Mud Rush Day of Learning

Understanding Mud Rushes from an Engineering Geological and Hydrogeological Context

Matthys A. Dippenaar

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Priority Hazard

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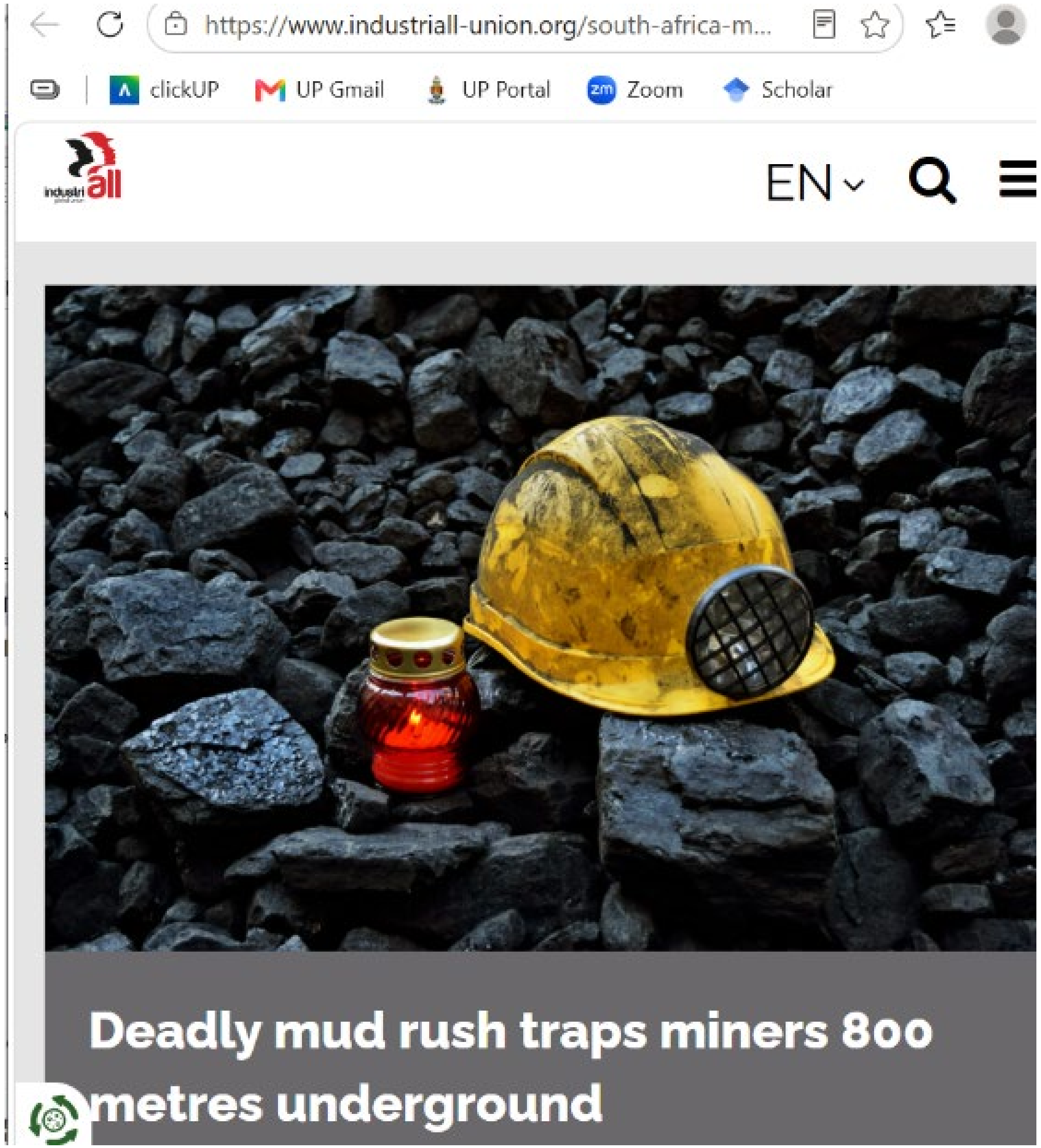
- Priority hazard criticality factors that emerge from the high resolution analyses wear and deterioration to walls' supports and liners due to impact-induced damage from
  - Abrasive ore
  - Structural failure, e.g.
    - Wedge/block failure
    - Cohesive and interlocking/frictional hang-ups
  - Stress-induced failure, including:
    - Spalling
    - Squeezing
    - Burst
    - Mud rush and Mudflow

- Potential risks associated with the design, implementation, operation, and maintenance of long ore passes include:
  - Mud rush events
  - Hang-ups
  - Excessive wear
  - Damage from impact
  - Loads
  - Stress-induced failures
  - Structural instability

Salmi et al. 2025

Mud Rush Example

- Ekapa Mine
- 17 February 2026
- 5 miners
- ~890 m underground



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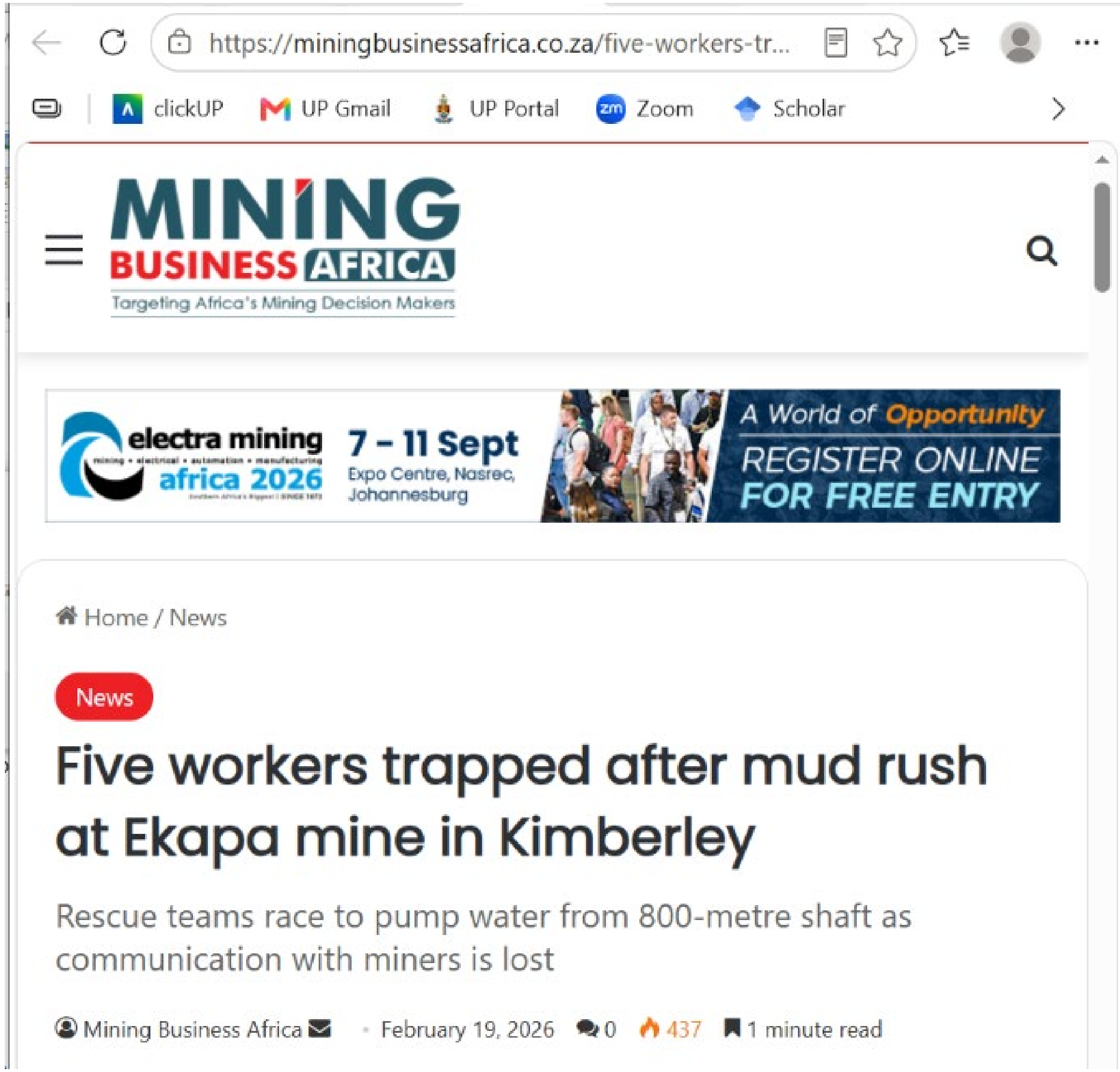

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Mudrush (sic.)

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- Uncontrolled ingress of assorted mixture of water and solids:
  - Mudrush
  - Mudflow
  - Mudpush
- Mudrush:
  - Underground equivalent of surface debris flow
- Subsurface

- Questions to be answered (verbatim):
  - Is there potential to generate fines?
  - Is there potential to accumulate water?
  - Is there potential to form mud?
  - What disturbance can mobilise and discharge the wet muck?

Jakubec 2018 (SRK Consulting)

Mud Rush

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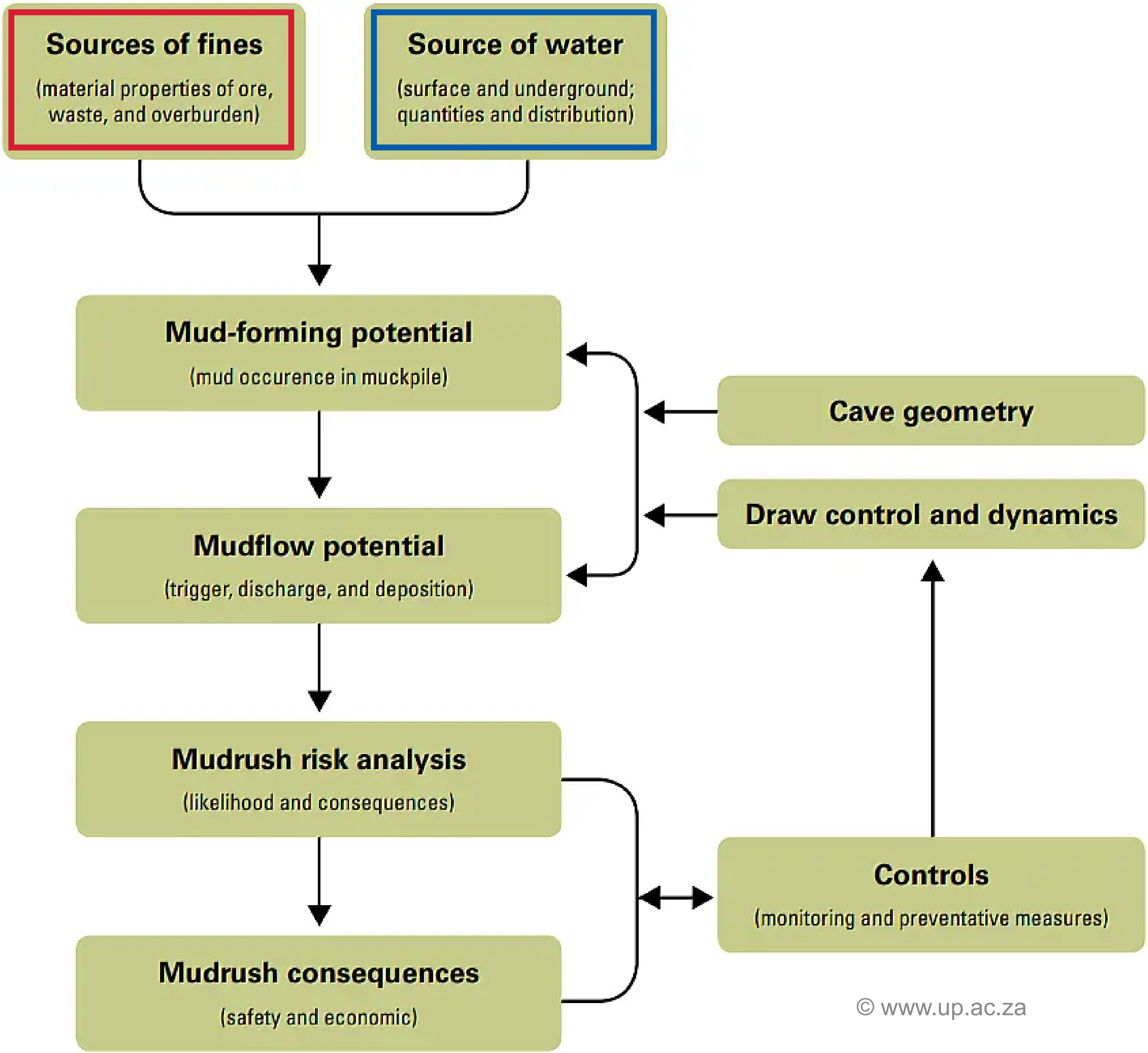
- “Catastrophic failure of a barricade results in the inrush of material into the mine workings, which is commonly referred to by miners as a “mud rush (i.e. liquefaction)”.

Rankine et al. 2007

Mud Rush



- Fines: engineering geology
- Water: hydrogeology

Jakubec 2018 (SRK Consulting)

Mud Rush

- Engulfment or inrush
- Engulfment hazard

- Pertains to being:
  - Overrun
  - Enveloped

- By a flow of materials including:
  - Rocks
  - Fines
  - Water

CNI et al. 1998 (in Verrall et a. 2024)

Mud Rush

- Wet muck spill

- Occur:
  - >20% sand-sized materials (<2mm)
  - >8.5% water content OR >80% saturation

- Elements required or present:
  - Potential mud-forming materials
  - Water
  - Disturbance of mud due to drawing or other mining activity
  - Discharge point for water and mud to pass through into the mine workings

Butcher et al. 2000 (in Verrall et a. 2024)

Mud Rush

- Conditions for wet muck/mud-forming material:
  - Fine grained
  - <5 cm grains size (fine-grained)
  - >5 cm, grain size
  - Saturated or near saturated (~80%)

Nicholas et al. 2011 (in Verrall et a. 2024)

Mud Rushes

- Excessive water content may lead to:
  - Ore compaction
  - Development of low-permeability zones
  - These potentially initiate mud rushes

- These conditions can cause hydrostatic pressures to accumulate…
- … notably when fines go into slurry-states

Achilleoudes and Krige 2005; Butcher et al. 2005 (in Salmi et al. 2025)

Water and Mud/Rock Inrush Hazard

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Table 1 Updated classification according to the material types

Class	Sediment volume concentration	Sediment contents	Subclass	Sediment contents
Water flow	< 10%	Random	Limpid water flow	None
			Turbid water flow	Random
Diluent mud flow	10 to 40%	> 80% clay, silt, sand, or gravel (< 60 mm); < 20% rock fragment or block (> 60 mm)	Diluent clayey-mud flow	> 80% clay or silt (< 0.075 mm)
			Diluent detrital-mud flow	> 80% sand or gravel (0.075 to 60 mm)
Viscous mud flow	40 to 60% (sometimes 80%)	> 80% clay, silt, sand, or gravel; < 20% rock fragment or block	Viscous clayey-mud flow	> 80% clay or silt
			Viscous detrital-mud flow	> 80% sand or gravel
Water-rock flow	10 to 40%	< 80% clay, silt, sand, or gravel; > 20% rock fragment or block	–	–
Mud-rock flow	40 to 60% (sometimes 80%)	< 80% clay, silt, sand, or gravel; > 20% rock fragment or block	–	

Xue et al. 2021

Mud Rush Day of Learning

Engineering Geology and Hydrogeology

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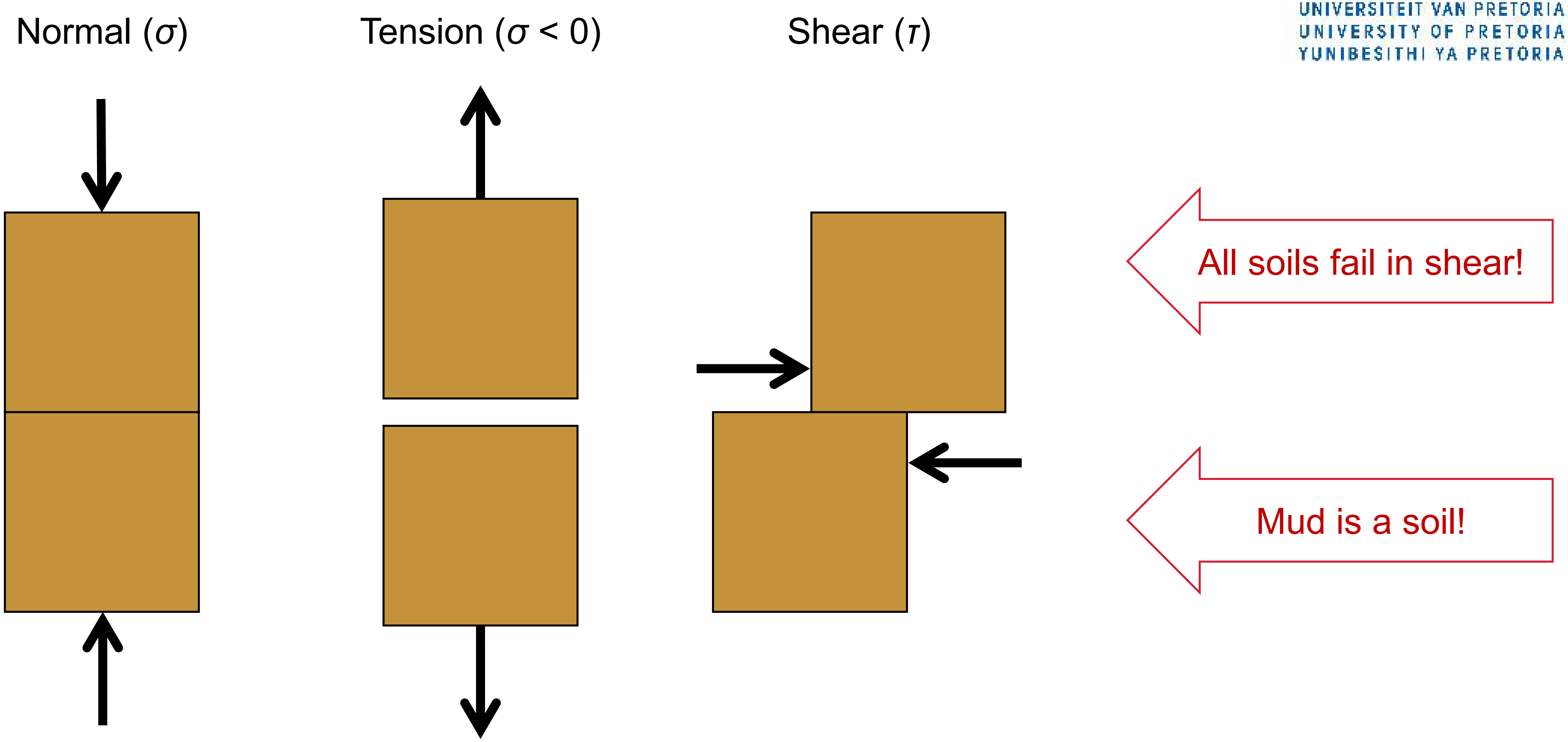
Geomaterials and Properties of Soils



Phase Relationships

- Water content by mass (w)
- Moisture content by volume ($\boldsymbol{\theta}$)

$$w = \frac{M_W}{M_S} \text{ and } \theta = \frac{V_W}{V_T}$$

- Specific gravity (G_S)

$$G_S = \frac{M_S}{V_S \cdot \rho_W} = \frac{\rho_S}{\rho_W}$$

- Water saturation (S_W)

$$S_W = \frac{V_W}{V_V} = \frac{m \cdot G_S}{e}$$

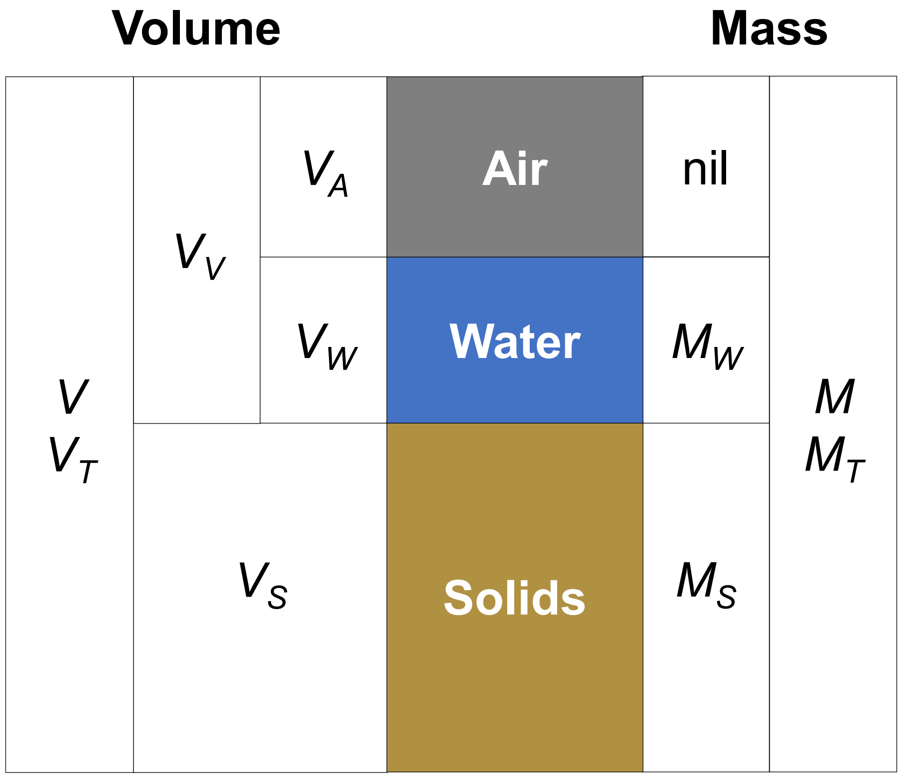
- Void ratio (e)

$$e = \frac{V_V}{V_S}$$

- Porosity ($\boldsymbol{\eta}$)

$$\eta = \frac{V_V}{V_T} = 1 - \left[\frac{\rho_{T(saturated)}}{\rho_S}\right]$$

$$\eta = \frac{e}{1+e} \quad and \quad e = \frac{\eta}{1-\eta}$$



Unsaturated (Suction) Systems

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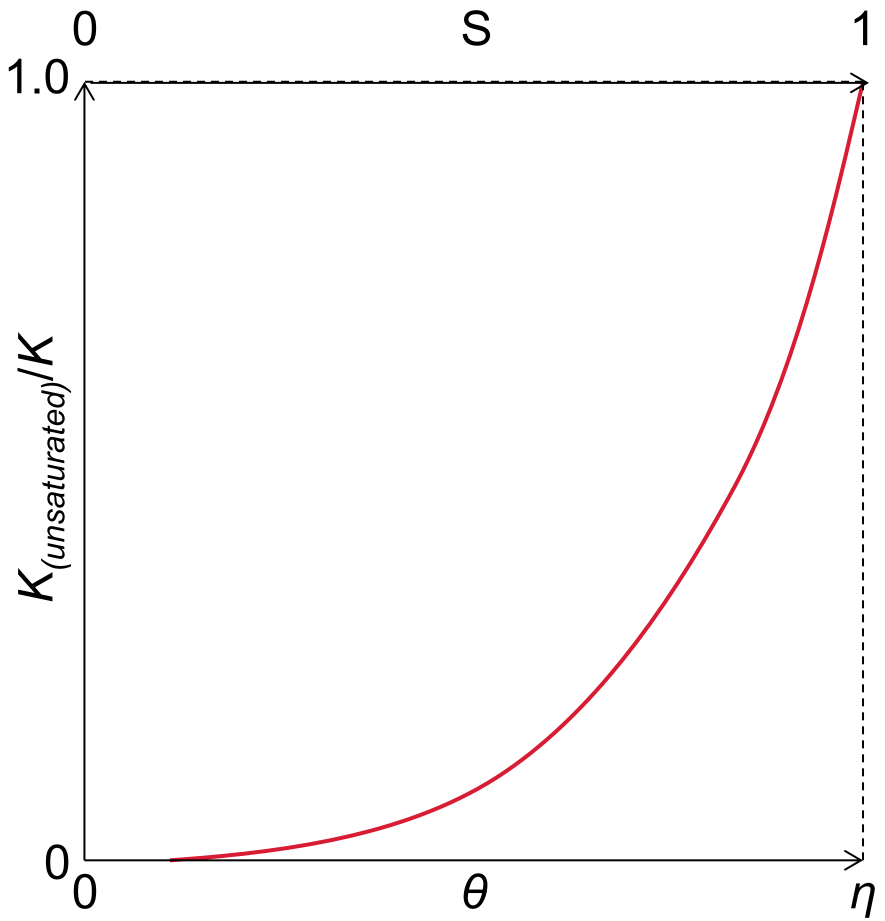
- Moist unconsolidated materials are not saturated with water
- The relative hydraulic conductive K_{unsat} is the ratio of:
  - Unsaturated hydraulic conductivity K_{unsat}
  - Saturated hydraulic conductivity
- At 100% water saturation:
  - Hydraulic conductivity is at a maximum
  - The moisture content equals the porosity
- K = hydraulic conductivity (m/s)
- θ = moisture content (-/-)
- η = effective porosity (-/-)

$$S = 1 \ \text{if} \ \theta = \eta$$



Unsaturated (Suction) Systems

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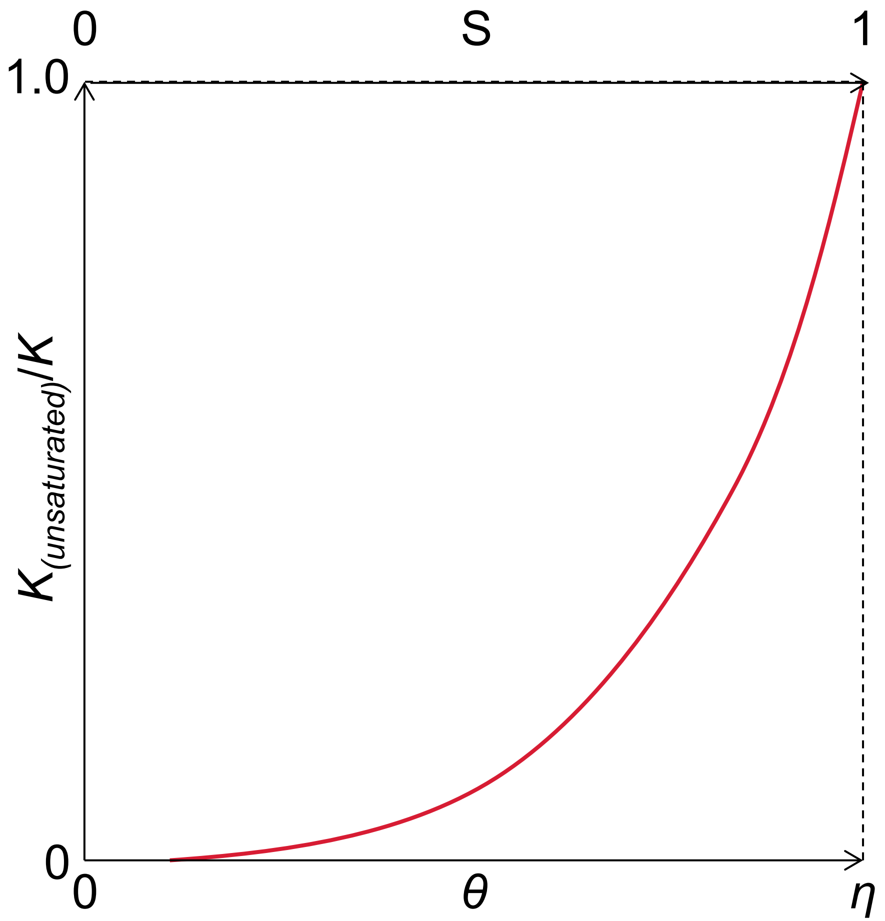
- We determine K_{sat} to be conservative and to be able to infer K_{unsat} based on grading and saturation
- Wetting of a dry soil (e.g. field tests) is not rapid flow

- The relative hydraulic conductive K_{unsat} is the ratio of:
  - Unsaturated hydraulic conductivity K_{unsat}
  - Saturated hydraulic conductivity K_{sat}

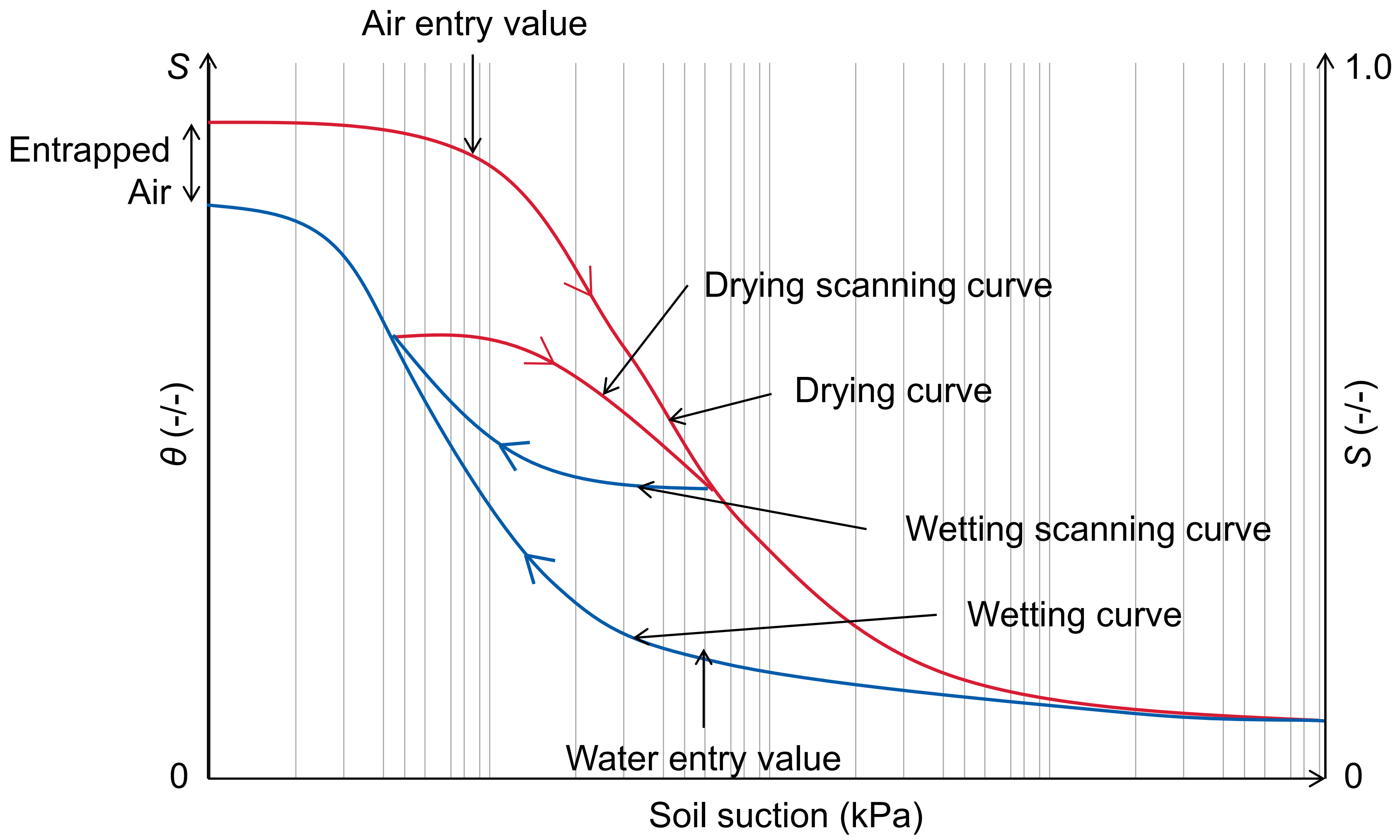
$$K_{rel} = \frac{K_{unsat(S<1)}}{K_{sat(S=1)}}$$

- Permeability is used by engineers and relate to K, density ρ, dynamic viscosity of water μ, and gravitational acceleration g

$$K = \frac{k\rho g}{\mu} \text{ and } K(m/s) \cong (9.77 \cdot 10^6)k(m^2)$$



Soil-Water Characteristic (Retention) Curves

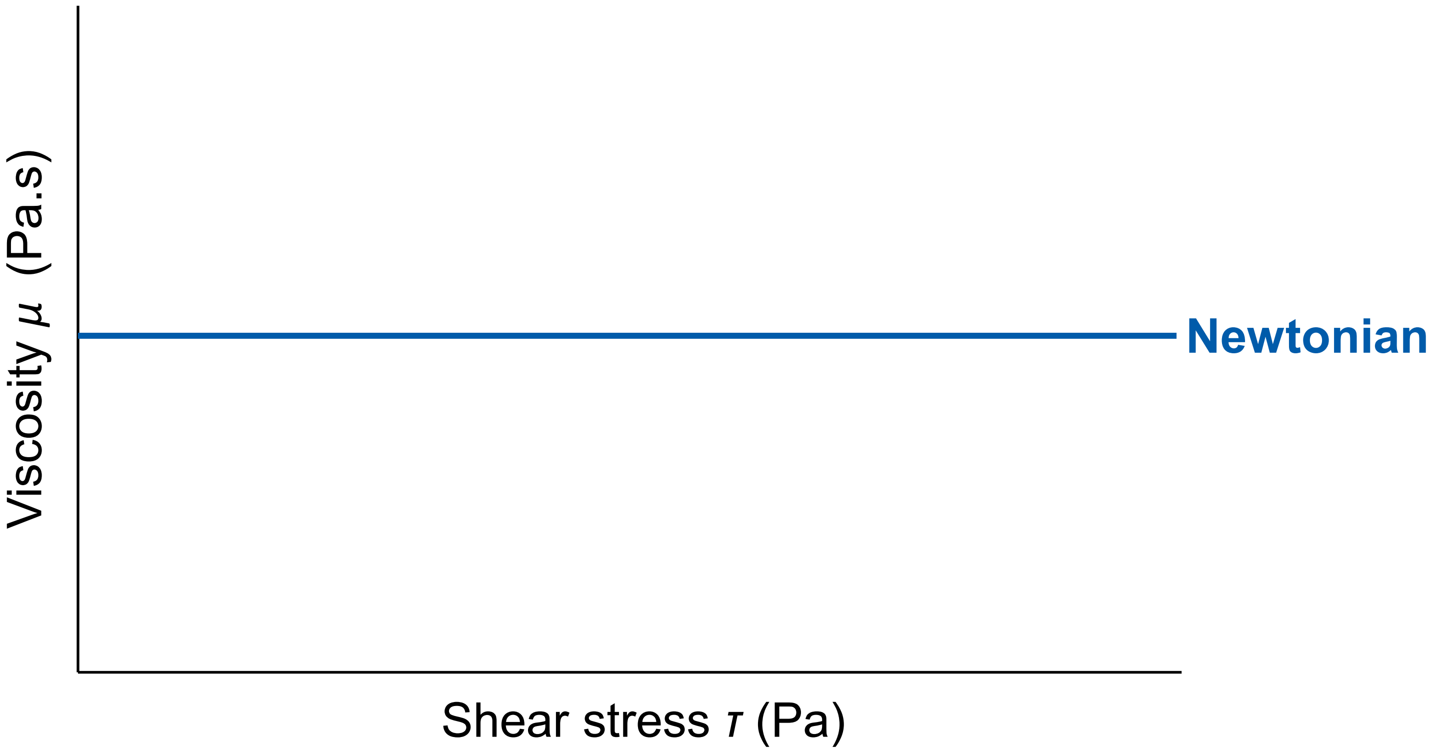


- θ = moisture content (-/-)
- S = water saturation (-/-)

Viscosity and Non-Newtonian Fluids

- Shear stress: τ
- Viscosity: μ

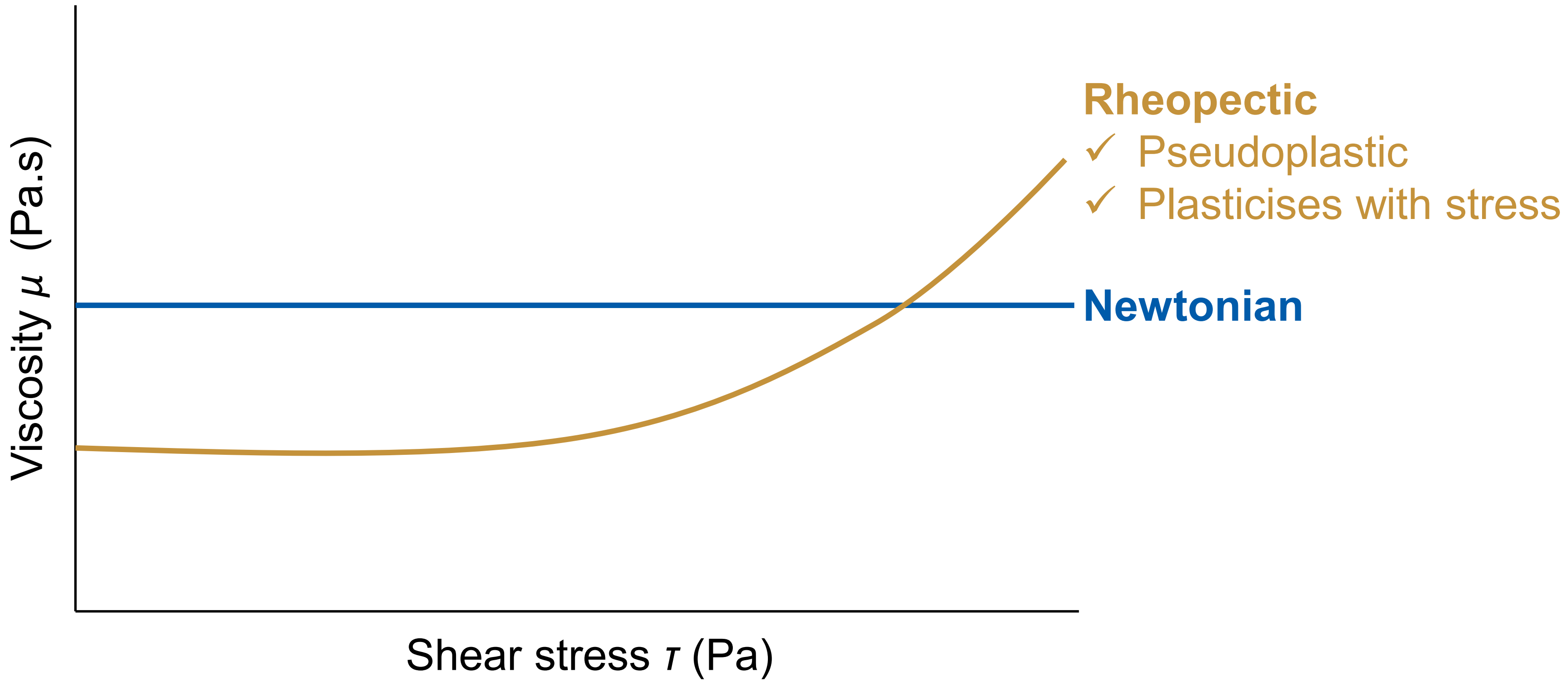
- Water flow normal with the same viscosity regardless of shear stress



Viscosity and Non-Newtonian Fluids

- Shear stress: τ
- Viscosity: μ

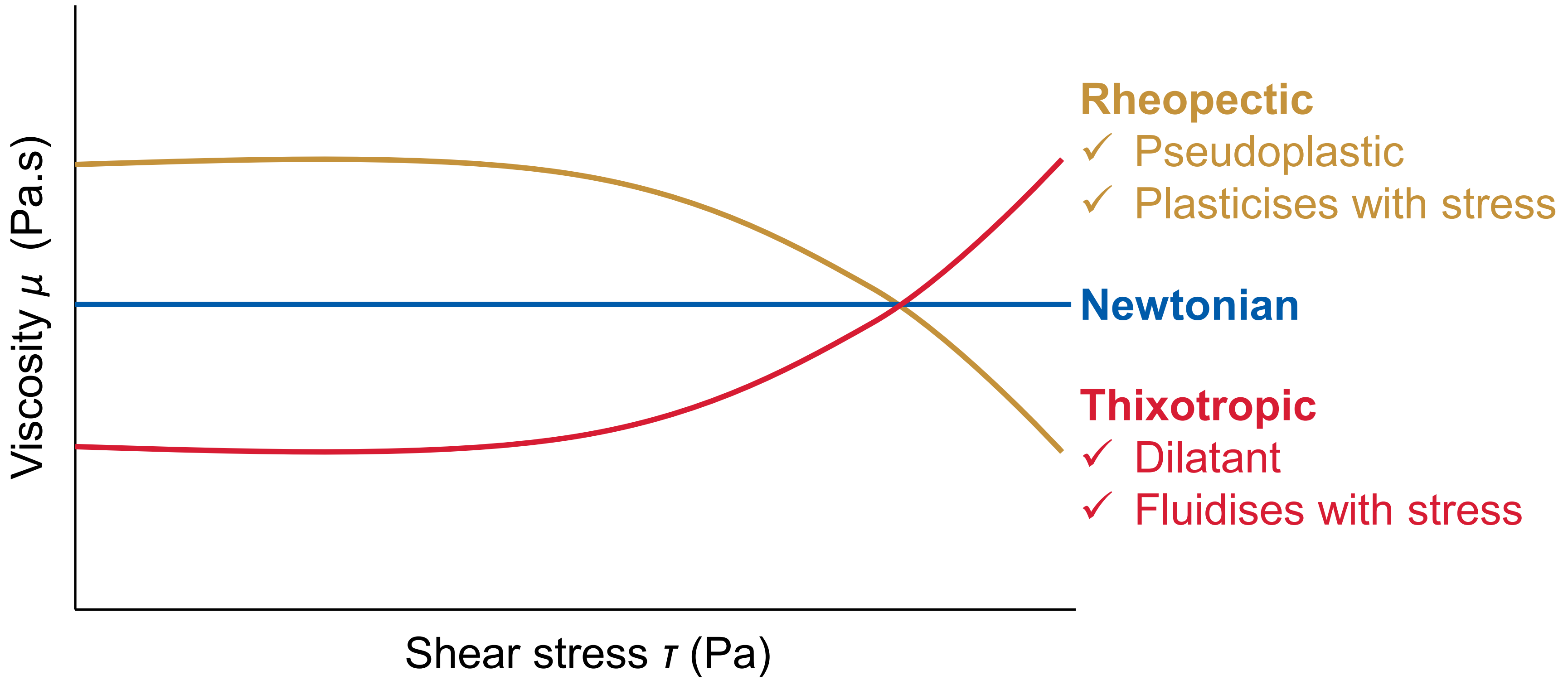
- Some fluids become more viscous under shear force



Viscosity and Non-Newtonian Fluids

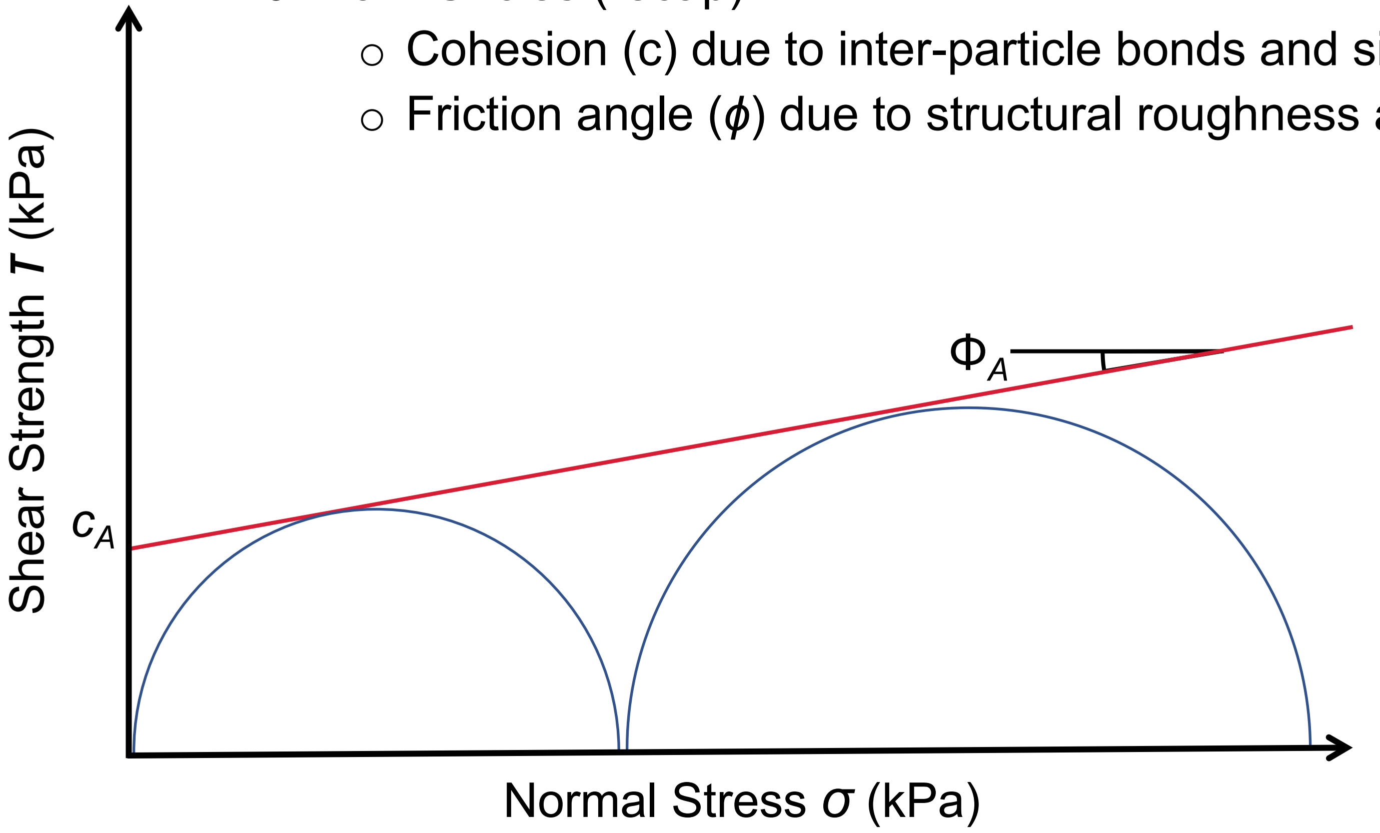
- Shear stress: τ
- Dynamic Viscosity: μ

- Other fluids lose viscosity and fail under shear:
  - Cement is kept fluid in trucks through movement
  - Mud can liquidise with increasing moisture
  - Liquefaction



Strength of Geomaterials: Cohesion and Friction

- Mohr Circles (recap)
  - Cohesion (c) due to inter-particle bonds and significant in clays but zero in sands
  - Friction angle (ϕ) due to structural roughness and higher in sand than clay



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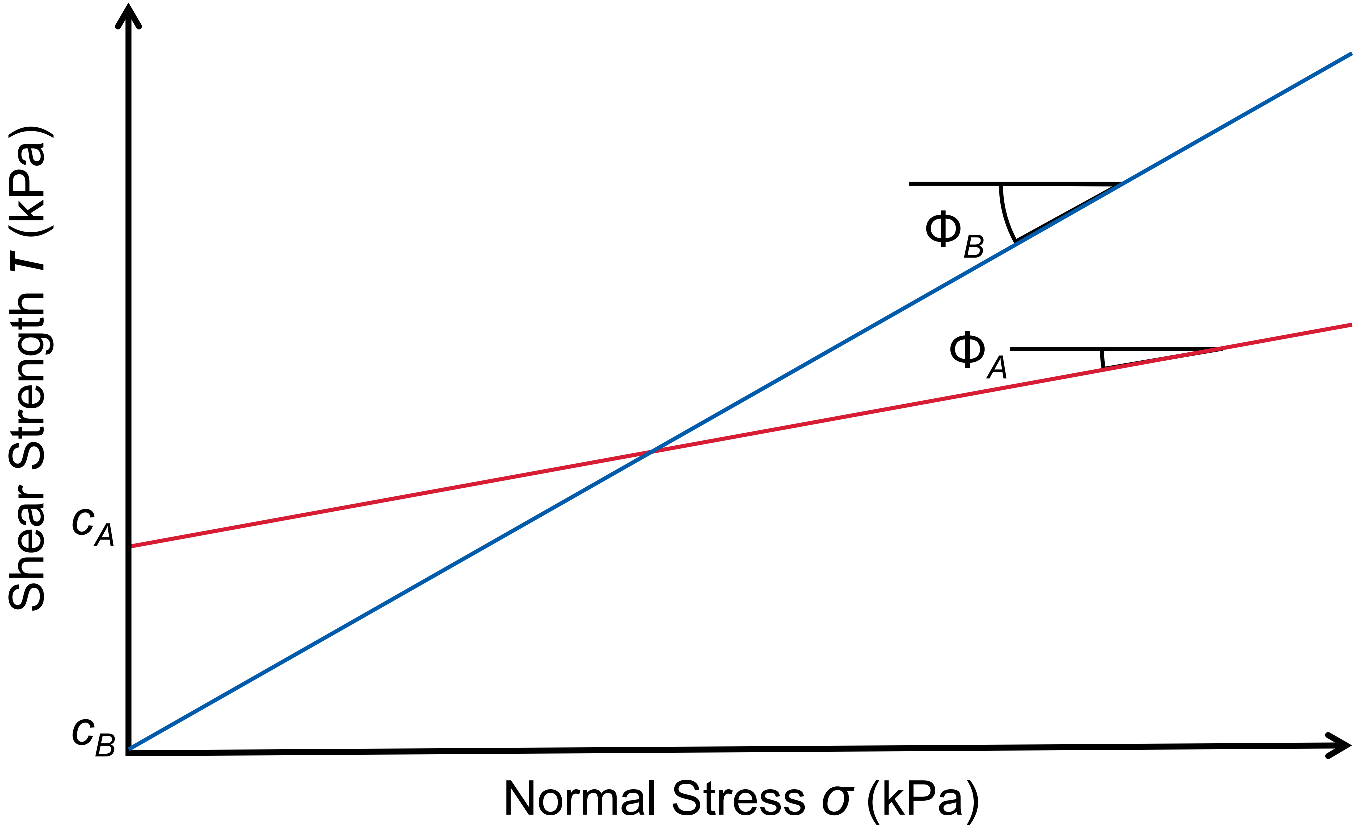


- Cohesion (c) due to inter-particle bonds and significant in clays but zero in sands
- Friction angle (ϕ) due to structural roughness and higher in sand than clay

- A: Clay
  - Low friction
  - High cohesion

- B: Sand
  - High friction
  - No to low cohesion

Cohesion and Friction

- Cohesion (c) due to inter-particle bonds and significant in clays but zero in sands
- (high likelihood of forming mud)

- Friction angle (ϕ) due to structural roughness and higher in sand than clay
- (no likelihood of forming mud)

Texture

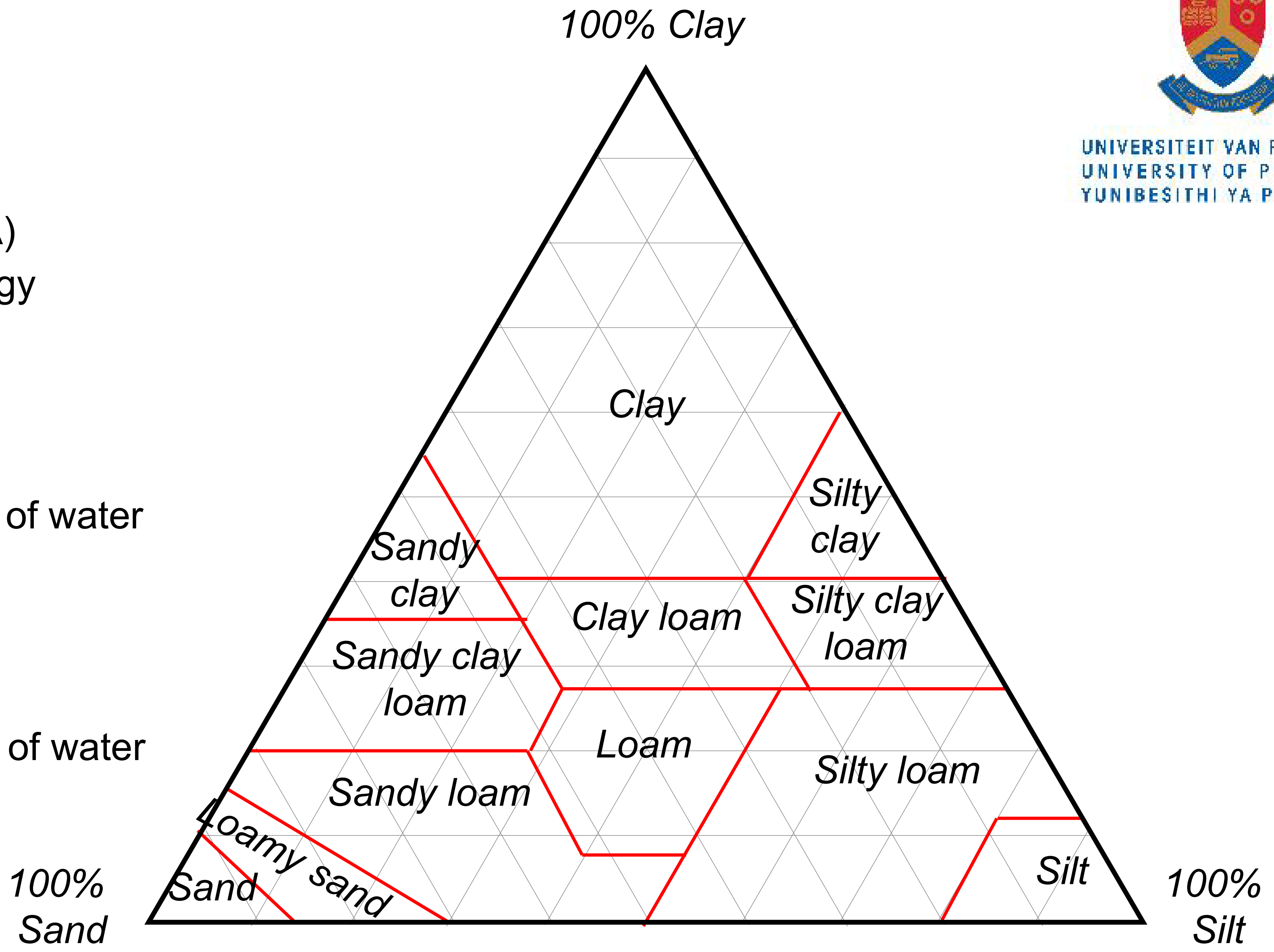
- Texture is the grain size distribution
- Colouration & pedocretes indicate changes in moisture
- Openings indicate volume decrease

Size (mm)	Textures	Pedocretes	Openings	Colouration
0.002	Clay			
0.006	Fine silt	Powder		
0.02	Medium silt			
0.06	Coarse silt	Concretions		
0.2	Fine sand		Pinholed	Speckles
0.6	Medium sand			
2	Coarse sand			
6	Fine gravel		Voided	Mottles
60	Medium gravel	Nodules	Large voids; specify	Blotches
60	Coarse gravel			Patches
200	Cobbles			
	Boulders			

Dippenaar et al. 2025

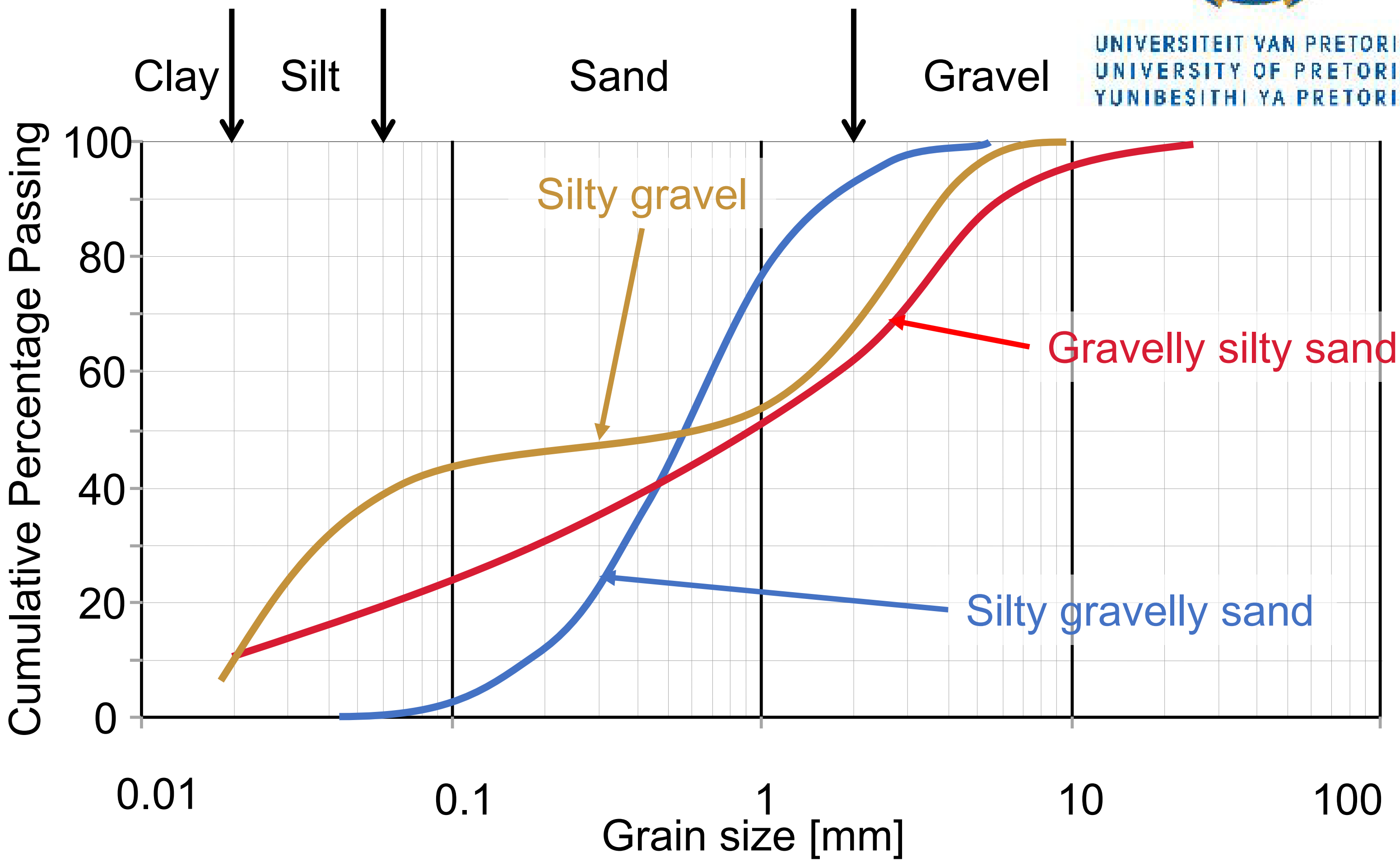
Texture

- Soil Texture Triangle (USDA)
  - Loam specific to pedology
- Coarser grained soils:
  - Drain more easily
  - More prone to cohesion of water
  - Higher friction
- Finer grained soils:
  - More prone to adhesion of water
  - Retain water more
  - Higher cohesion
  - Likely to form mud



Hydraulic Behaviour of Soils

- **Well-graded**:
  - Good mix of different particle sizes
  - Sufficient finer fractions to clog pore space generated by the coarser fraction
- **Poorly graded**:
  - Steeper gradients
- **Gap-graded**:
  - Flat middle portions
  - (absence of middle fraction)



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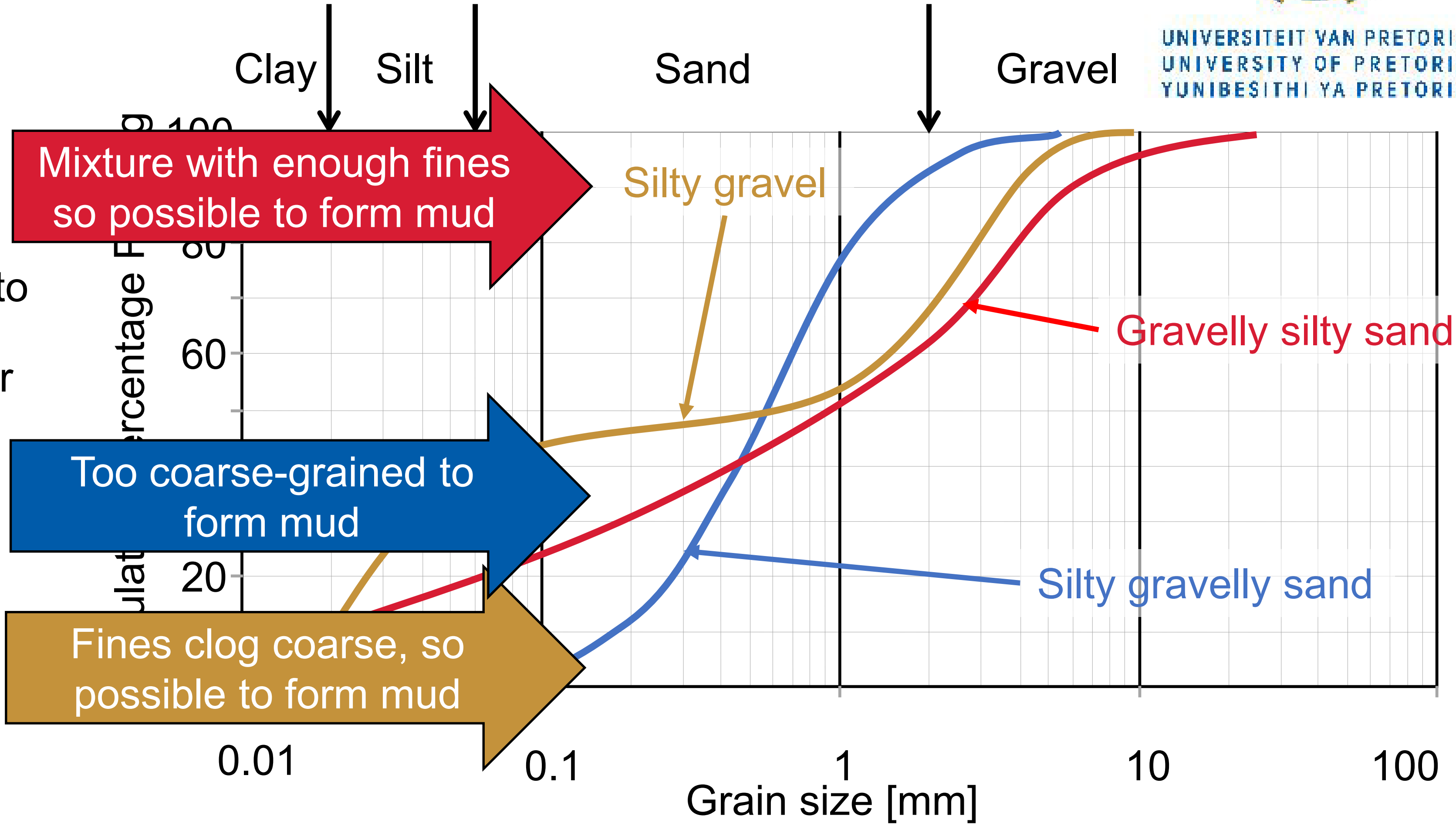
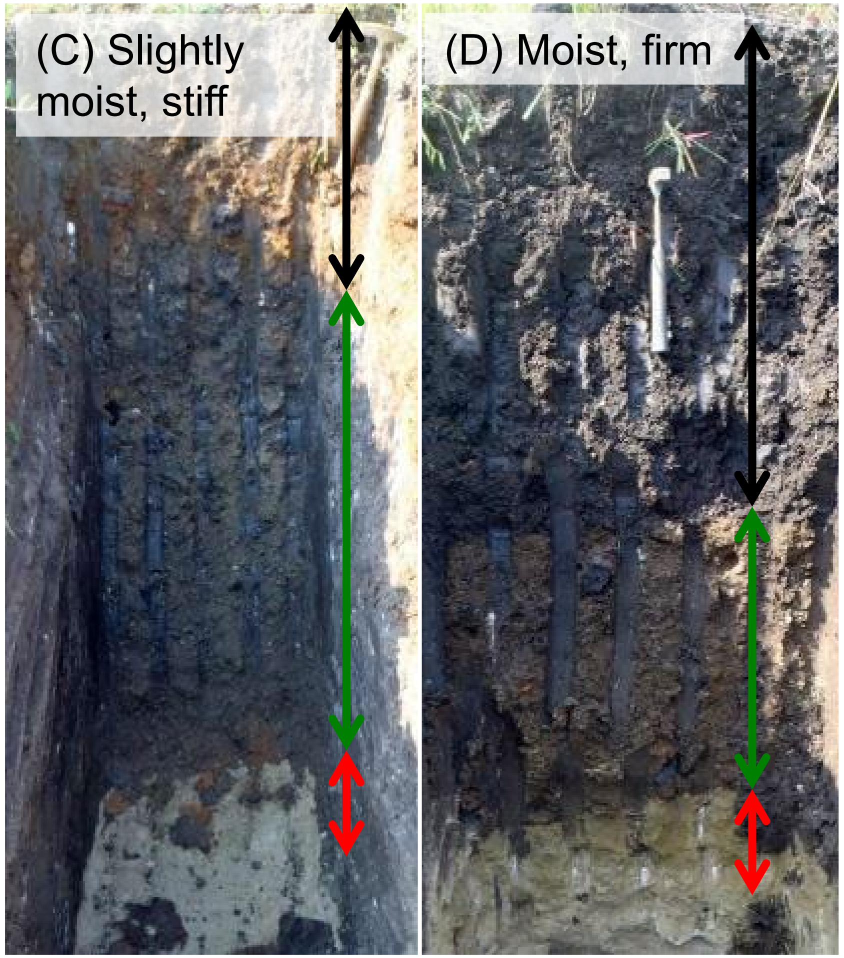
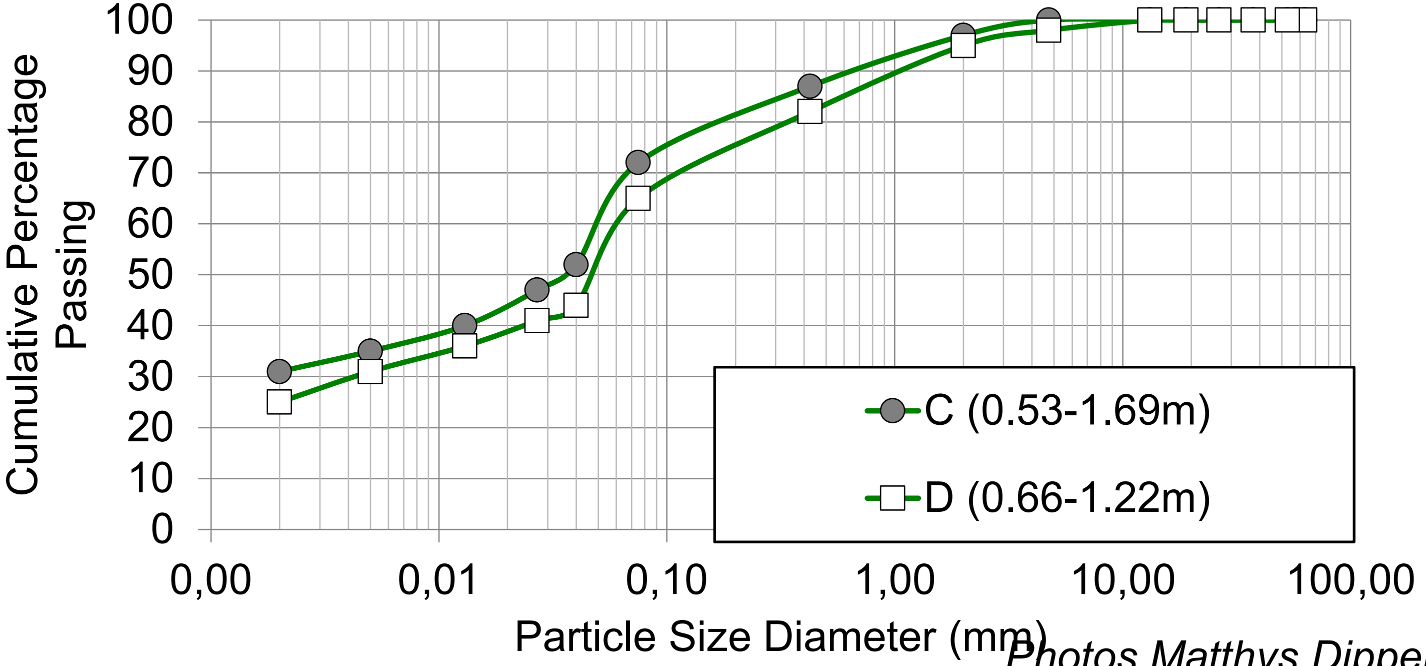


Importance of Particle Size Distribution



- Rustenburg Layered Suite (Marikana, South Africa)
- Located <100 m apart, with only in situ moisture content different
- Despite this, the mechanical behaviour is similar, as is evident by the grading and the similar mineralogy



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Particle Size Distribution

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- “The particle-size distribution (PSD) is key in mud-flow events.
- “In this study, coarse fragments in the PSD were usually observed in the cohesive hang-ups previous to a mud-flow event.
- “However, some questions still must be studied, such as
  - the relation between the PSD and cohesive hang-ups,
  - the amount of mud material that could be retained by the PSD in cohesive hang-ups,
  - and the relationship between PSD in mud-flow events and the magnitude of the event.

Castro et al. 2023

Particle Size Distribution

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- Immobile sample:
    - 6% more material below 300μm
    - Required 2% higher moisture content to induce slumping; plastic to soft flow
    - Higher plasticity
    - Cohesive strength of 23.08 kPa compared
- Mobile sample:
    - Shear/Cohesive strength of 9.16 kPa.
    - Lower iron oxide, and higher silicon oxide content
- High fine fractions <0.6mm
    - Affect laboratory test results that are hypothesised to relate mud flowability and potential hazard
    - Higher iron oxide content, shear strength, wettability, and moisture content required to transition from plastic to soft in slump testing points to lower mobility

Musolino et al. 2023

Shear Failure due to Moisture

- Induration with iron oxides and some clays make these aeolian sands somewhat cohesive
- Any soil (natural or made) will fail under shear when wetted
- This may cause slurries or mud (lower mobility based on previous slide…)



Photos Matthys Dippenaar

Mud in Percussion Drilling Samples

- Percussion drilling is often used in exploration or for water supply or dewatering in mines
- Here, in dolomites, wad (very low density silty soil) is encountered
- This mud caves into cavities forming sinkholes and erode very easily; highly mobile

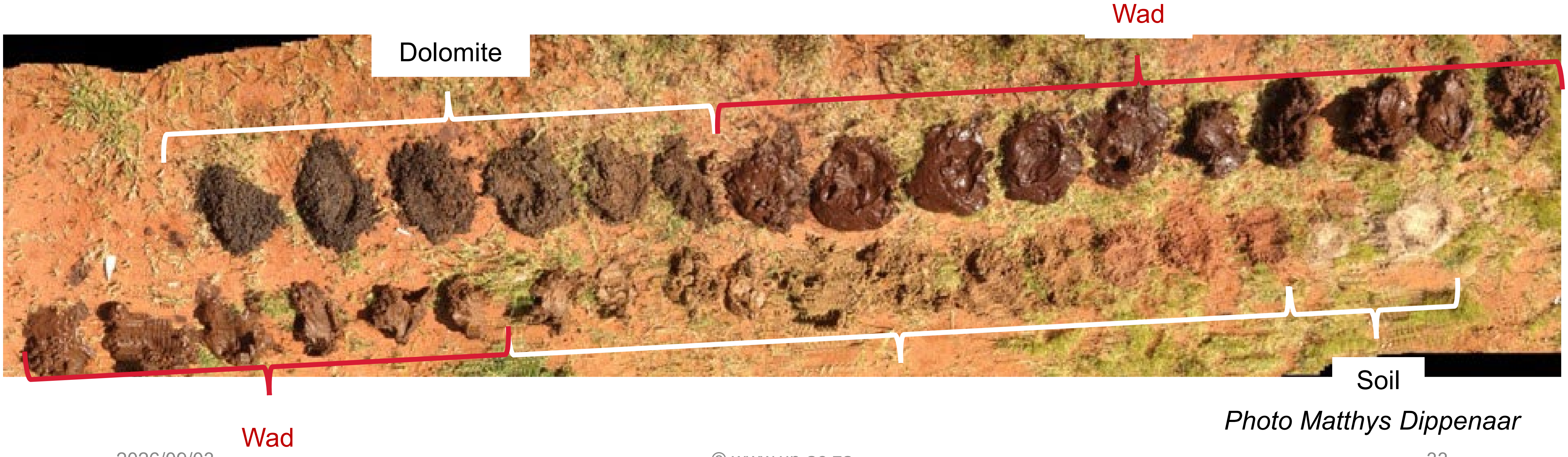

Photo Matthys Dippenaar

Mud in Percussion Drilling Samples

← Wad (very soft mud)

Photos Matthys Dippenaar

Mud

- Sources of mud include:
  - Accumulation of fines that are produced by the comminution of rock
  - Backfill used in mining materials

- The sources include:
  - Material that weather readily (e.g. shale; kimberlite) occurring in the ore and country rocks
  - Tailings impoundments located on surface above or adjacent to mine workings
  - Backfill that is placed in underground stopes and is used for support or disposal

Butcher et al. 2005

Mud

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Engineering Geology

Butcher et al. 2005

Water

- Sources of water include:
  - Rainwater
  - Groundwater
  - Drilling and operation water
  - Water from leaking or burst pipes

- Primary risks:
  - Water accumulation (internal and external)
  - Mud-forming mineral accumulation (internal and external)
  - Proximity of mud to discharge point (or draw point)
  - Freedom for mud to discharge

Butcher et al. 2005

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Hydrogeology

Butcher et al. 2005

Understanding the Mud from an Engineering Geological and Hydrogeological Context (examples)

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- Rustenburg Layered Suite:
    - Highly expansive clays, changing in texture based on climate (Marikana high; Northam less)
    - Corestones common that will divert and concentrate water (Pretoria)
    - Mud will be clayey but containing a mixture of the materials that are available in the area
    - Highly variable and therefore require proper field and laboratory testing
    - High water retention accompanied by swell and desiccation that can alter the storage and movement of water

Rustenburg Layered Suite (Climate & Weathering)

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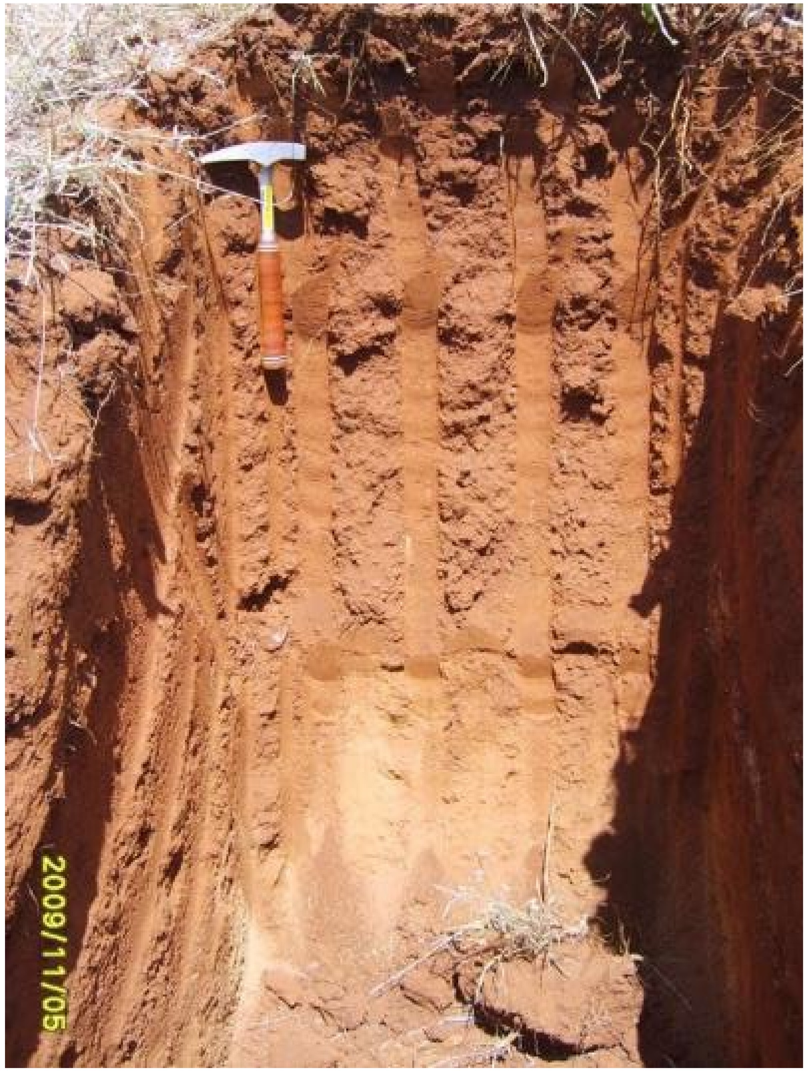
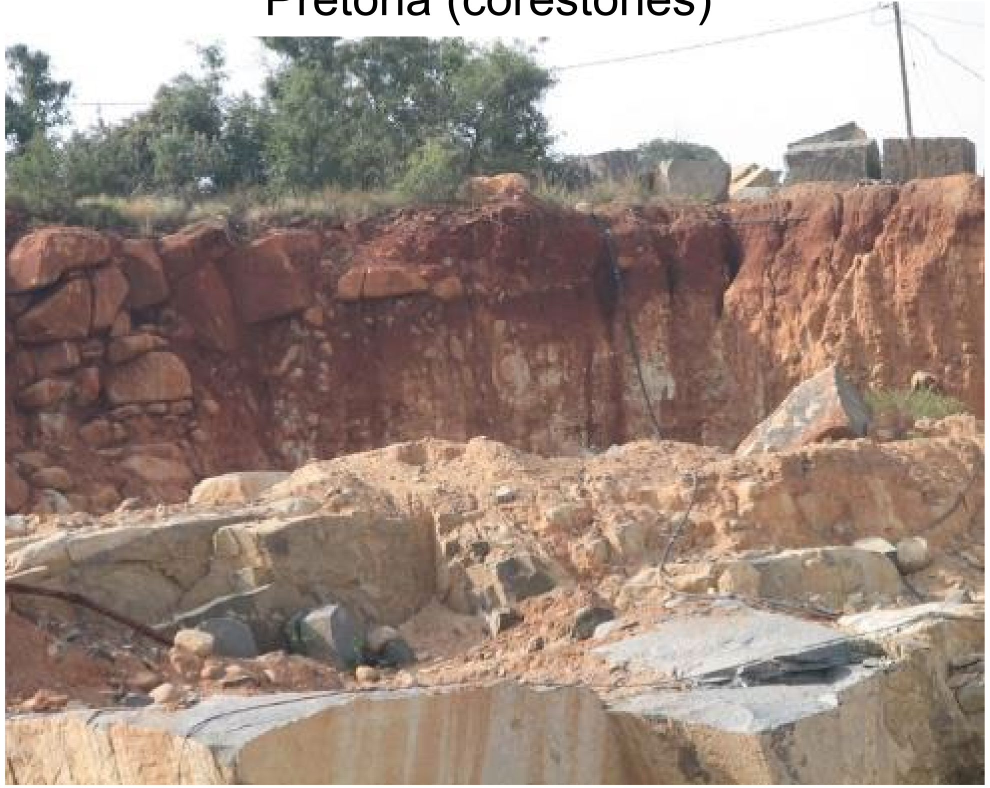
Marikana (>>clays)

Northam (clays)



Pretoria (corestones)



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- Witwatersrand Supergroup
  - Different soils occur (various clastic sediments), but are mostly silty sand in the areas where mining occur
  - Made materials are abundant, and this includes tailings that can erode and be transported
  - Water is affected through dewatering that reduces the moisture content in the soils
  - Water is affected by acid mine drainage that deteriorate other minerals in the soils and act in a corrosive manner to made materials such as cement and steel
  - The underlying basement granites weather more, and the overlying dolomites are affected by the decant
  - Most to all of these soils can mobilise on wetting (notably also due to the steep dip of the bedrock due to the Johannesburg Dome)

Witwatersrand Supergroup

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Polluted water (AMD; iron enriched)

Tailings (eroding via gravity, wind, and water)

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Understanding the Mud from an Engineering Geological and Hydrogeological Context (examples)

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- Karoo Supergroup
  - Different soils occur depending on lithologies
  - Water ingress and flow into subsurface can form fine-grained soils (mud) that can fail in shear and flow
  - Burning cause material to densify and open to form to surface
  - Foundations are verify heavy for production of energy, and this can cause consolidation and movement of subsurface water and materials
  - Water quality may affect soils and transported materials
  - Highly variable soil types and textures may form different types of mud:
    - Residual and weathered shales; siltstones; sandstones; tillites; coal; basalt; dolerite
    - Transported soils
    - Made ground

Karoo Supergroup

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Underground burning causing sinkhole

Water accumulation and/or groundwater

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Thank you for your time! References

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Mud Rush Day of Learning

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Matthys A. Dippenaar

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA