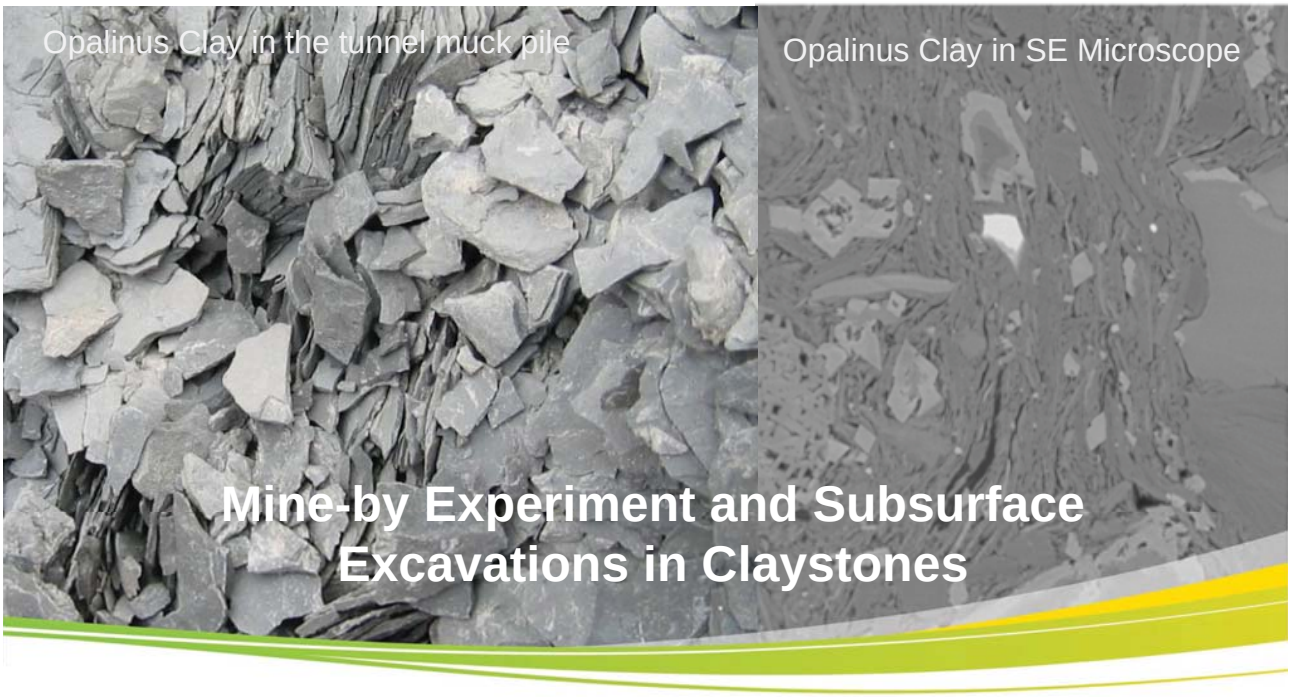
Symposium questions to be answered:

- What are the anticipated in-situ stress magnitudes and orientations at a depth between 400 and 900 m at the potential repository sites, and how reliable are these estimates?
- What are the time-dependent rock mechanical processes relevant for the development of the excavation damage zone in space and time and consequently for the long-term safety?
- What is the influence of natural discontinuities on the rock mass behavior?
- How reliable can complex HM-coupled processes be reproduced using numerical models?
- Which measures (e.g. underground ventilation or support) can be taken to minimize time-dependent damage of the geological barrier?
- How do rock mechanical and geological conditions influence the layout, construction, operation and closure of the repository?
- **How can knowledge gained from the Mont Terri Underground Research Laboratory and other sites be transferred to future site conditions?**

ROCK MECHANICS AND ROCK ENGINEERING OF GEOLOGICAL REPOSITORIES IN OPALINUS CLAY AND SIMILAR CLAY-RICH ROCKS



Mine-by Experiment and Subsurface Excavations in Claystones

UNIVERSITY OF ALBERTA

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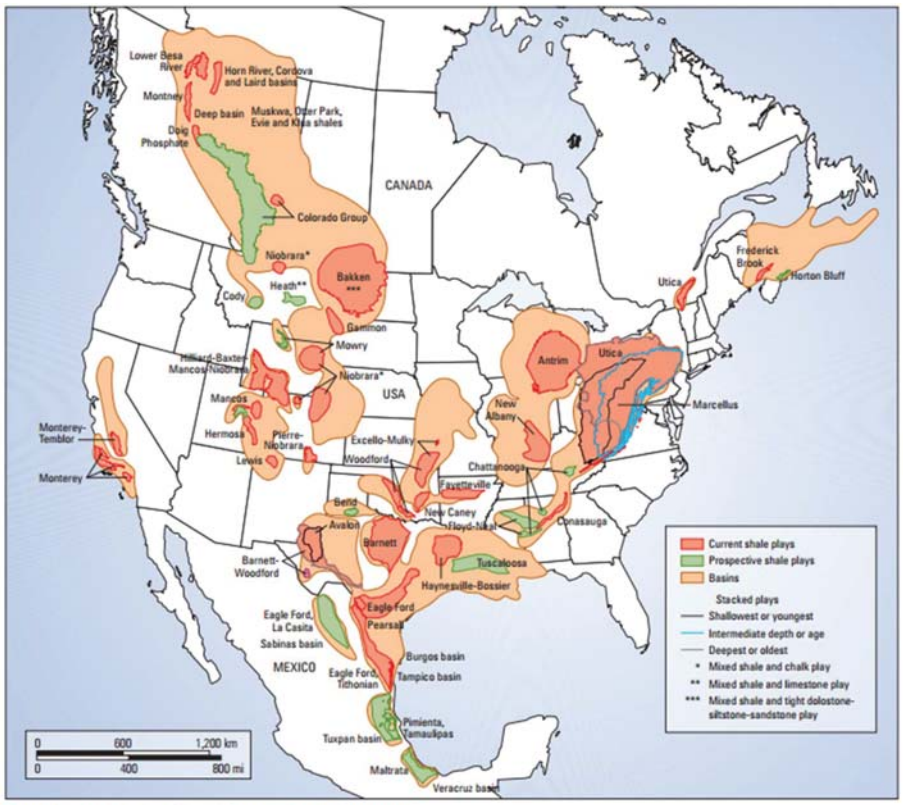
Geotechnical behaviour of clay shale

- Clay shales are widespread
- Clay shales are notorious for creating difficulties in geotechnical engineering
  - collection of undisturbed samples
  - determination of representative strength and stiffness properties
  - change in properties with water content
  - role of suction (Water retention characteristics)
  - effective versus total stress response
  - prediction of their behaviour.

Morgenstern (1979): *"….the exchange of relevant experience in dealing with this class of materials is one of the most effective ways of improving our practice."*

North American – Argillaceous (Clay) shales



^ North America shale plays. (Adapted from Kuuskraa et al, reference 6.)

Case Histories

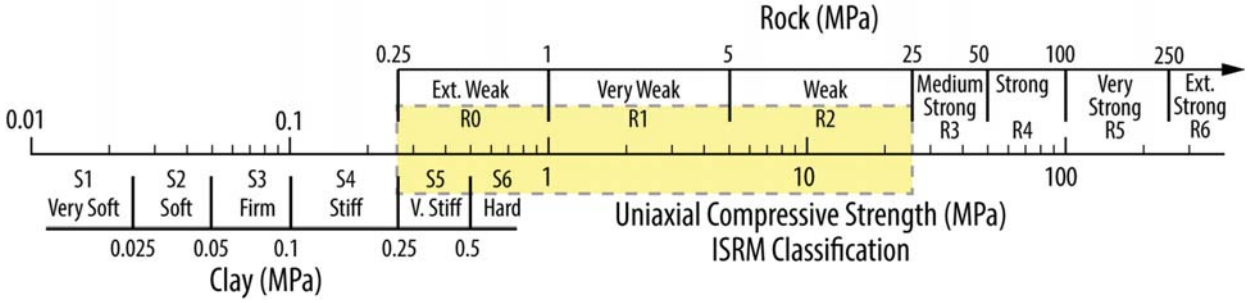
Site C – Shaftesbury Formation
Niagara – Queenstown Shales

MT – Opalinus Clay
Hades – Boom Clay
Bure – Callovian-Oxfordian

Weak Rock: Transitional material (Clay shale)

We regard clay shale:

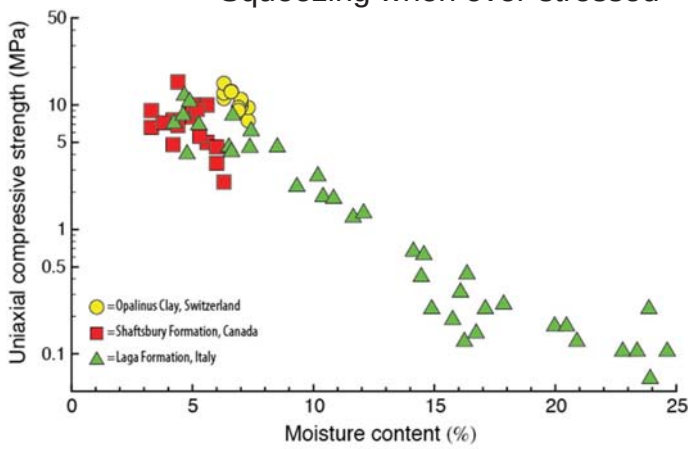
- as **transitional materials** between soil mechanics and rock mechanics.
- geological material having geologic structure, faults, joints, defects, **micro and macro structures**.
- a sedimentary formation that can be somewhat fissile and stratified and yet **behaviour very much like a hard/stiff clay** (soil mechanics) and is very heavily overconsolidated.

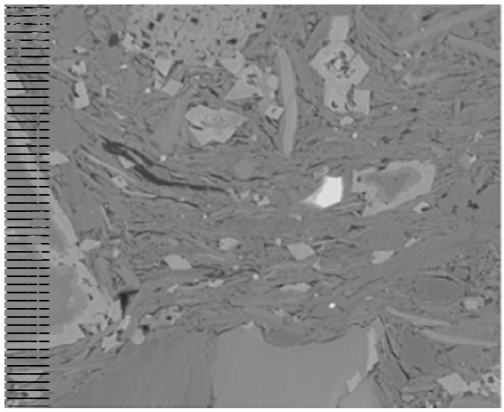


Characteristics of clay shales

Characteristics (very challenging for laboratory testing):

- Contains a significant amount of clay minerals
  - Contains weak minerals: smectites
- Porosity >4%
- Strength a function of moisture content
- No or little true cohesion (influence of water retention – suction)
- Time-dependent deformations:
  - Swelling upon unloading
  - Squeezing when over-stressed

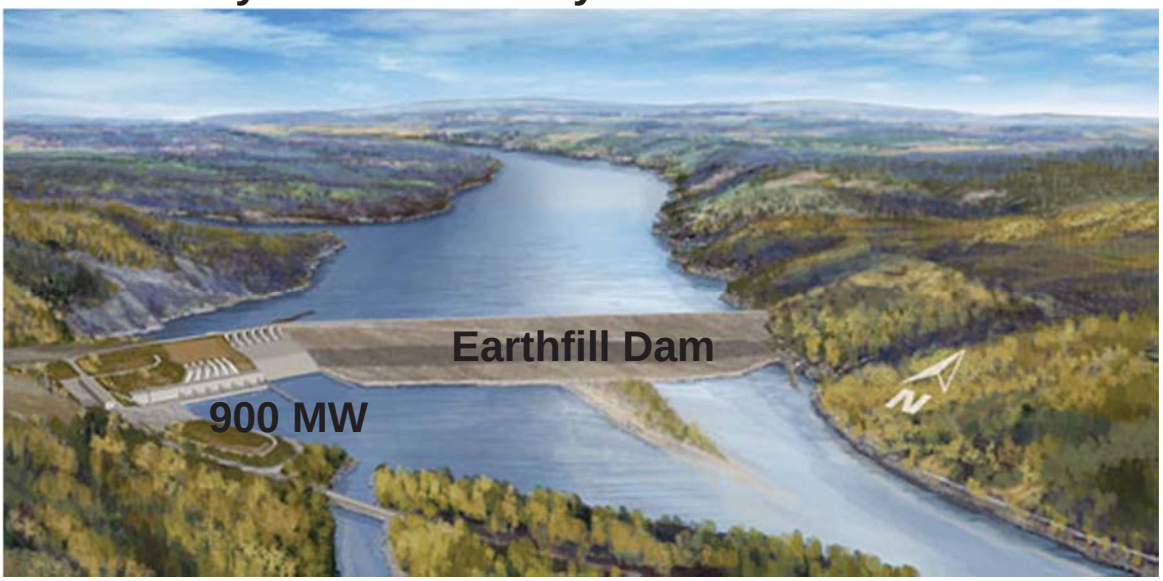




Site C Project: Site characterisation (1978-1981)

Because of the difficulties with laboratory characterisation, there is a greater reliance assessing performance based on in-situ tests, e.g, Mine-by tunnels

Shaftesbury Formation: Clay shale

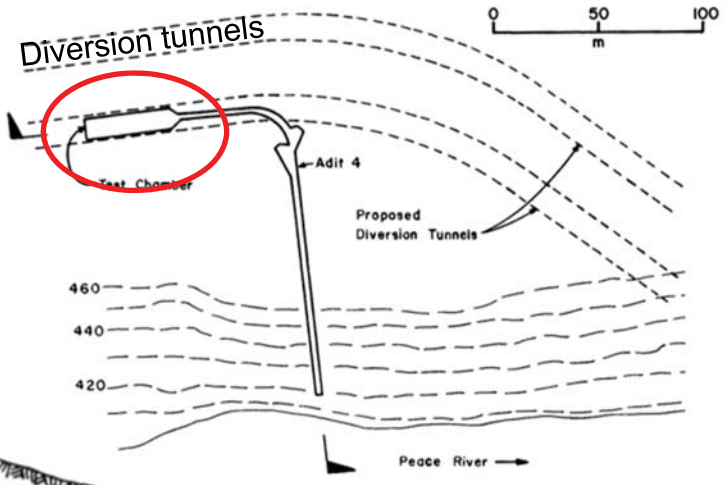


Site C

	Oldman River Dam	Dickson Dam	Site C Dam	Gardiner Dam
Formation	Porcupine Hills	Paskapoo	Shaftesbury	Bearpaw
Age	Paleocene	Tertiary to Upper Cretaceous	Lower Cretaceous	Upper Cretaceous
Deposition environment	Non-marine	Deltaic	Marine	Marine
Bedrock	Mudrock and sandstone	Sandstone, siltstone claystone and shale	Shale, silty shale, and siltstone	Shale, silty shale, and siltstone

Site C Test Chamber

Little, 1989

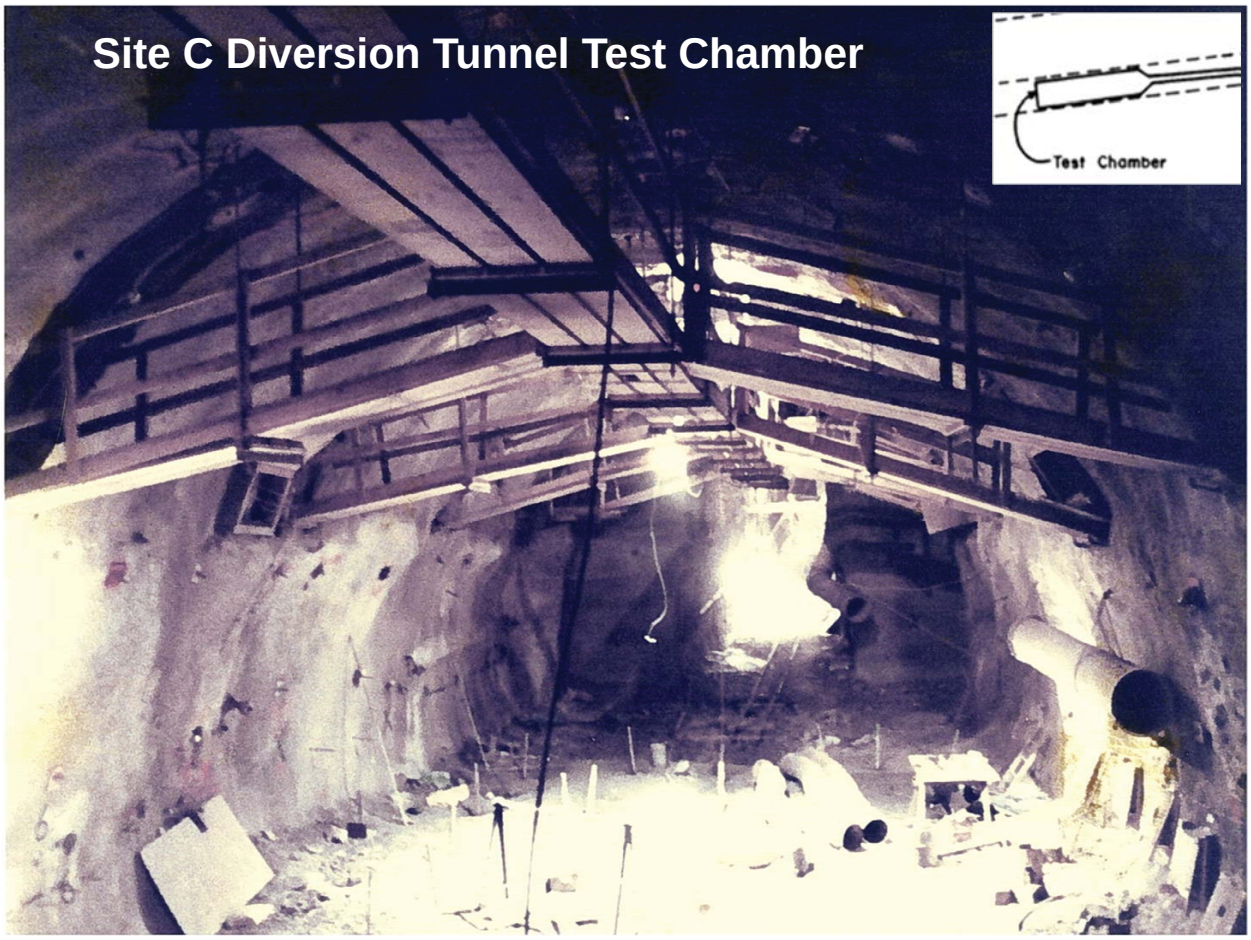


Test chamber- 11 m diameter

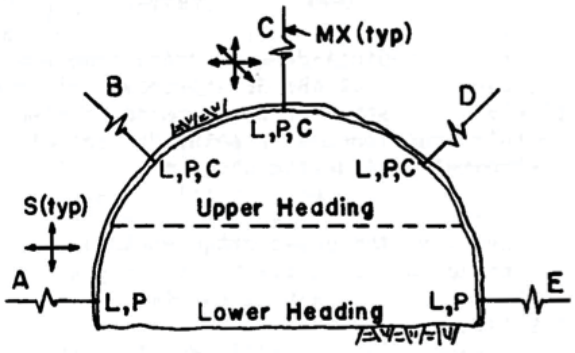
Could it be constructed?

Left Abutment

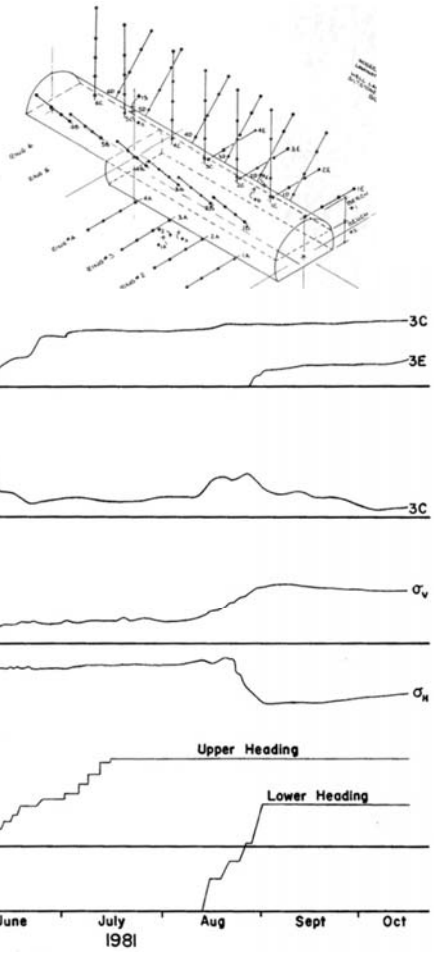
Site C Diversion Tunnel Test Chamber



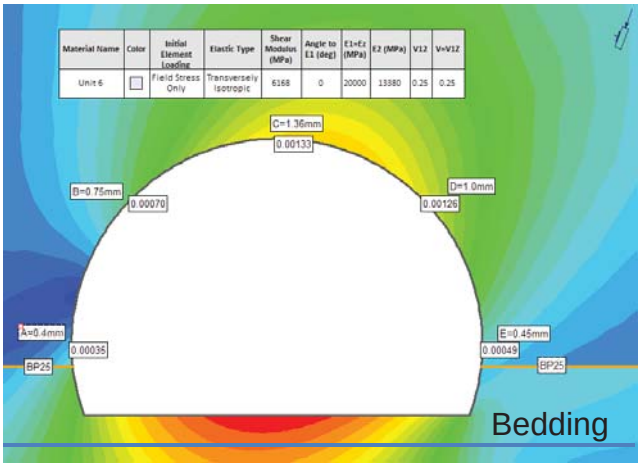
Test Chamber: Rock mass response

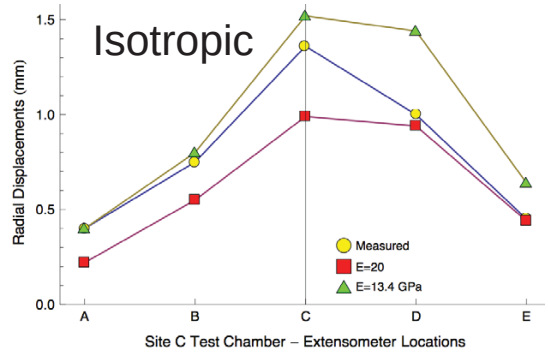


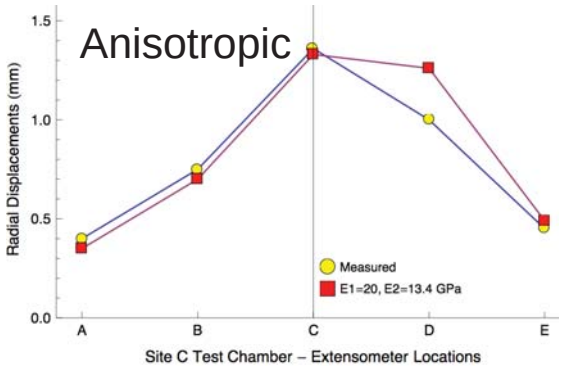
Unconfined compressive strength	- 6 MPa
Static modulus perpendicular to bedding	- 3 to 4 GPa
Static modulus parallel to bedding	- 6 to 8 GPa
Static Poisson's ratio	- 0.24
Effective peak shear strength across bedding	- 52° (c=0)
Effective peak shear strength along bedding	- 46° (c=0)



Anisotropic response



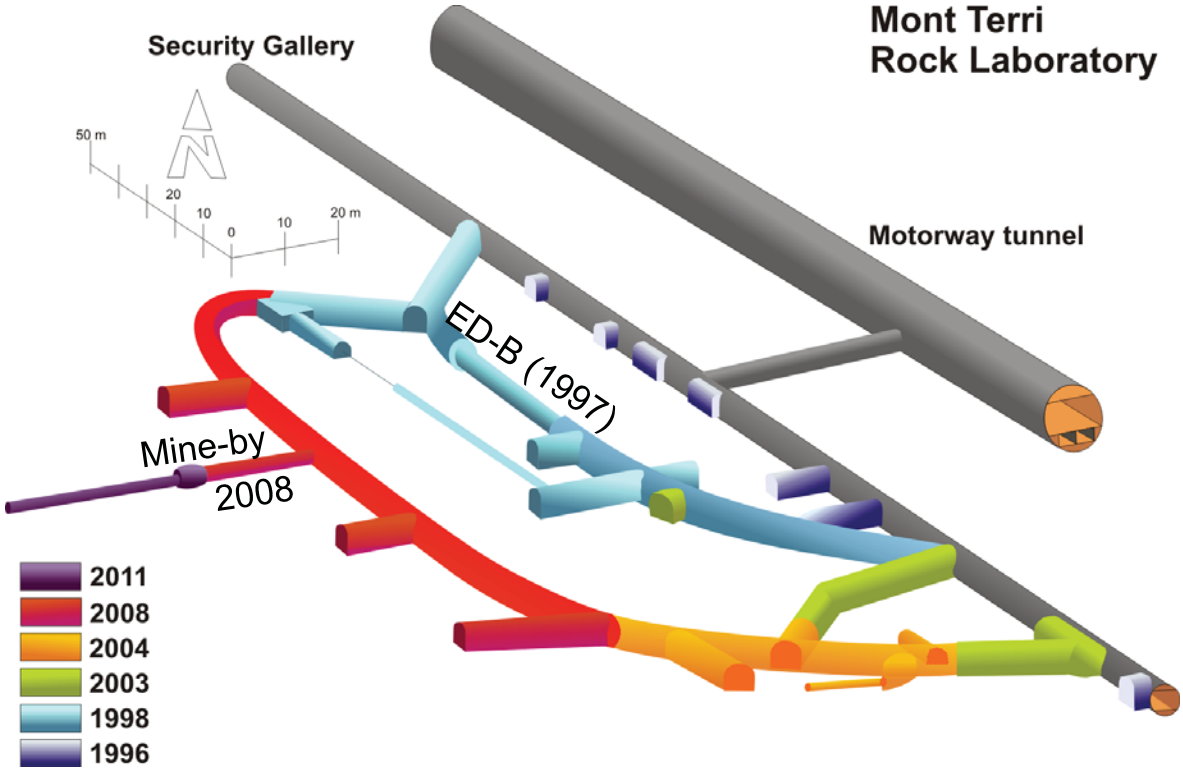




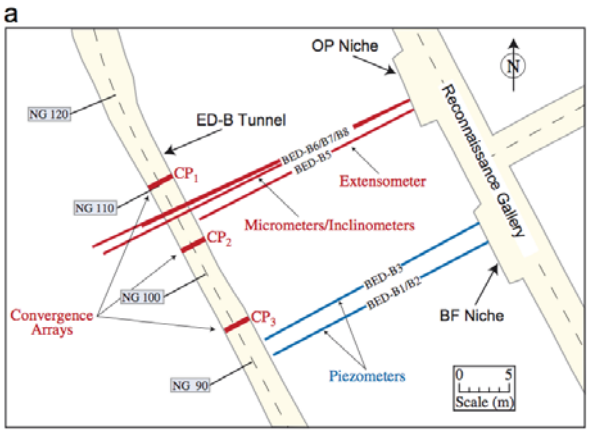
Findings:

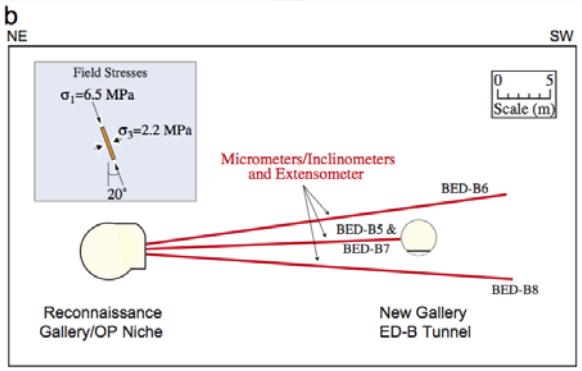
1) Anisotropic elastic response
2) Weak bedding planes can influence behaviour
3) Rock must be sealed immediately to prevent moisture uptake/swelling

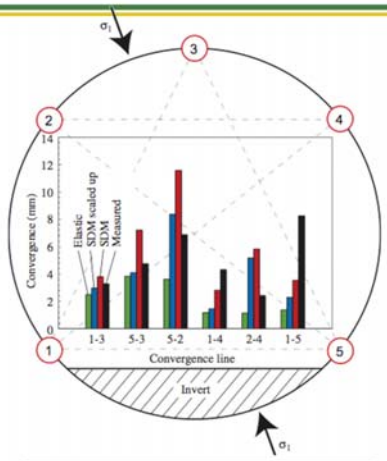
Mont Terri

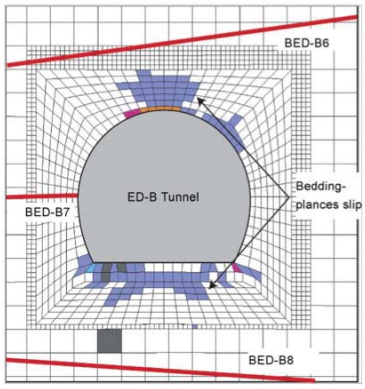


ED-B (3.6 m diameter) **Results**



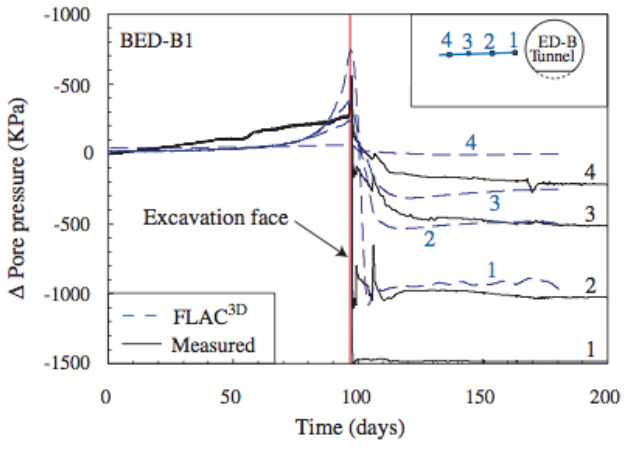


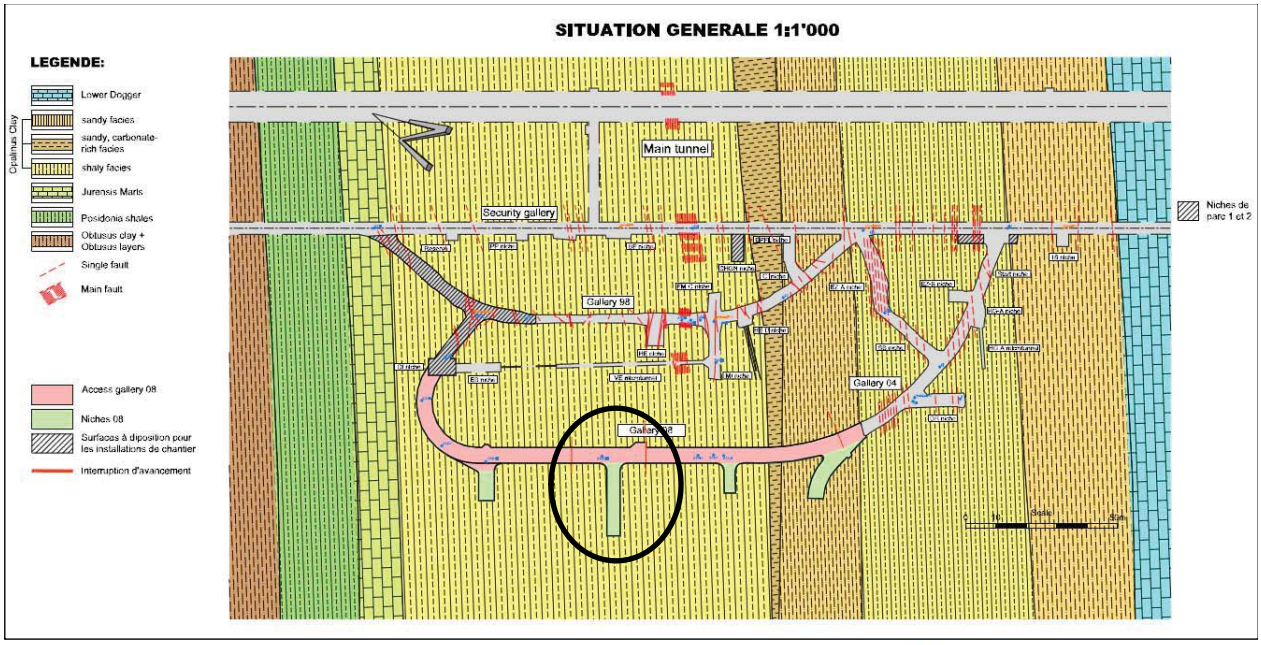


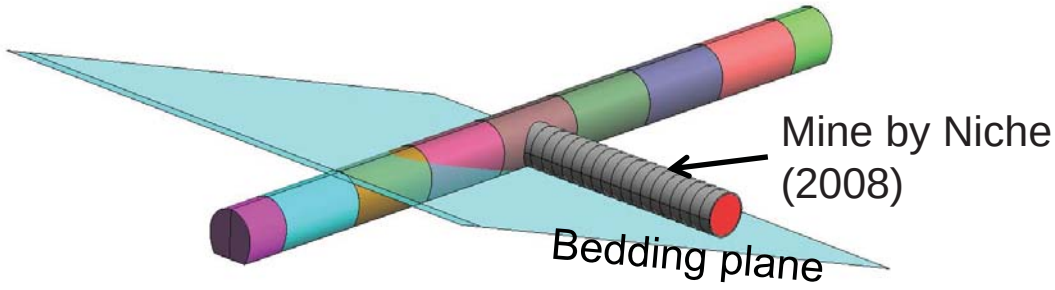


ED-B Findings

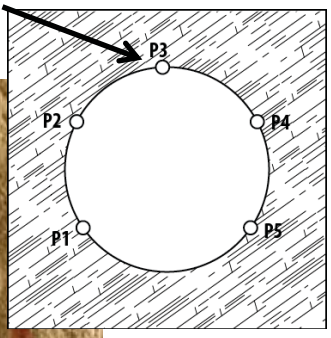
- Challenges of doing in-situ tests in Clay shales
- EDZ was relatively small, but convergences were relatively large (Dε=0.1 to 0.2%)
- Slip along the bedding was minor but nonetheless present
- Time-dependent deformations were evident but relatively minor
- Pore pressures responded to the tunnel advance by first gradual loading and then rapid unloading





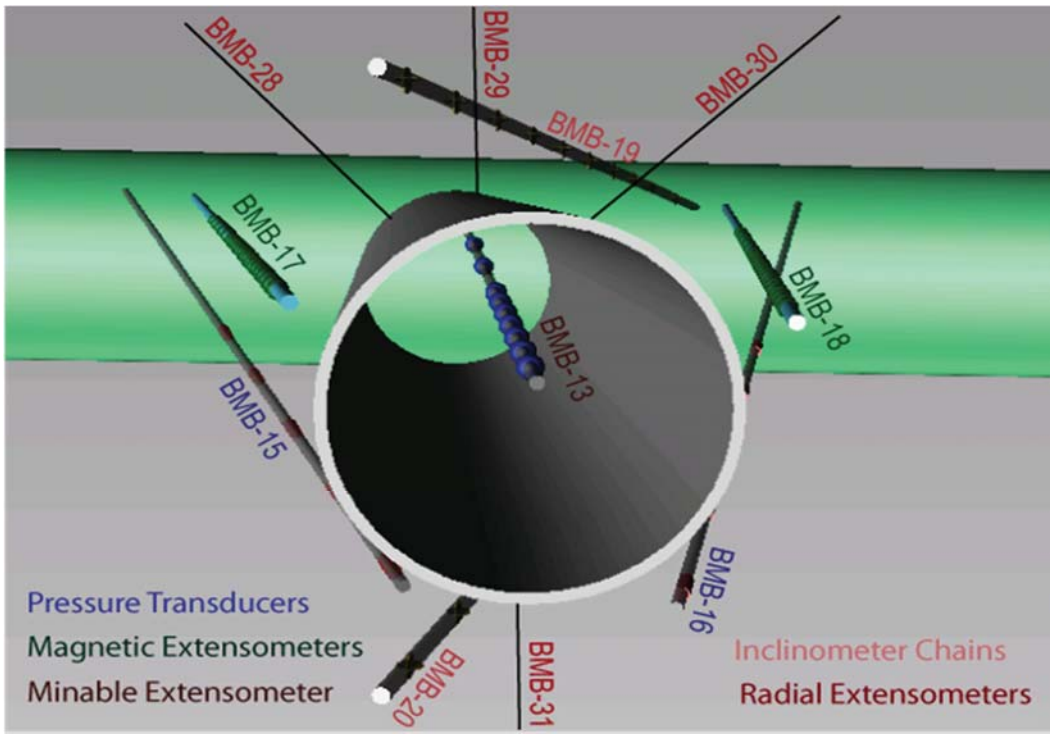


Mine-by Niche: Excavated parallel to strike of Bedding

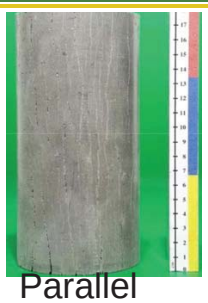


Mine-by Niche Instrumentation

Major enhancement to instrumentation compared to ED-B Tunnel

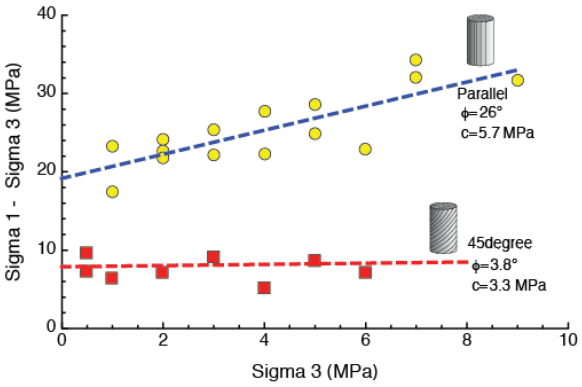


Opalinus Clay: Laboratory response to loading



Parallel

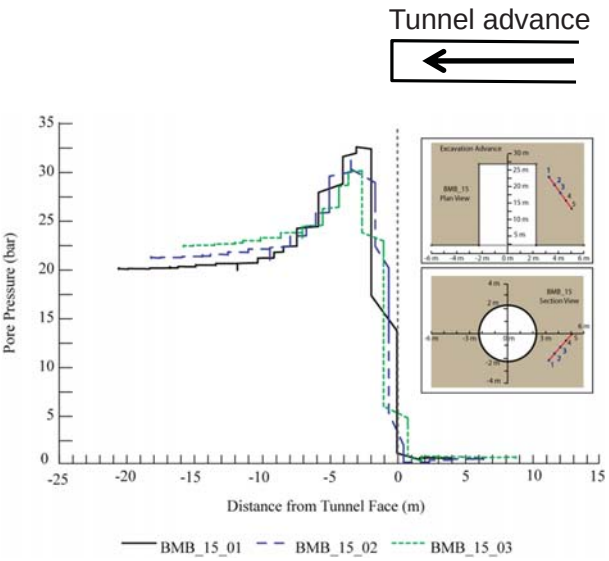
45degree



"Total stress -No pore pressures"

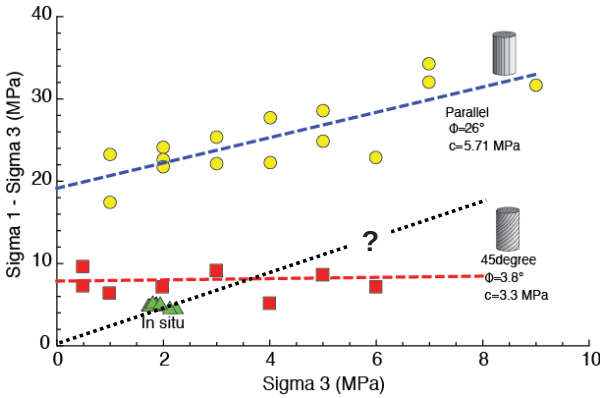
K.-H. Lux, U. Düsterloh, O. Czaikowski
Clausthal University of Technology
(Rock-like testing – No pore pressures)

Pore-pressure response & Yielding



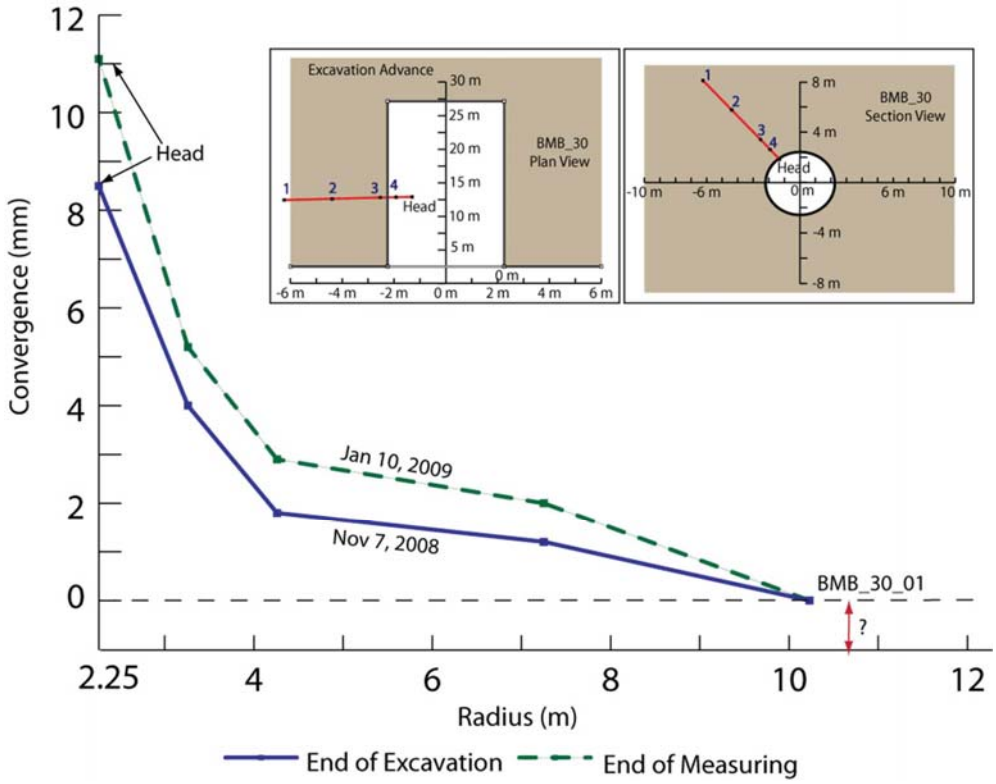
Pore pressure response to excavation

K.-H. Lux, U. Düsterloh, O. Czaikowski
Clausthal University of Technology
(Rock-like testing – No pore pressures)



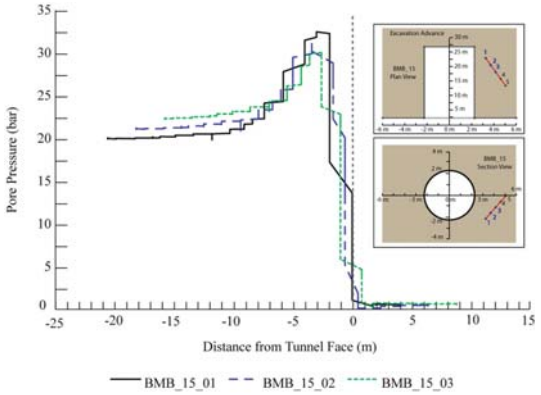
Lab strength and in situ strength

Time dependent deformations



Mine-By Niche Findings

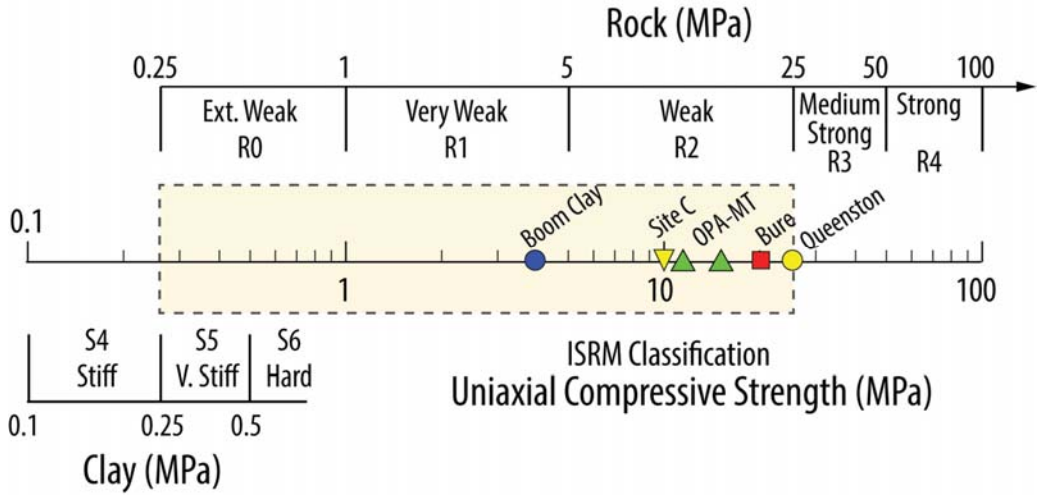
- Tunnel orientation relative to bedding is important at Mont Terri
- EDZ much larger compared to ED-B tunnel
- Convergence very large (Dε=1 to 1.5%), order of magnitude greater compared to ED-B tunnel
- Support system adequate for ED-B, no longer adequate
- Time-dependent deformations were much more evident
- Pore pressures responded to the tunnel advance by first gradual loading and then rapid unloading ahead of the tunnel face



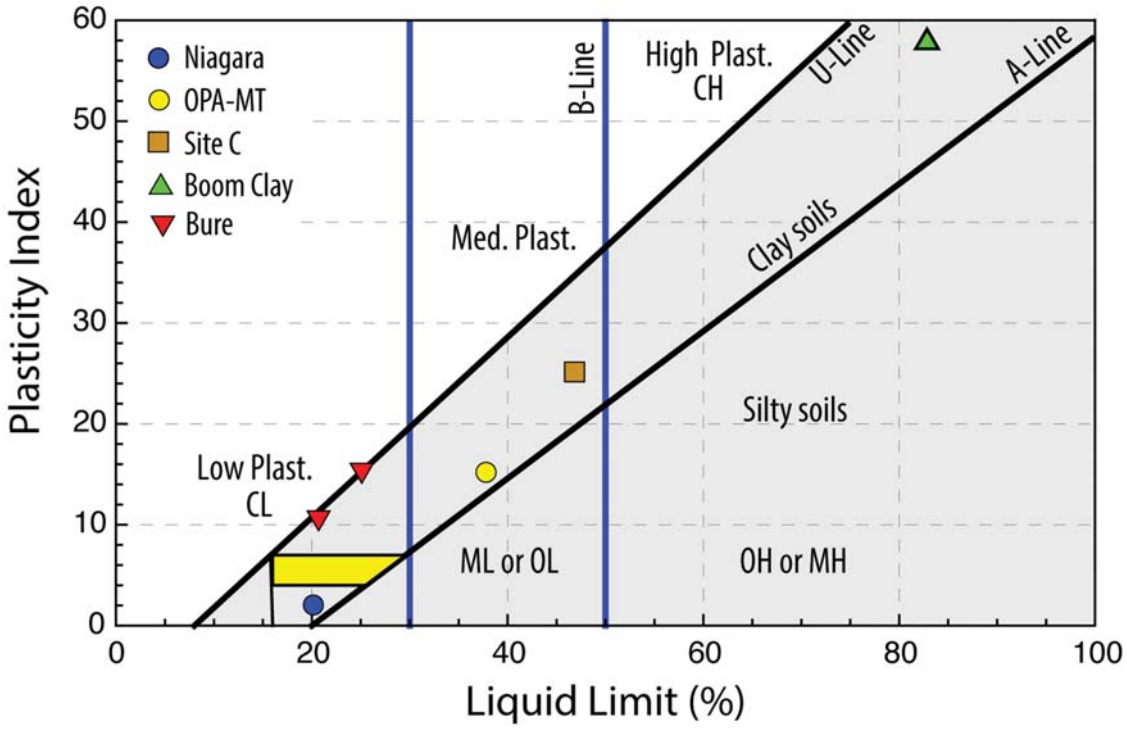
What did we learn from these in-situ experiments?

Morgenstern (1979): *"….the exchange of relevant experience in dealing with this class of materials is one of the most effective ways of improving our practice."*

Comparison: Uniaxial strength

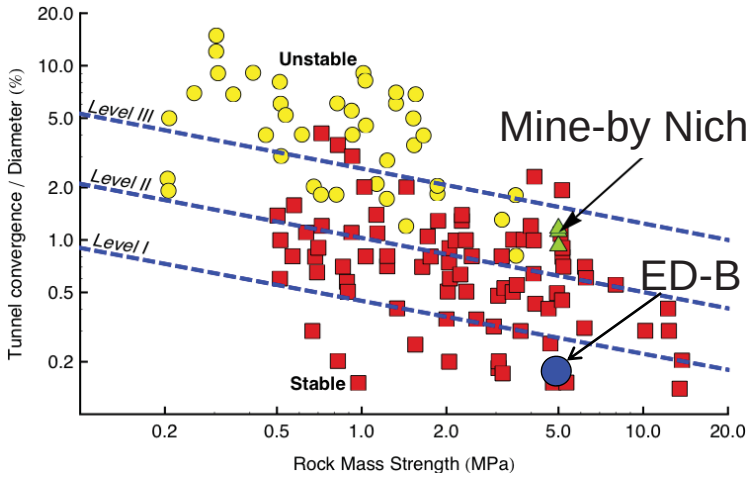


Comparison: Plastic behaviour



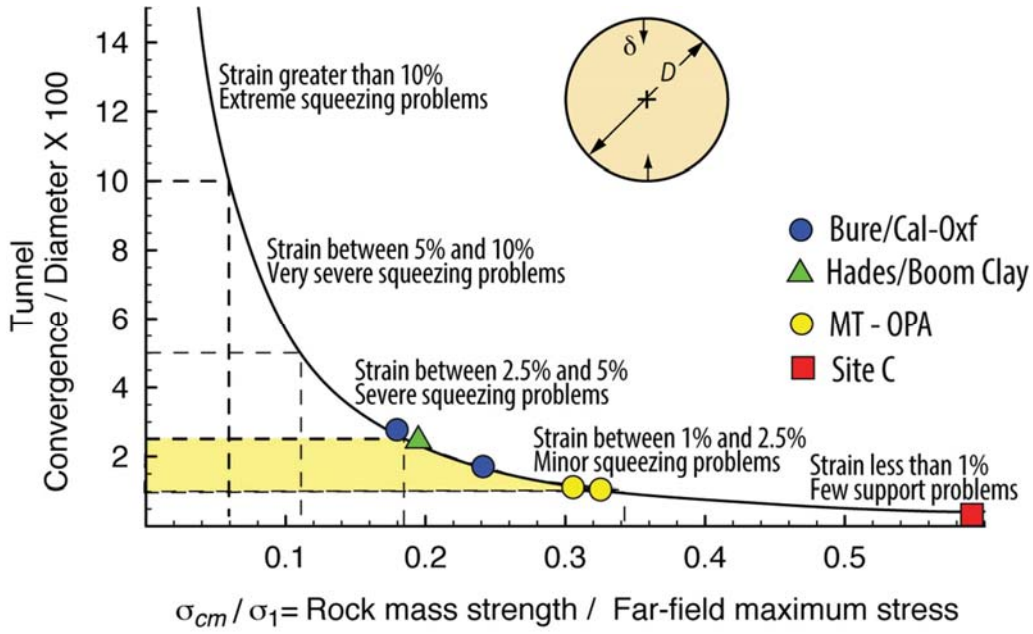
Tunnel Performance in Weak Rocks

Empirical correlation between tunnel performance and rock mass strength by Chern et al, (1998).



Below Level I	• Construction can continue • No special action required
Level I-II	• Construction can continue • Increase frequency of monitoring and field observations
Level II-III	• Tunnel is susceptible to instability, suspend construction temporarily • Conduct detailed inspection of tunnel lining and increase monitor frequency • Conduct thorough investigations of potential causes of the problem including support quality, timing of support installation and excavation procedure • Install additional support and/or revise tunnelling procedure, if required
Above Level III	• Construction work should be stopped • Increase frequency of monitoring and field observations • Conduct thorough investigations of potential causes of the problem and implement remedial measures • Revise the support design and/or construction procedures • Construction can be resumed only after remedial measures have been implemented and the trend of instability has been reversed

Underground experience



Summary:

- Mudrocks (Clay shales) are located in many countries
- Extensive experience with the performance of engineered structures in and on clay shales
- Their geotechnical behaviour has been studied extensively both in the laboratory and in-situ
- Greater reliance on in-situ testing to quantify their geotechnical characteristics
- Prediction of their in-situ behaviour remains challenging

Zusammenfassung

- Tonsteine (Tonschiefer) findet man in vielen Laendern
- Es existieren intensive Erfahrungen in Zusammenhang mit Bauprojekten in Tonsteinen
- Ihr geotechnisches Verhalten wurde bereits intensiv auf der Laborskala und der in-situ Skala untersucht
- Groesseres Vertrauen in in-situ Tests bezueglich der Quantifizierung ihres geotechnischen Verhaltens
- Vorhersage ihres Verhaltens in-situ bleibt herausfordernd

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