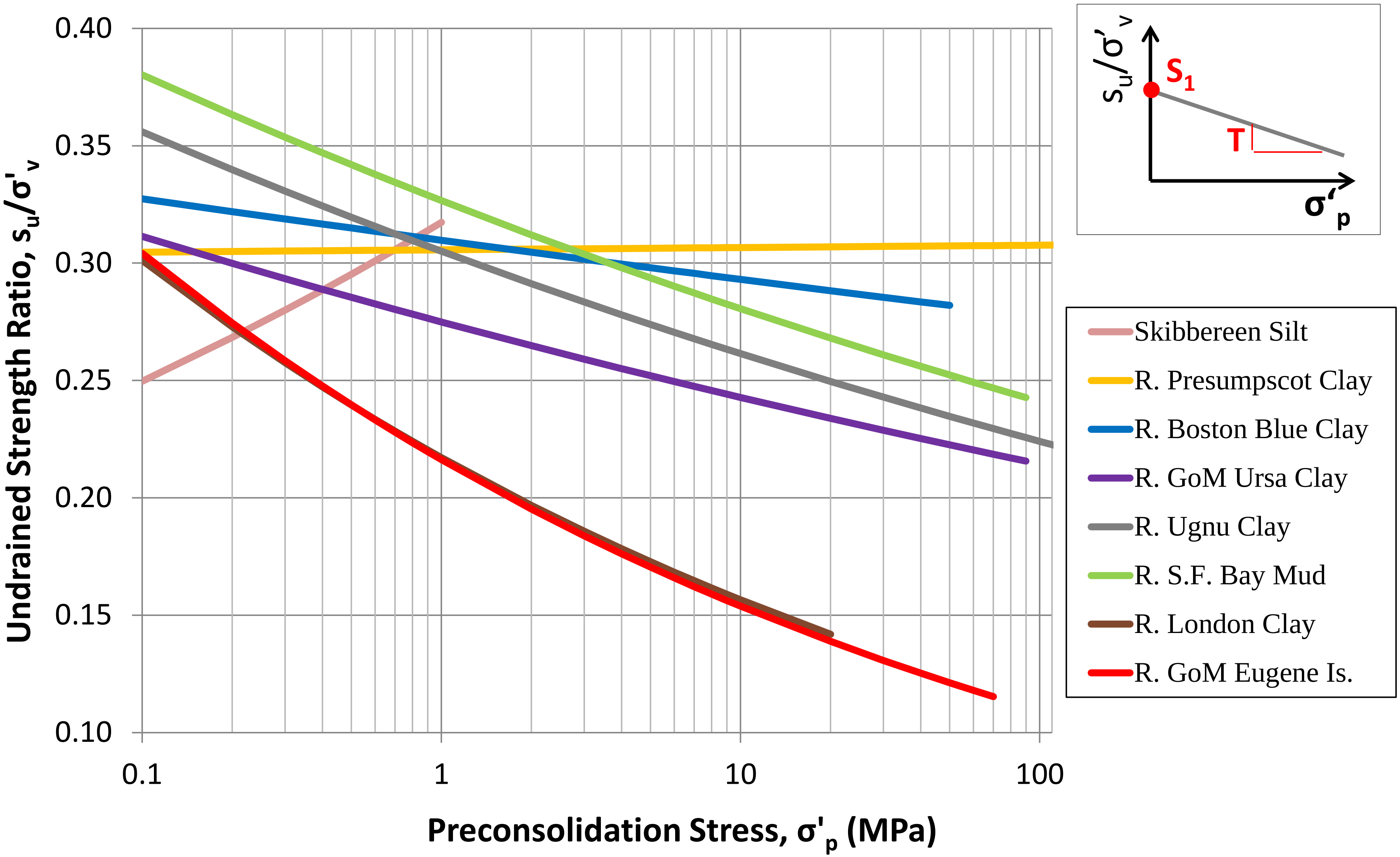
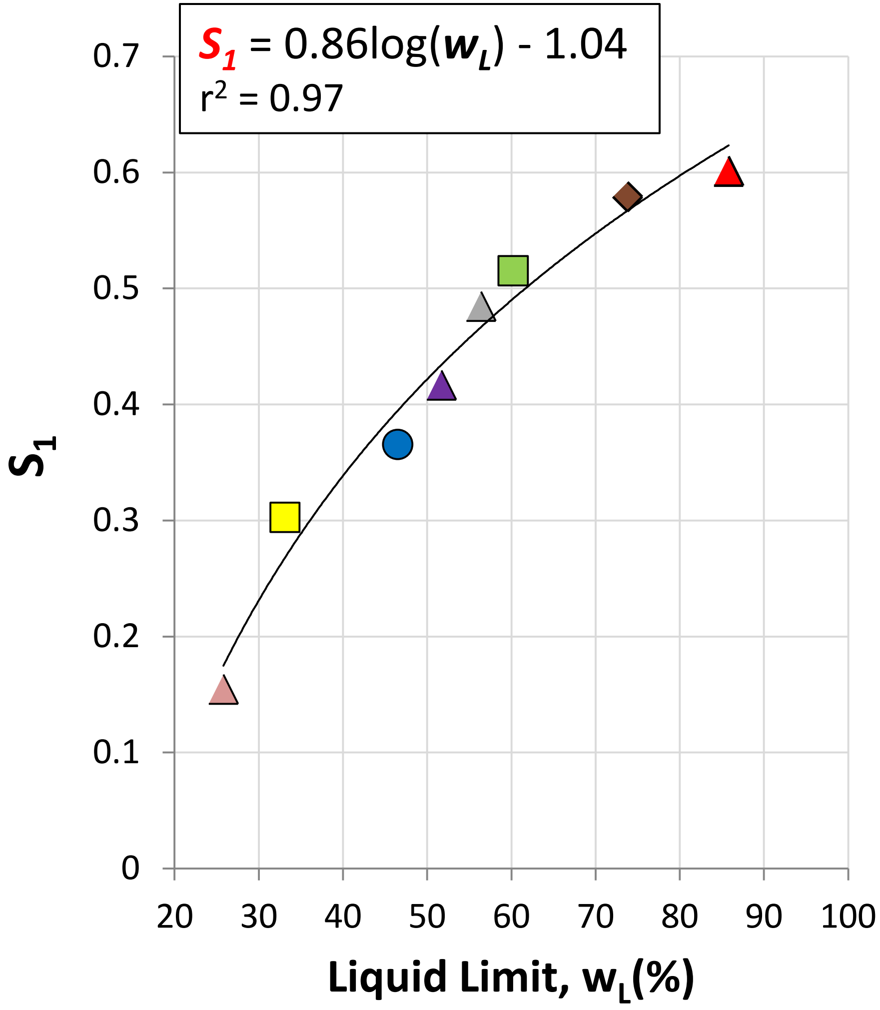
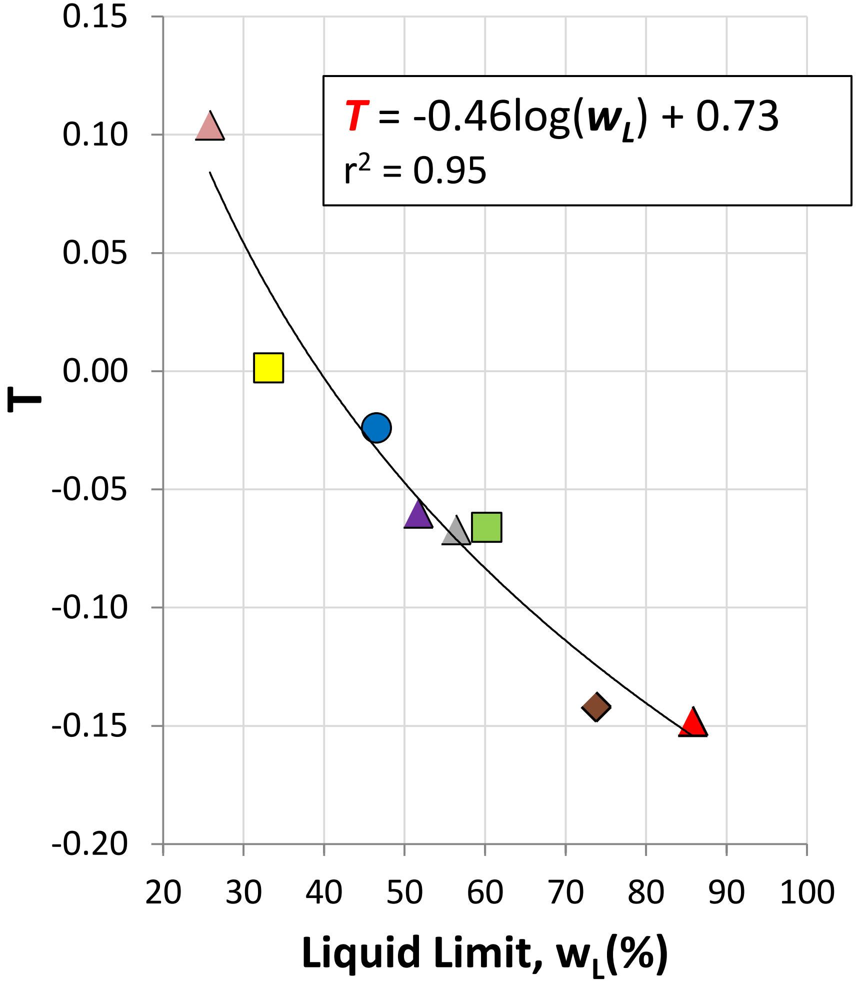
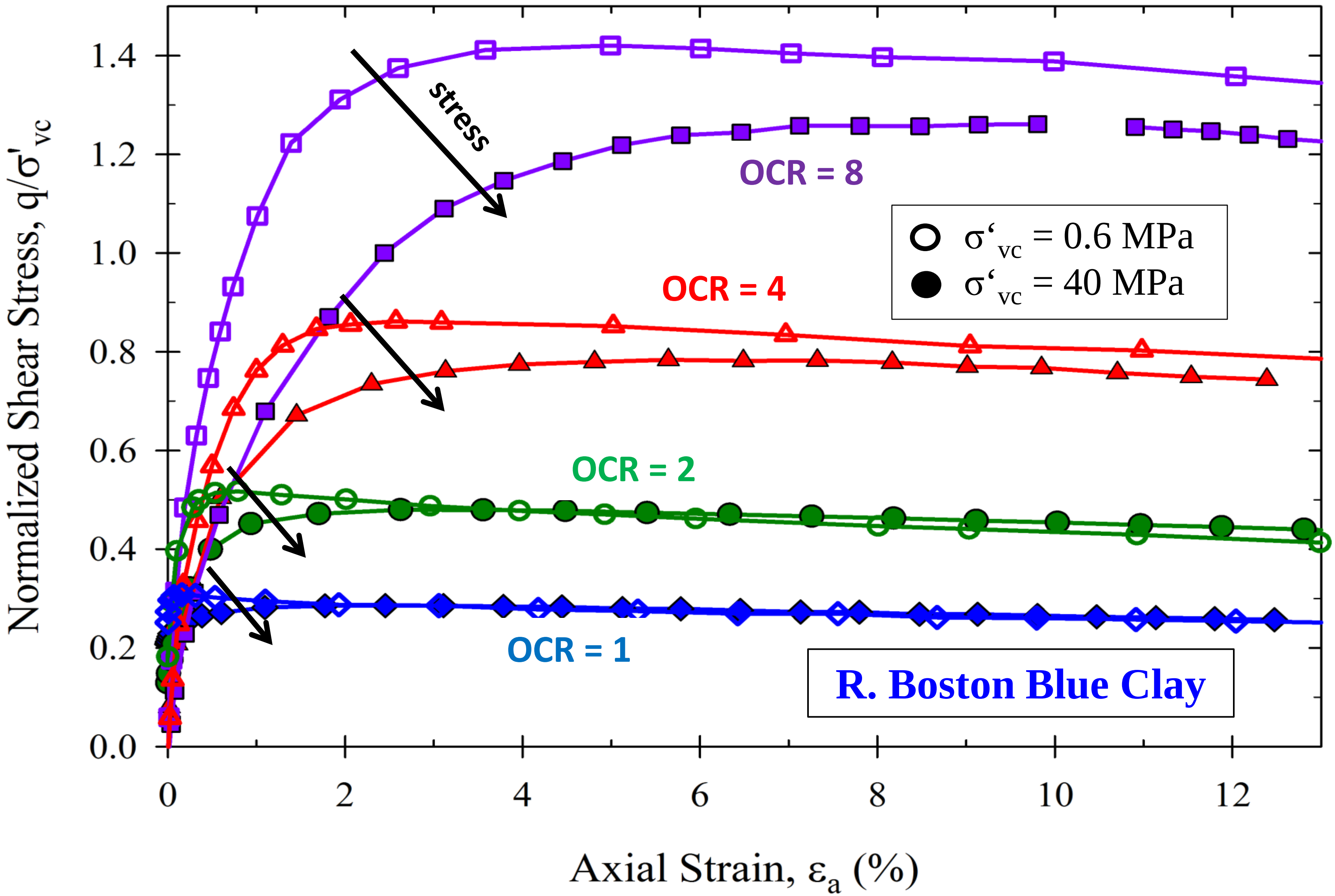


Undrained Strength - Liquid Limit Correlations

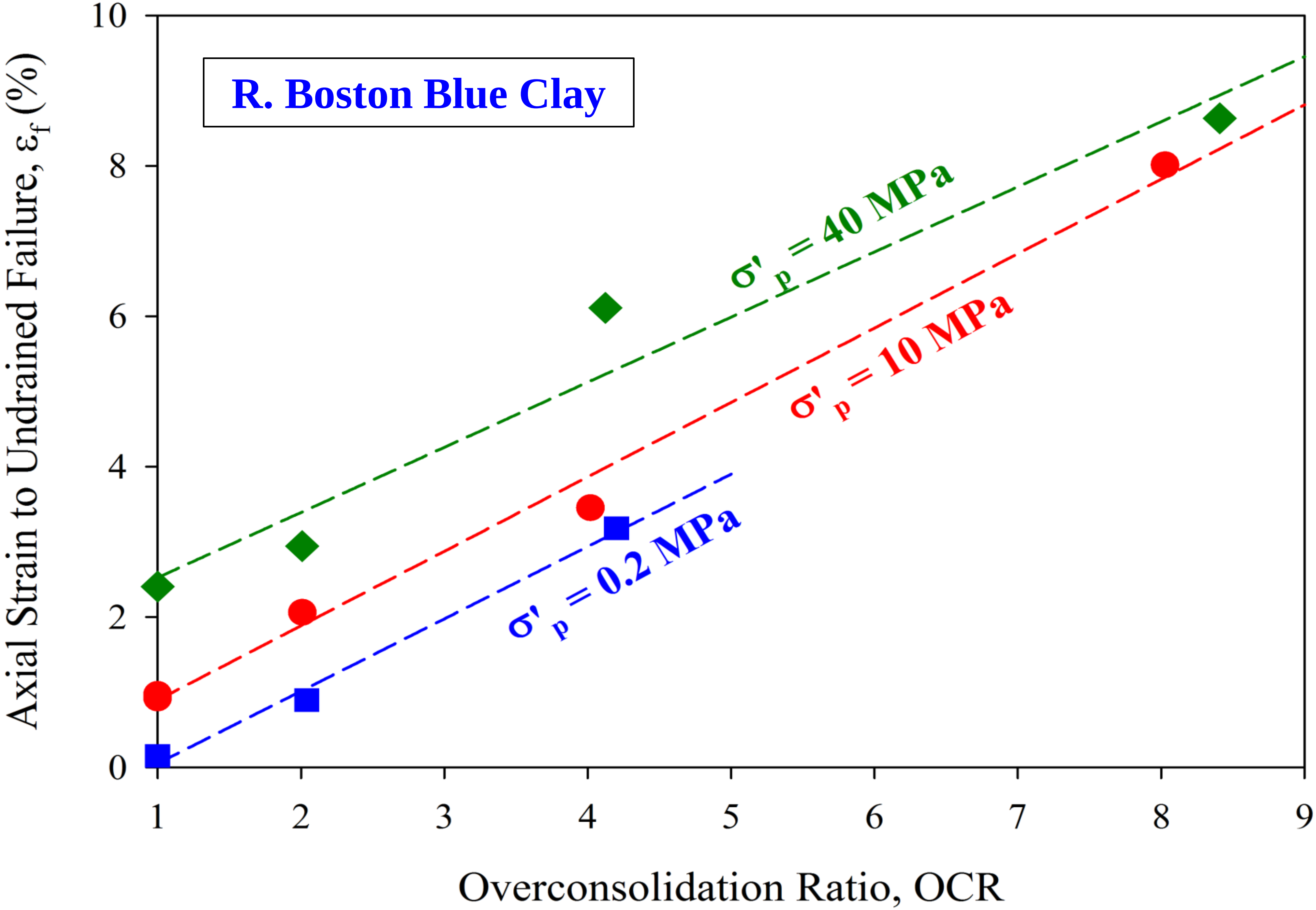




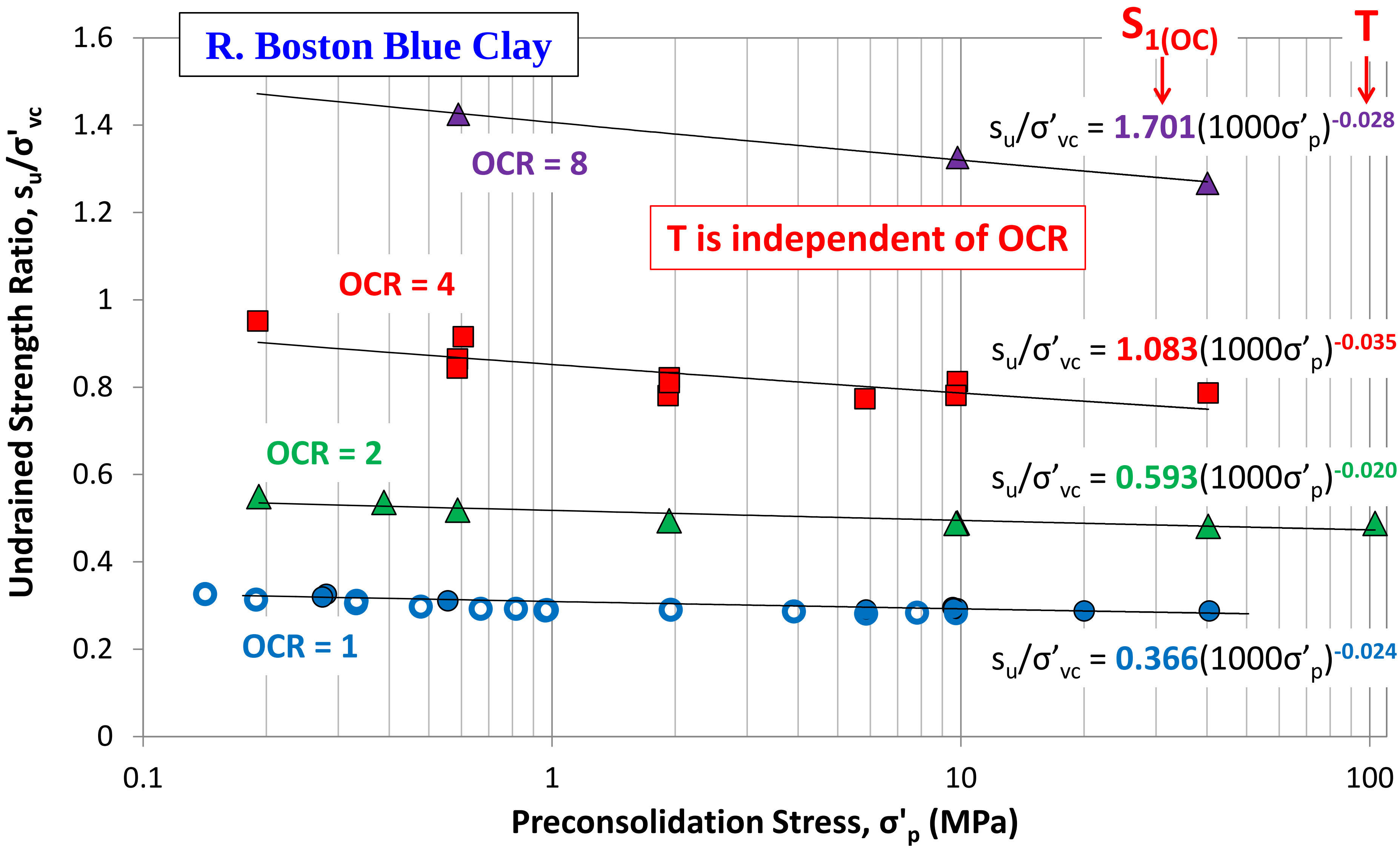
Overconsolidated Behavior



Increase in Ductility with Stress



Undrained Strength: Overconsolidated Soil



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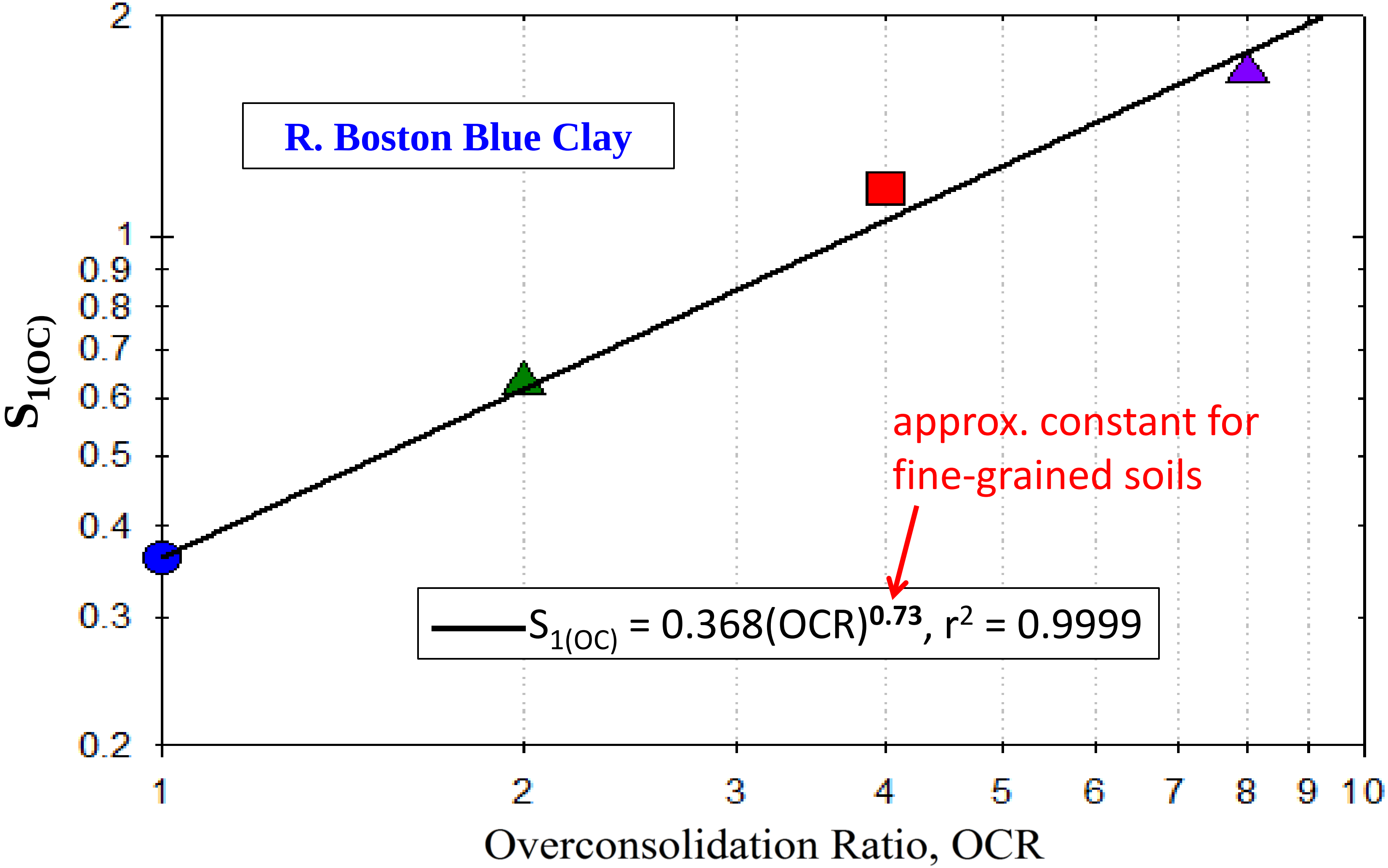


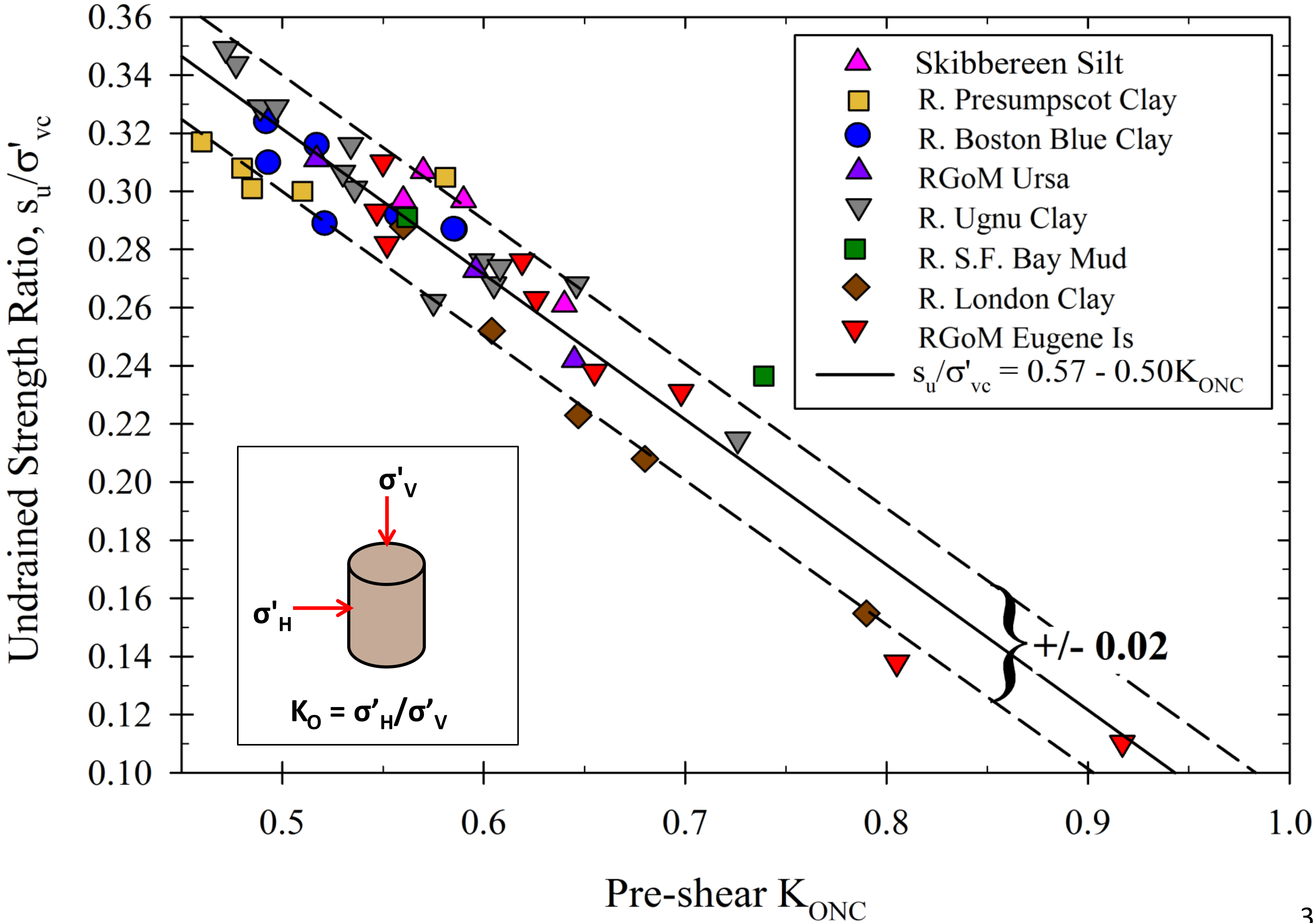
Summary of Strength Equations

- Undrained triaxial compressive strength:

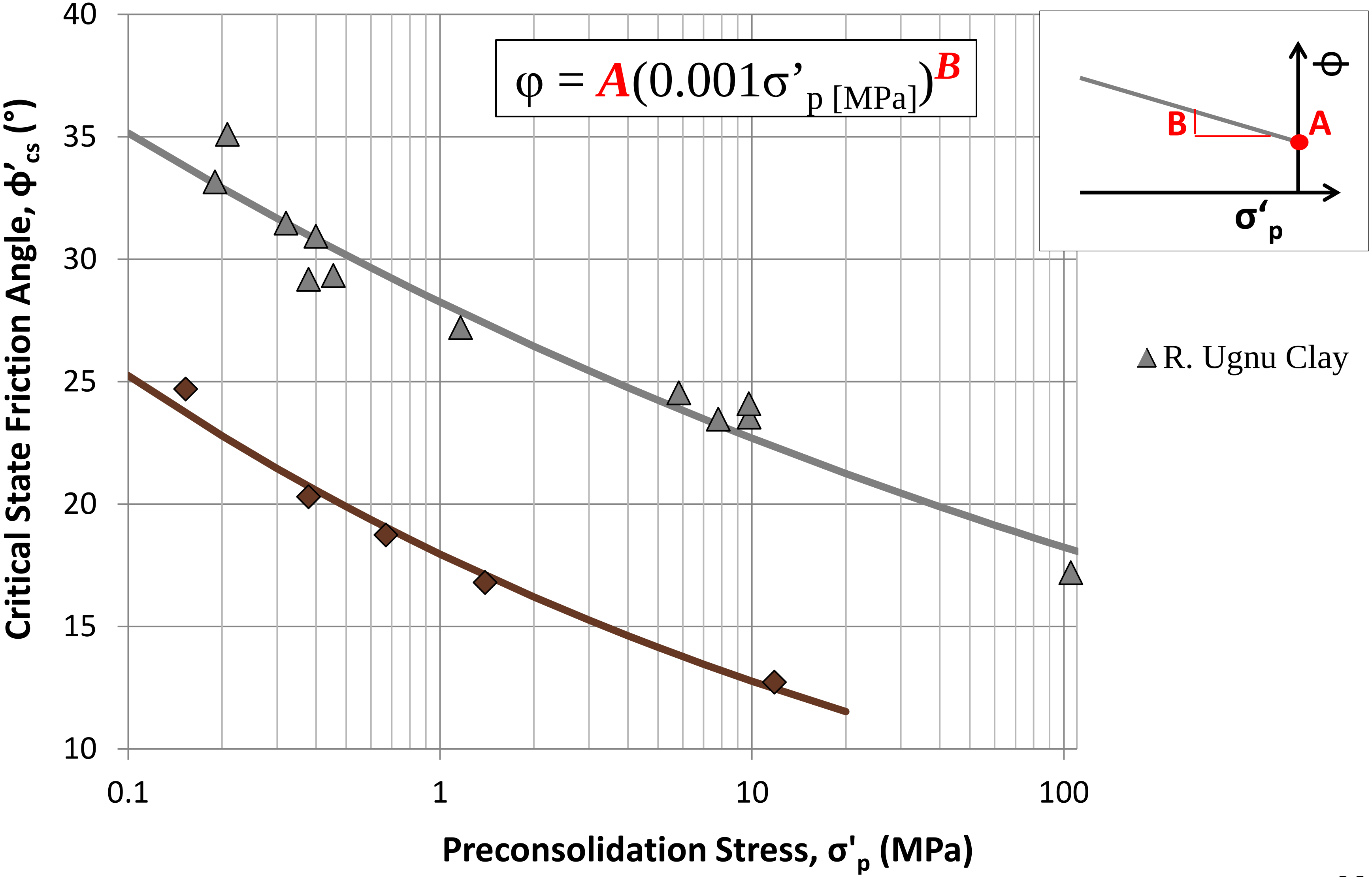
$$s_u/\sigma'_{vc} = \mathbf{S_1}(1000\sigma'_{p\ [MPa]})^{\mathbf{T}}(OCR)^{0.73}$$

  - $\boldsymbol{S_1} = 0.86\log(w_L) - 1.04$
  - $\mathbf{T} = -0.46\log(w_L) + 0.73$

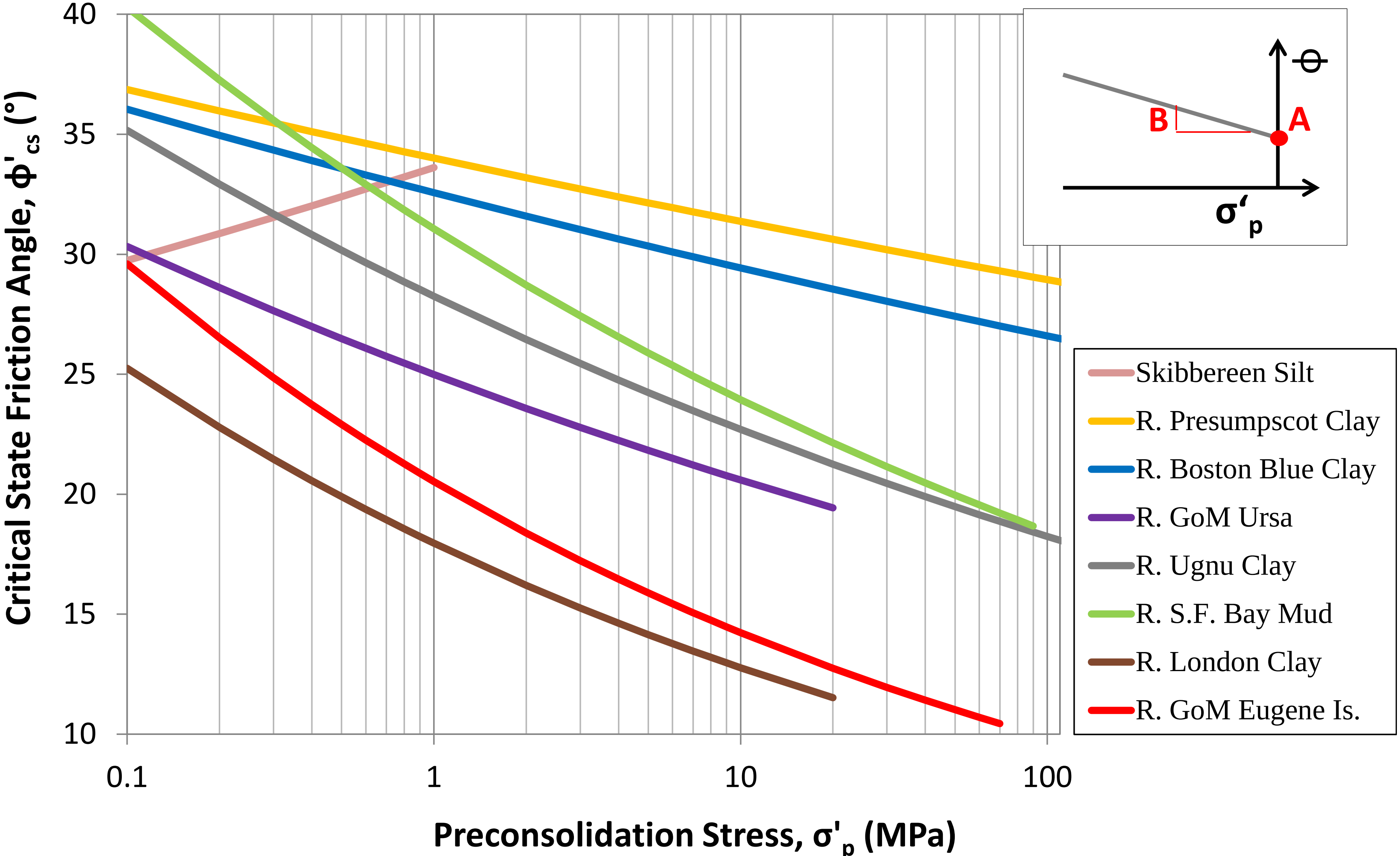
Effect of K_O on Undrained Strength @ OCR=1



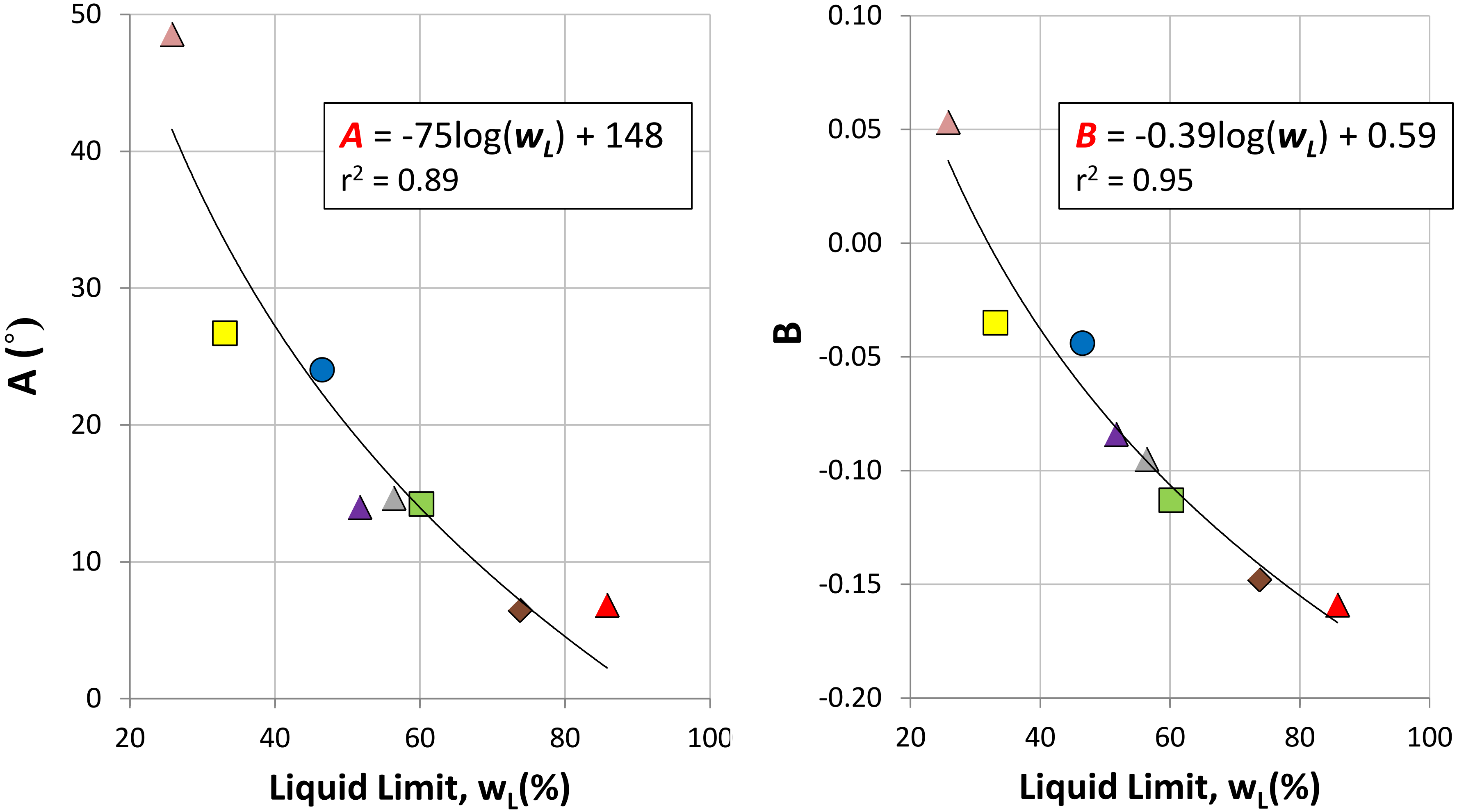
Friction Angle



Friction Angle



Friction Angle - Liquid Limit Correlations



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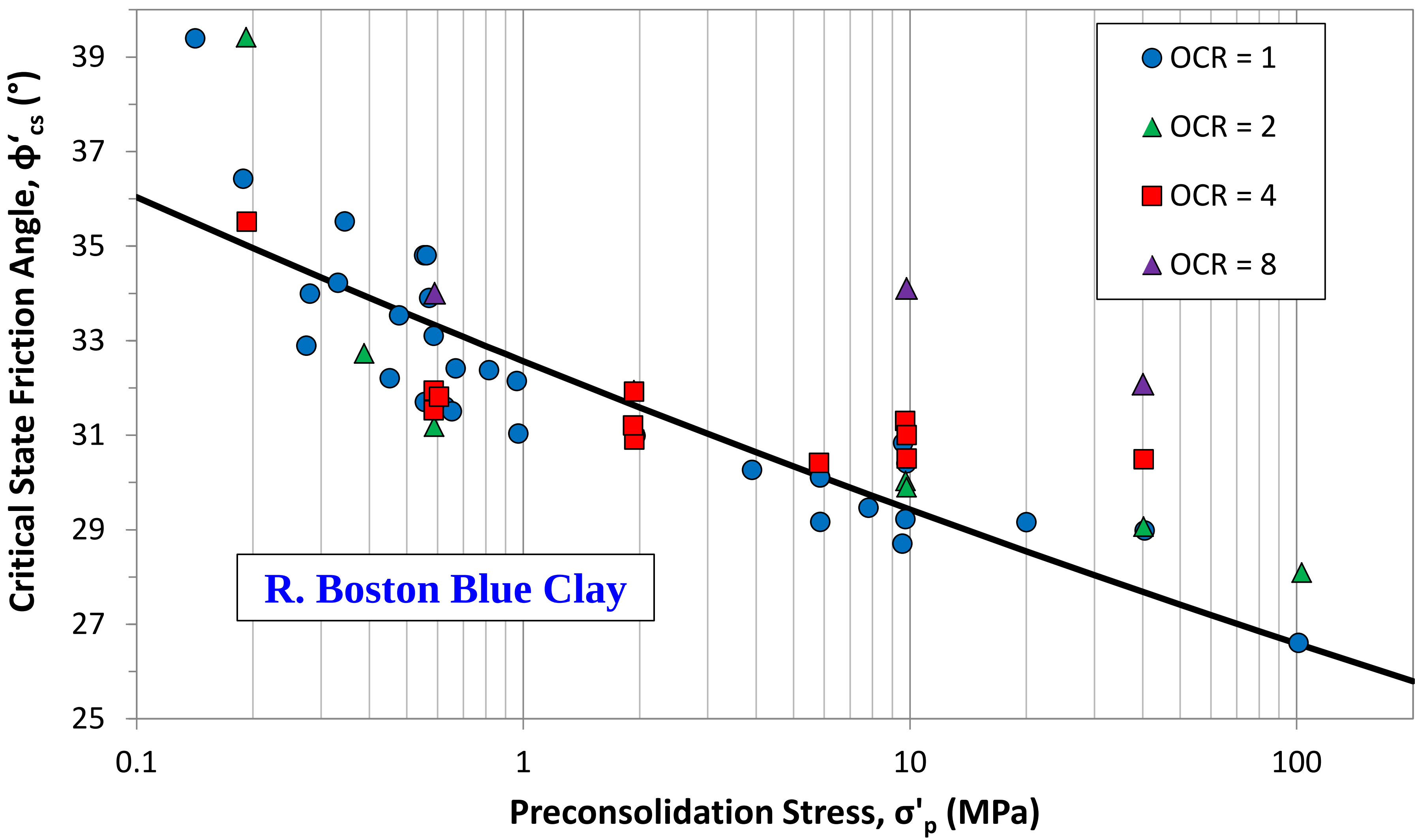
  - $S_1 = 0.86\log(w_L) - 1.04$
  - $\mathbf{T} = -0.46\log(w_L) + 0.73$

- Drained triaxial compressive strength:

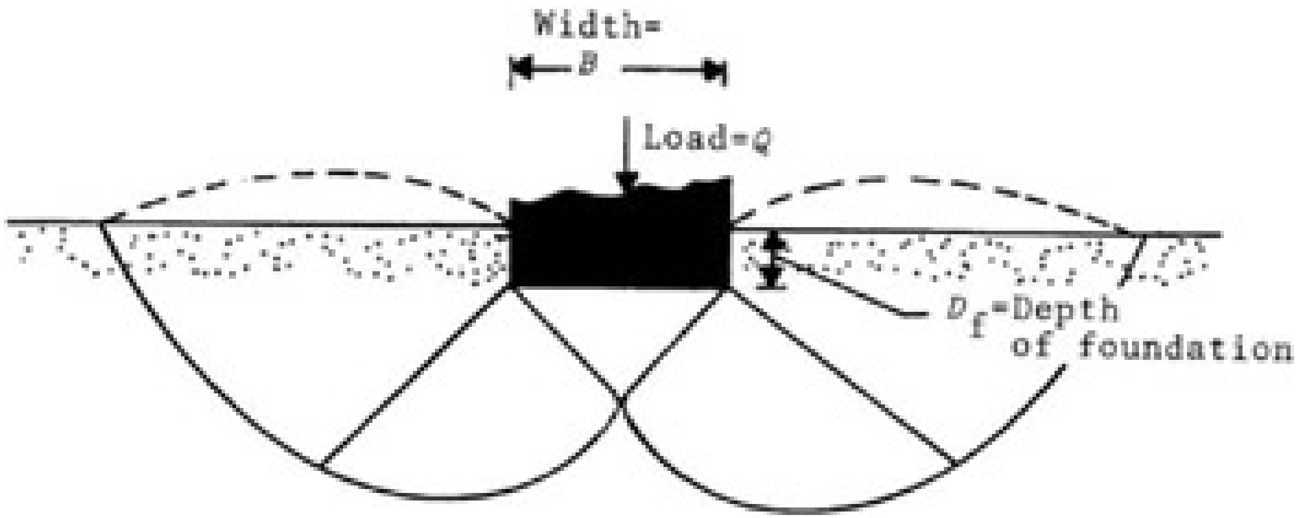
$$\varphi'_{cs} = A(0.001\sigma'_{p\ [MPa]})^{B}$$

  - $A = -75\log(w_L) + 148$
  - $B = -0.39\log(w_L) + 0.59$

Effect of OCR on φ'_{cs}



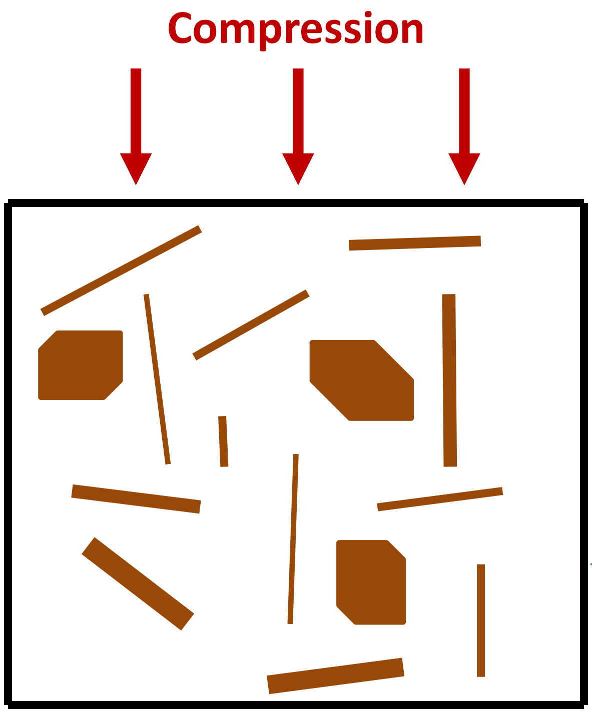
Example: Bearing Capacity



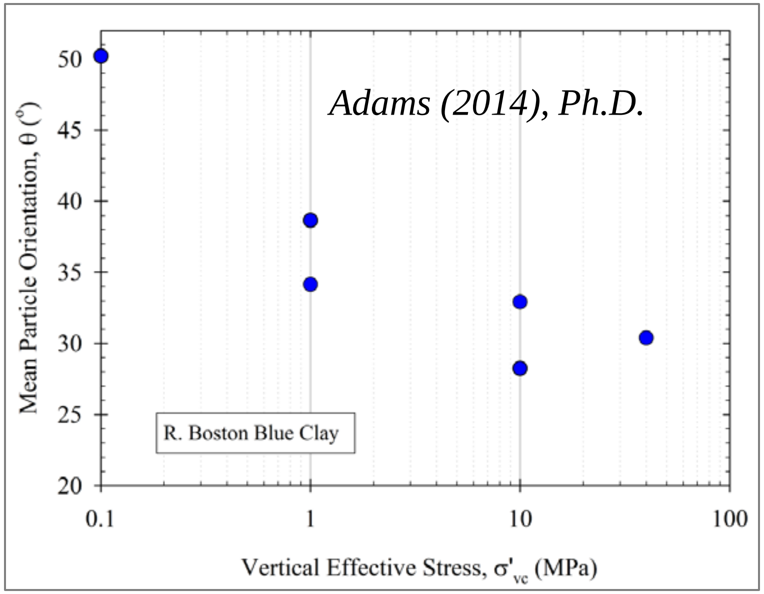
(assuming drained conditions and no surcharge)

- a change in friction angle from 40° to 35° reduces bearing capacity by 56 %
- a change in friction angle from 40° to 30° reduces bearing capacity by 80 % *!*

Particle Reorientation



Courtesy of Taylor Nordquist



….but failure in triaxial compression occurs at ~ 50°→65°

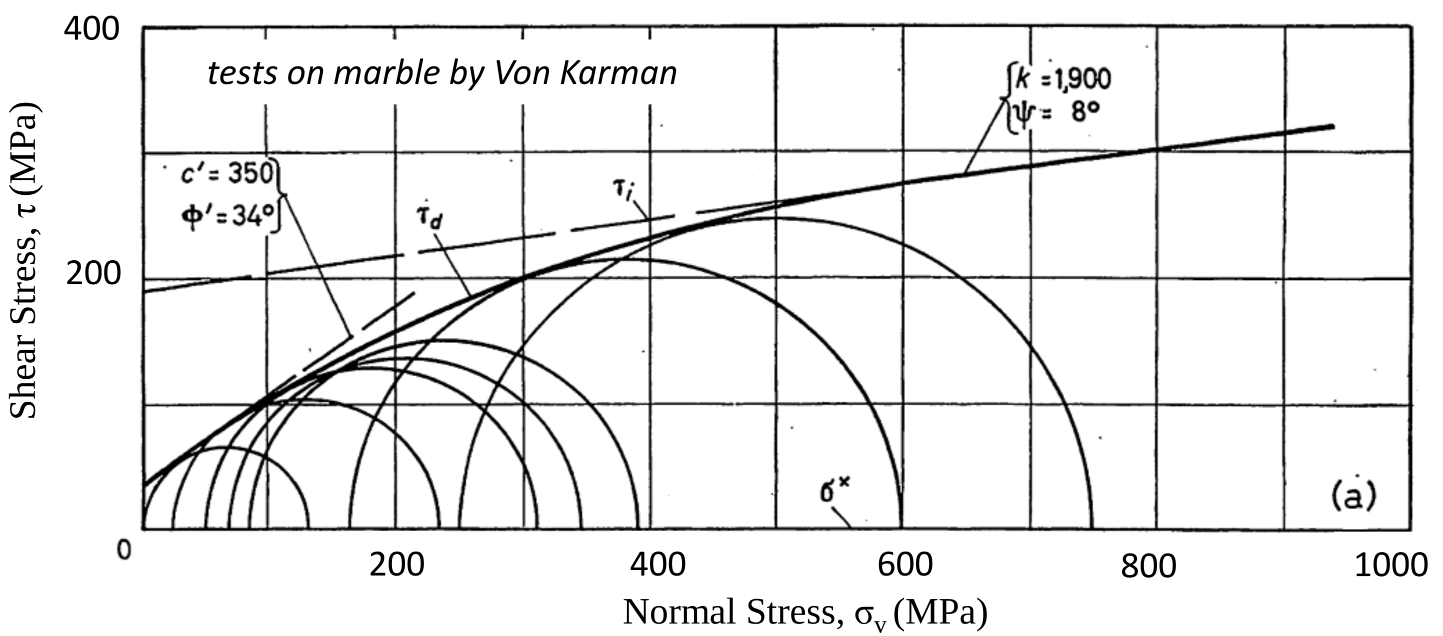
→ Particle reorientation with stress cannot explain strength behavior

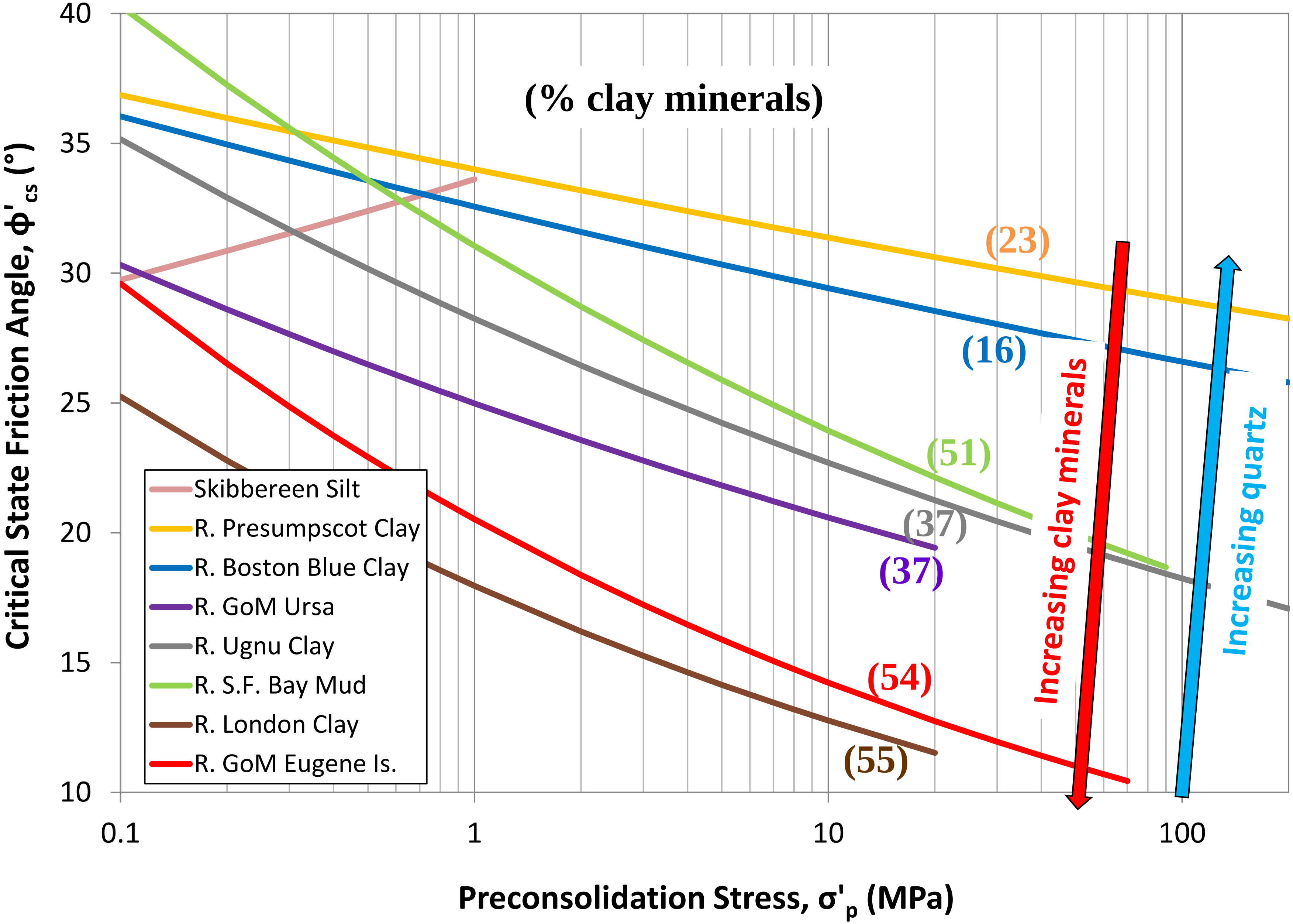
At very high stresses…

- Porous materials will ultimately reach the friction angle of the solid material, referred to as the *intrinsic friction angle ψ* (Skempton 1960)
- Tests on marble, metals, quartz and limestone

Material	Ψ (°)
Limestone	8
Calcite	8
Quartz	**16**
Clay minerals	**~ 5–10**

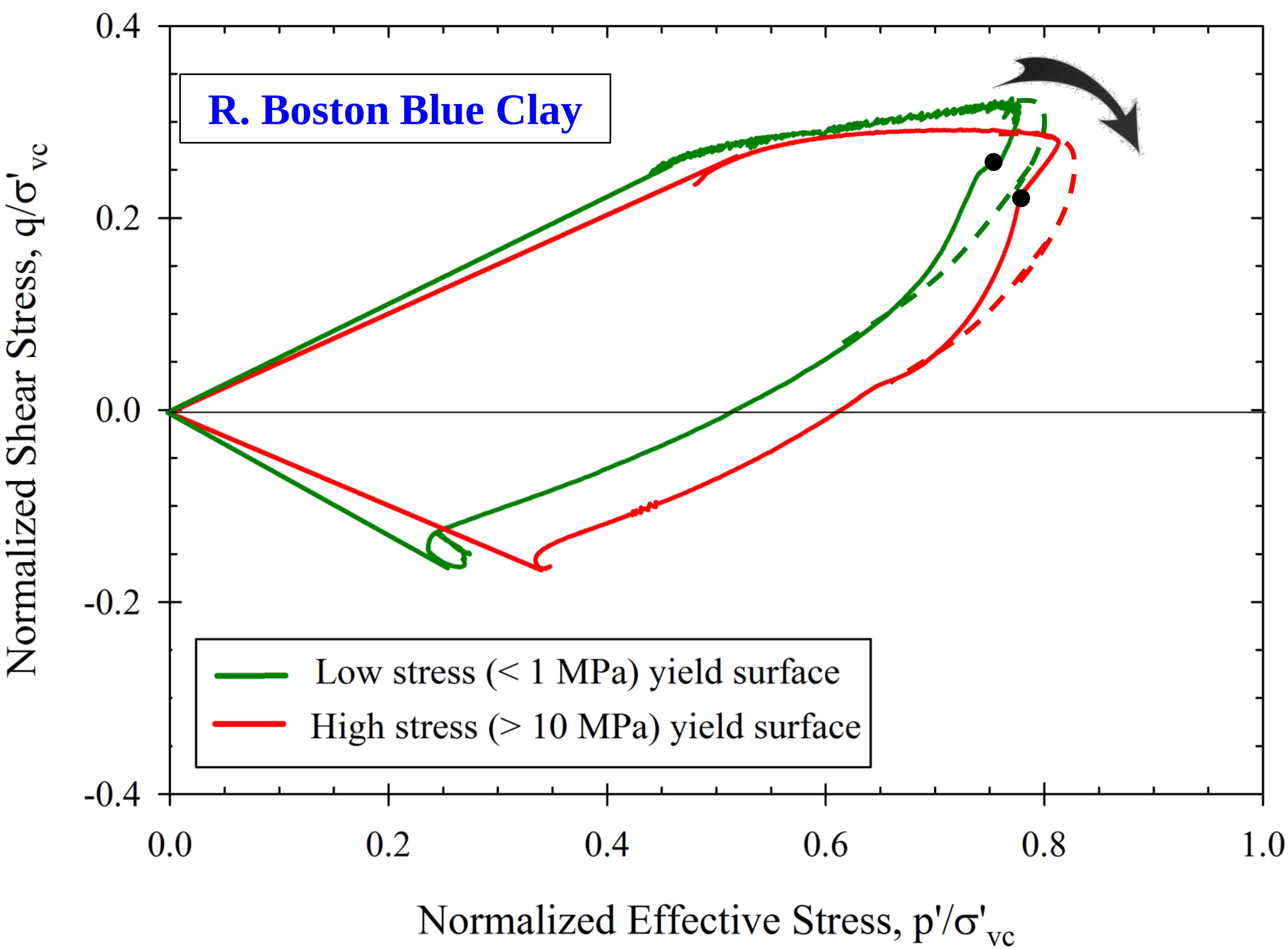
from Skempton (1960)





Critical State Friction Angle, φ'cs (°)
40
35
30
25
20
15
10
0.1
1
10
100
Preconsolidation Stress, σ'p (MPa)
(% clay minerals)
(23)
(16)
(51)
(37)
(37)
(54)
(55)
Increasing clay minerals
Increasing quartz
Skibbereen Silt
R. Presumpscot Clay
R. Boston Blue Clay
R. GoM Ursa
R. Ugnu Clay
R. S.F. Bay Mud
R. London Clay
R. GoM Eugene Is.

Yield Surface Evolution



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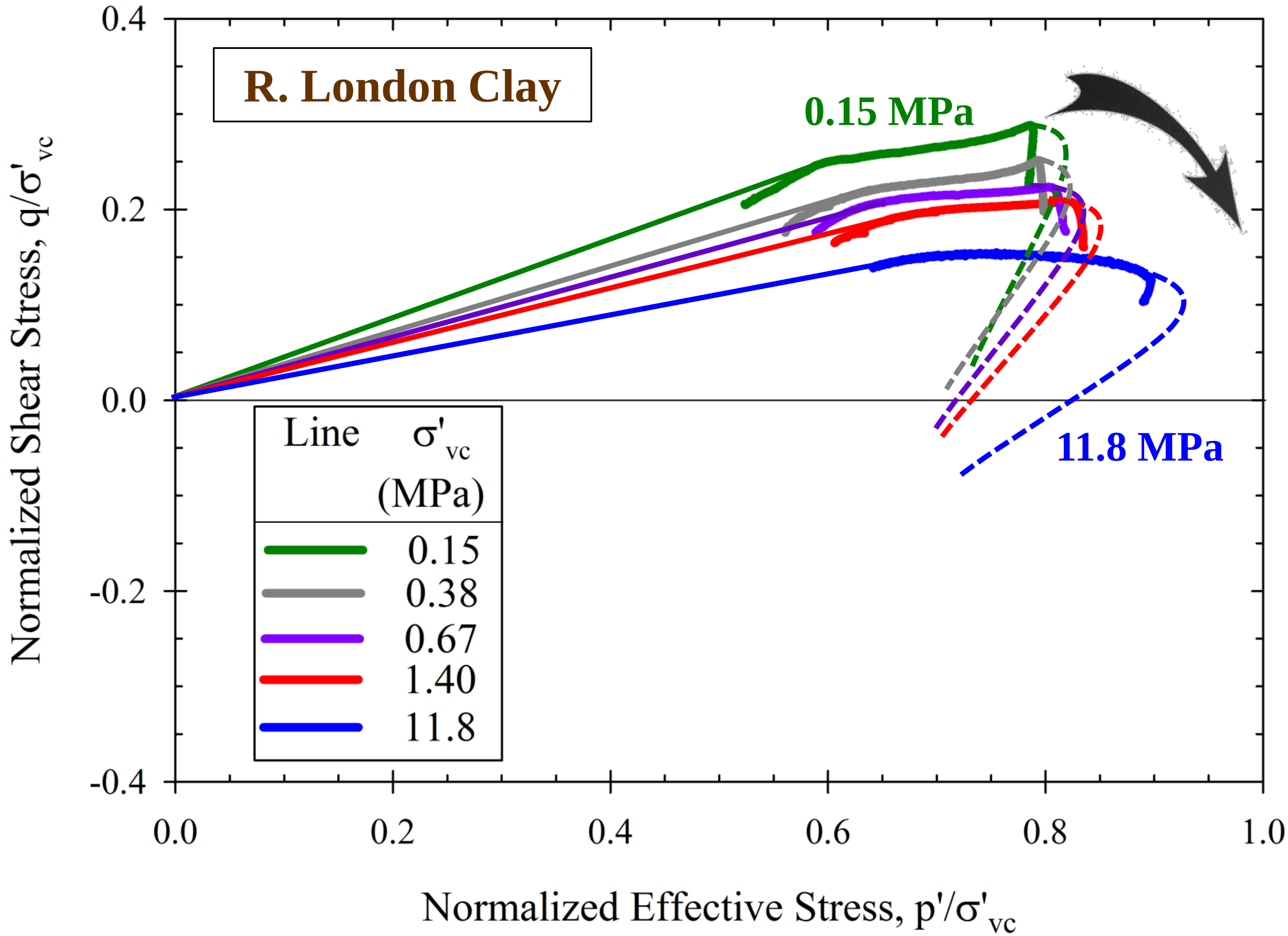

Conclusions

- Resedimentation is a technical necessity and practically advantageous to study the behavior of soils systematically
- Correlations developed from resedimented soil using liquid limit can predict intact permeability, a robust indicator of composition
- Conventional Terzaghi definition of effetive stress is valid for fine-grained soils at high in situ pore pressures
- Shear strength properties vary consistently with stress level and are closely linked to composition/plasticity
- Variations in strength properties with stress reflect an evolving yield surface

Motivation

For soils and 'soft' rock, shear strength is complex a function of:

$$\tau_{max} = f \left\{ \begin{array}{l} \text{composition } (w_L) \\ \text{effective stress } (\sigma') \\ \text{stress history } (OCR) \\ \text{mode of shear } (b, \alpha) \\ \text{temperature } (T) \\ \text{strain rate } (\dot{\varepsilon}) \\ \text{water saturation } (S_w) \\ \text{diagenesis} \end{array} \right\}$$

- composition (w_L) ← **This work**
- effective stress (σ') ← **This work**
- stress history (OCR) ← **This work**
- mode of shear (b, α) ← **Future Work**
- temperature (T) ← **Future Work**
- strain rate ($\dot{\varepsilon}$) ← **Future Work**
- water saturation (S_w) ← **Future Work**
- diagenesis ← **Future Work**

This work

Future Work

Publications

- Casey, B. and Germaine, J.T. (2013). "**The Stress Dependence of Shear Strength in Fine-Grained Soils and Correlations with Liquid Limit**", *Journal of Geotechnical and Geoenvironmental Engineering*, 139 (10), 1709-1717. doi: 10.1061/(ASCE)GT.1943-5606.0000896
- Casey, B., Germaine, J.T., Flemings, P.B., Reece, J.S., Gao, B., and Betts, W. (2013). "**Liquid Limit as a Predictor of Mudrock Permeability**", *Journal of Marine and Petroleum Geology*, 44, 256-263. http://dx.doi.org/10.1016/j.marpetgeo.2013.04.008
- Casey, B. & Germaine, J.T. (2013). "**Variation of Cohesive Sediment Strength with Stress Level**", *Advances in Multiphysical Testing of Soils and Shales, Springer Series in Geomechanics*
- Casey, B., Fahy, B.P., Flemings, P.B. & Germaine, J.T. (2014). Shear Strength of Two Gulf of Mexico Mudrocks and a Comparison with Other Sediments, *Fourth EAGE Shale Workshop*, 6-9 April 2014, Porto
- Casey, B. & Germaine, J.T. (2014). "**An Evaluation of Three Triaxial Systems with Results from 0.1 to 100 MPa"** *Geotechnical Testing Journal*, in review