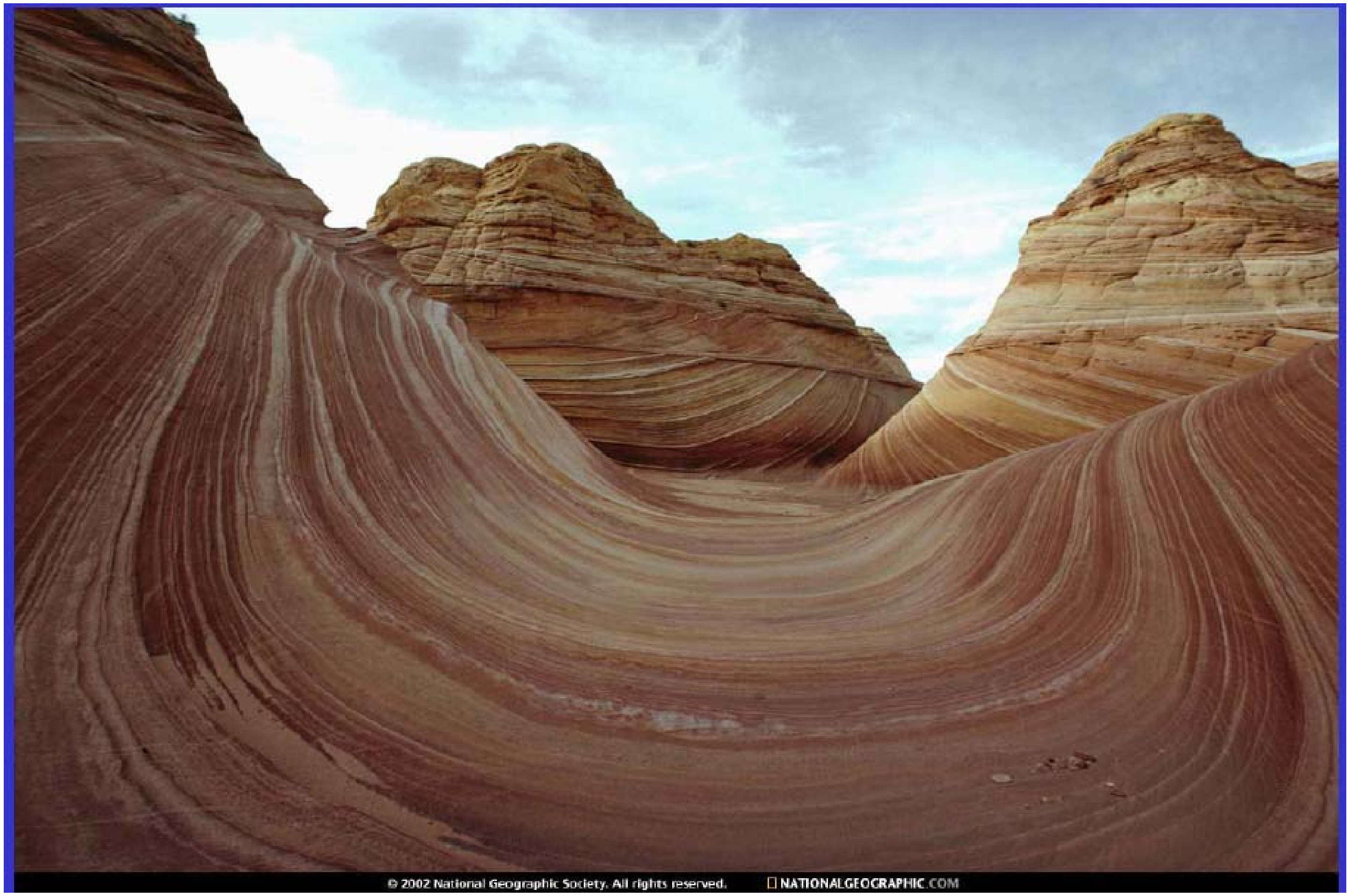
Lectures on Rock Mechanics

- SARVESH CHANDRA
  Professor
  Department of Civil Engineering
  Indian Institute of Technology Kanpur
  KANPUR, 208016 India
  email: sarv@iitk.ac.in

ROCK MECHANICS

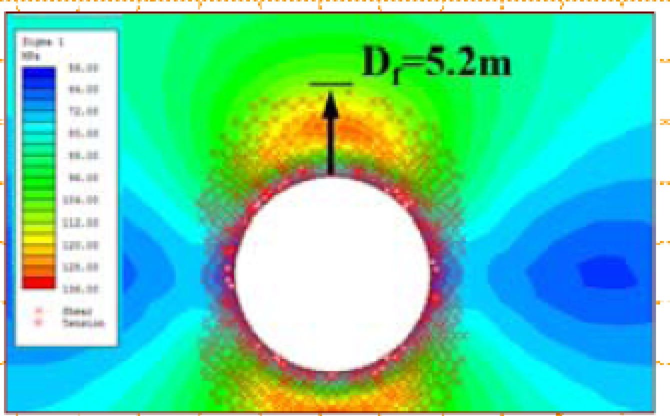
The problem in mathematics is black and white but the real world is grey –Albert Einstein

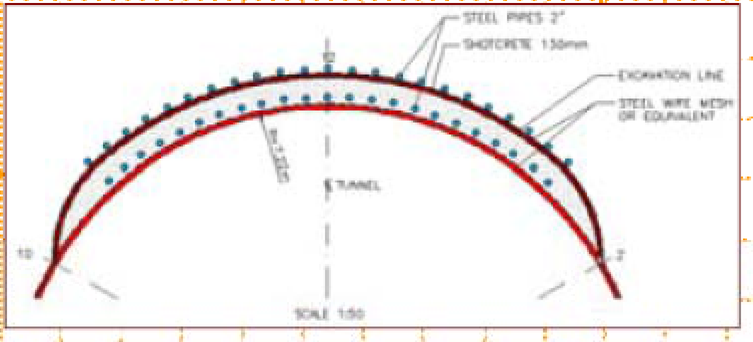


Engineering Design

Engineering design is defined as a creative, iterative and open-ended process, subject to constraints imposed through legislative codes, project economics, health, safety, environmental and societal considerations.

It integrates mathematics, natural sciences and engineering sciences in order to develop elements, systems and processes to meet specific needs.





Complexity & Uncertainty

What makes geotechnical engineering unique is the complexity and uncertainty involved when interacting with the natural geological environment.

Rock masses are complex systems!

Often, field data (e.g. geology, geological structure, rock mass properties, groundwater, etc.) is limited to surface observations and/or limited by inaccessibility, and can never be known completely.

Complexity & Uncertainty

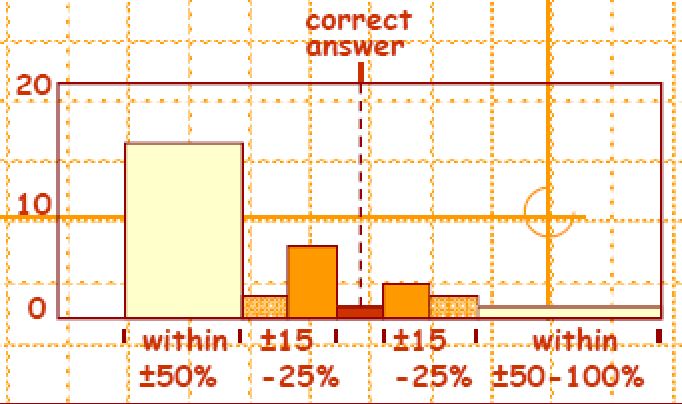
Morgenstern's Casagrande Lecture (1995):

Parameter Uncertainty: concerned with spatial variations, e.g. rock mass strength, and the lack of data for key parameters.

Model Uncertainty: arises from gaps in the scientific theory that is required to make predictions on the basis of causal inference.

Human Uncertainty: can range from subjectivity to simple human error to corruption.

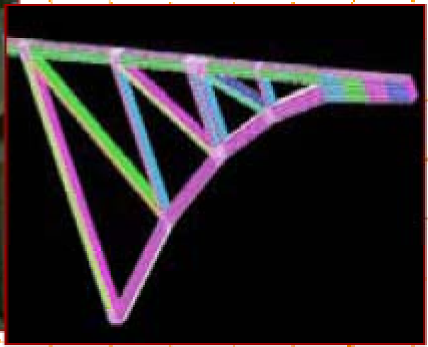
MHA prediction competition – collapse height of slope in soft clay. A substantial amount of shear strength data was provided to the 31 participants.



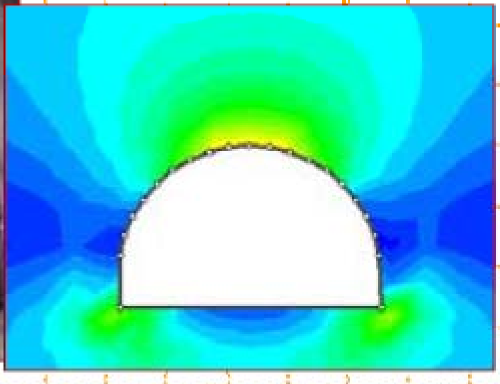
Engineering Design & Problem Uncertainty

Although geotechnical engineers routinely deal with natural conditions that are largely unknown and must be inferred from limited and costly observations, many of the design tools used are borrowed from other engineering disciplines where the accuracy and completeness of the problem conditions are significantly different.

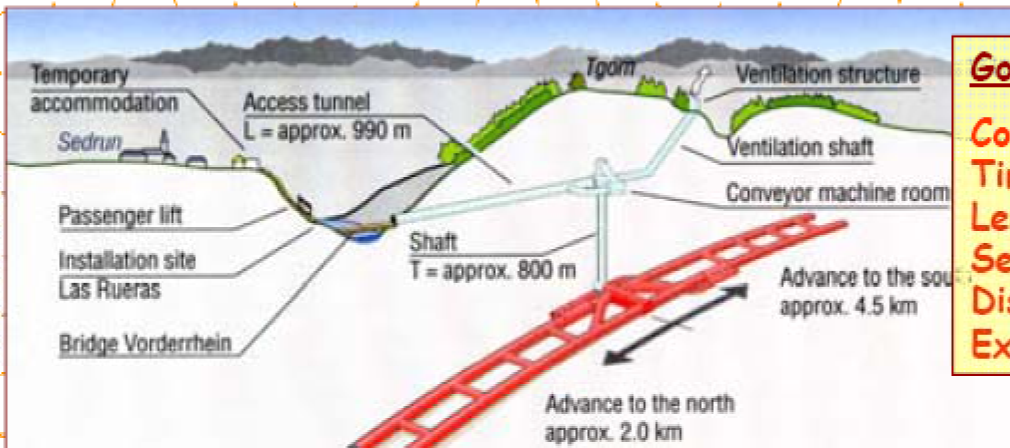
Structural engineering is largely deductive: we start from reasonably well known conditions, where models are employed to deduce the behavior of a reasonably well-specified universe.



In contrast, geotechnical engineering is largely inductive: we start from limited observations, and use judgment, experience, knowledge of geology and statistical reasoning to infer the behavior of a poorly-defined universe.

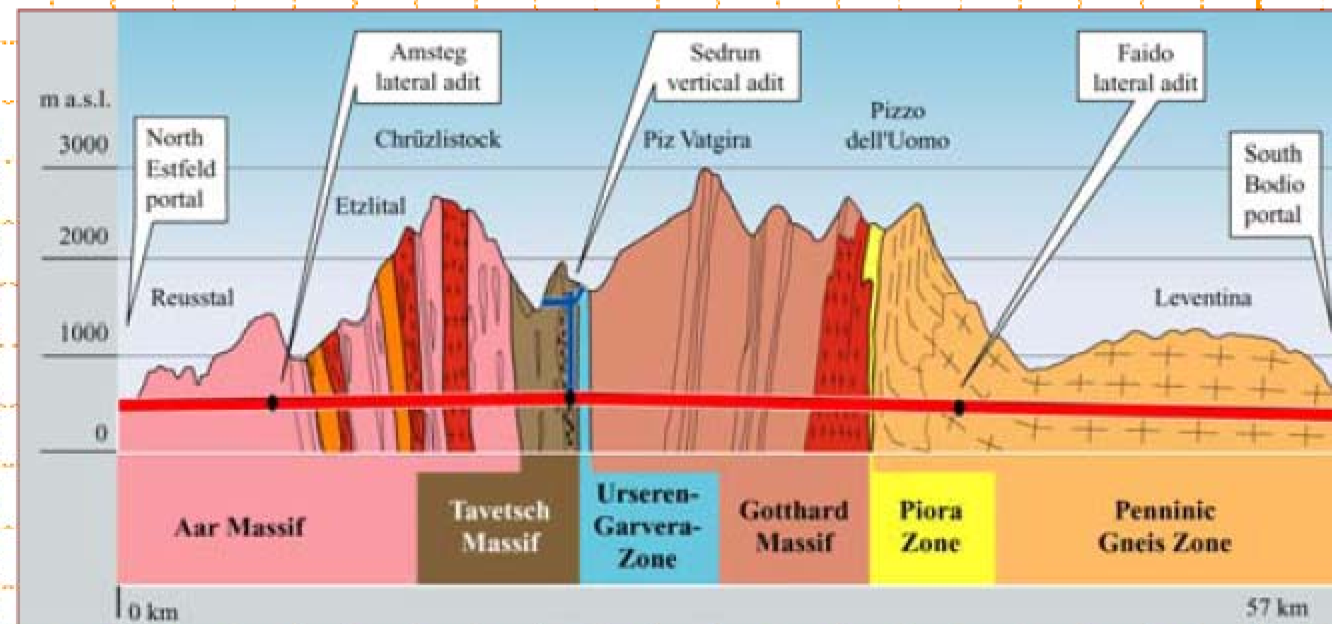


Deep Tunnels



Gotthard Base-Tunnel (CH)

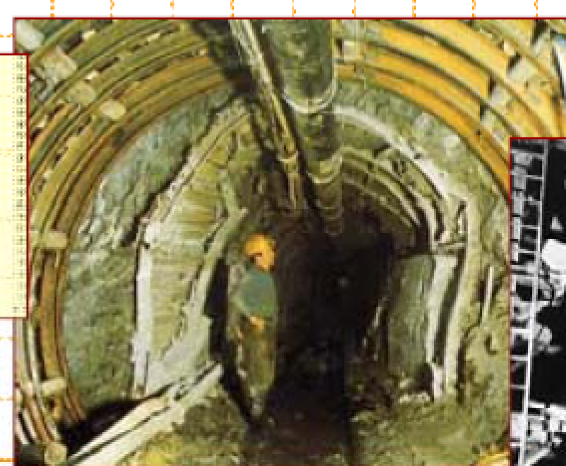
Cost = $7 billion (and counting)
Time to build = 12+ years
Length = 57 km
Sedrun shaft = 800 m
Distance between parallel tubes = 40 m
Excavated material = 24 million tonnes

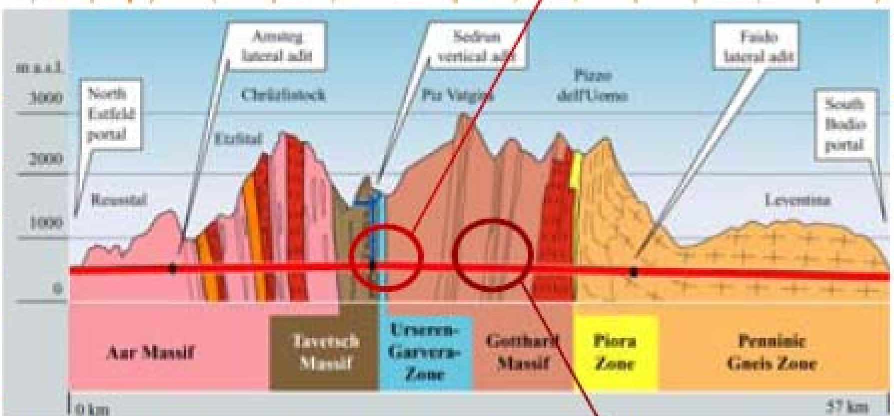


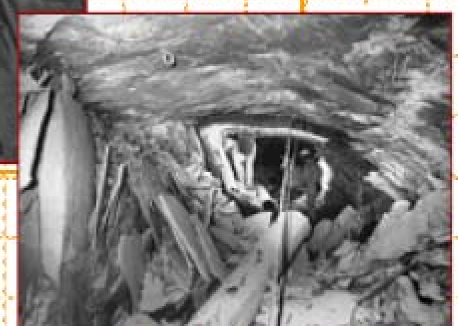
Loew et al. (2000)

Deep Tunnels – Importance of Geology

Weak rock under high stresses may lead to squeezing ground conditions, which may result in damage/failure to the ground support system, or require the costly re-excavation of the tunnel section.







In strong brittle rock, high stress conditions may lead to rockbursting (the sudden release of stored strain energy). Bursts manifest themselves through the sudden ejection of rock into the excavation.

SCOPE OF ROCK MECHANICS

- CIVIL ENGINEERING
- MINING ENGINEERING
- PETROLEUM ENGINEERING
- GEOLOGY
- GEOPHYSICS

SCOPE OF ROCK MECHANICS

- Evaluation of GEOLOGICAL HAZARDS .. landslides, seismic etc.
- Selection of CONSTRUCTION MATERIALS
- Selection and layout of CONSTRUCTION SITES
- Analysis of STABILITY
- Design of BLASTING OPERATIONS
- Design of SUPPORT SYSTEMS
- Design of HYDRAULIC FRACTURING PROGRAMS
- Design of INSTRUMENTATION PROGRAMS
- Evaluation of EXCAVATION CHARACTERISTICS
- Studies of rock deformation at high temperatures and pressures (STRUCTURAL GEOLOGY)

APPLICATION OF ROCK MECHANICS

- DEEP EXCAVATIONS
  - Mines (Temporary and Permanent)
  - Tunnels (Roads, H.E.P.)
  - Underground chambers (Power stations, storage, recreational)
- ENERGY DEVELOPMENT
  - Petroleum
  - Geothermal
  - Nuclear (Power plants, Waste Disposal)
  - Energy storage caverns

Rock Mechanics Problems

- How will rock react when put to men's use?
- What is the bearing capacity of rock on surface an at depths?
- What is the shear strength of rocks?
- What is the response of rocks under dynamic / earthquake type loading?
- What is the modulus of elasticity of rock and how to get it?
- What are the effects of rock defects (jointing bedding planes, schistocity, fissures, cavities and other discontinuities) on its strength?
- What are the mechanisms of failure of rocks?

Rock as a Construction Material

- For laying structural foundations to support structures
- For constructing Underground openings
- For protecting slopes
- For supporting railway tracks – Ballasts
- As base and sub-base for roads and runways
- As aggregate in concrete
- Making facia for buildings.

Geologic Time Scale

Greenland

Era	Period	Epoch	Time Boundaries (Years Ago)
Cenozoic	Quaternary	Holocene - Recent	10,000
		Pleistocene	2 million
	Tertiary	Pliocene	5 million
		Miocene	26 million
		Oligocene	38 million
		Eocene	54 million
		Paleocene	65 million
Mesozoic	Cretaceous		130 million
	Jurassic		185 million
	Triassic		230 million
Paleozoic	Permian		265 million
	Carboniferous	Pennsylvanian	310 million
		Mississippian	355 million
	Devonian		413 million
	Silurian		425 million
	Ordovician		475 million
	Cambrian		570 million
Precambrian			3.9 billion
Earth Beginning			4.7 billion

What are we calling a rock?

Grade	Description	Lithology	Excavation	Foundations
VI	Soil	Some organic content, no original structure	May need to save and re-use	Unsuitable
V	Completely weathered	Decomposed soil, some remnant structure	Scrape	Assess by soil testing
IV	Highly weathered	Partly changed to soil, soil > rock	Scrape NB corestones	Variable and unreliable
III	Moderately weathered	Partly changes to soil, rock > soil	Rip	Good for most small structures
II	Slightly weathered	Increased fractures and mineral staining	Blast	Good for anything except large dams
I	Fresh rock	Clean rock	Blast	Sound

Engineering classification of weathered rock

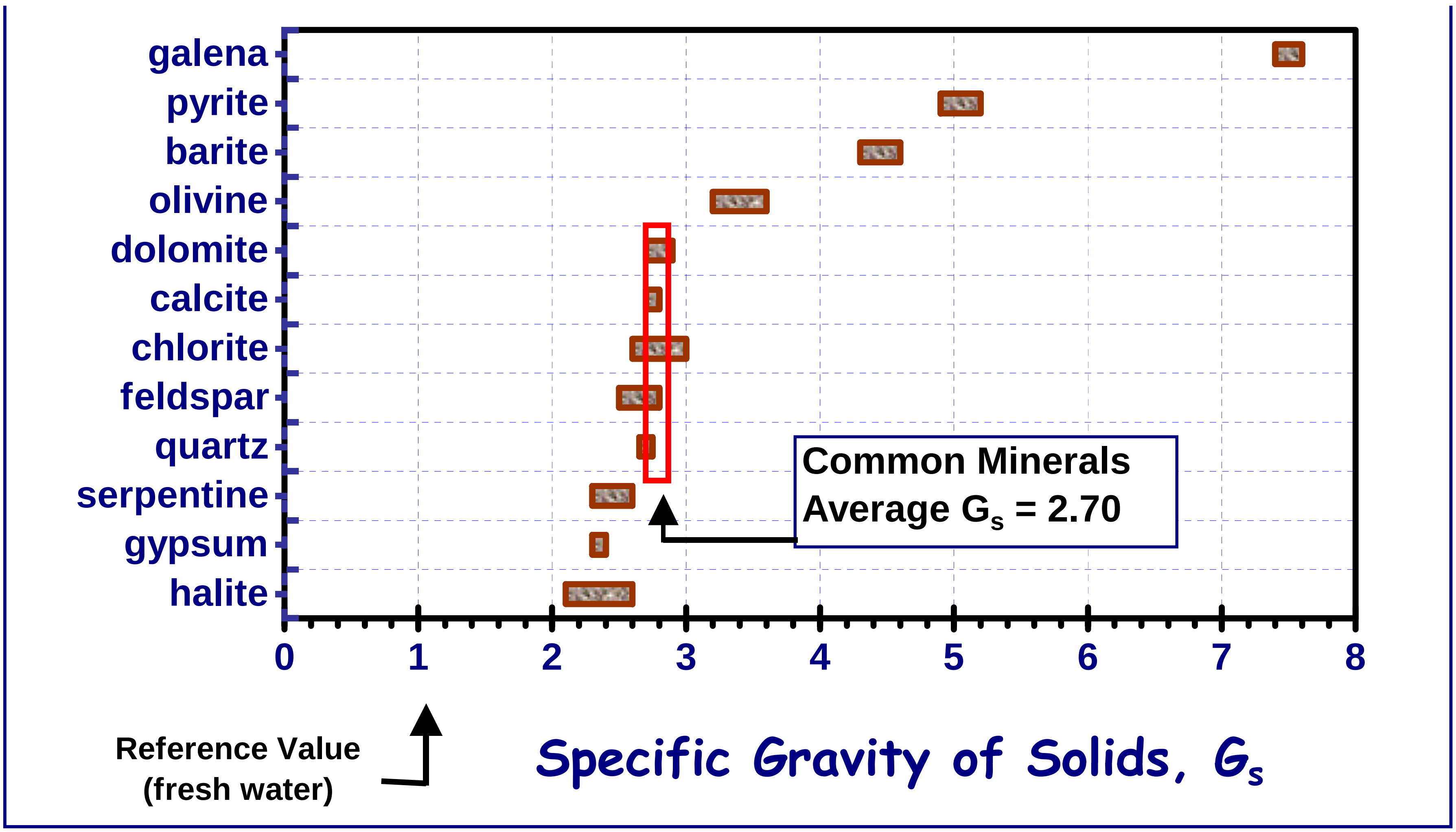
Primary Rock Types by Geologic Origin

	Sedimentary Types		Metaphorphic		Igneous Types	
Grain Aspects	Clastic	Carbonate	Foliated	Massive	Intrusive	Extrusive
Coarse	Conglomerate Breccia	Limestone Conglomerate	Gneiss	Marble	Pegmatite Granite	Volcanic Breccia
Medium	Sandstone Siltsone	Limestone Chalk	Schist Phyllite	Quartzite	Diorite Diabase	Tuff
Fine	Shale Mudstone	Calcareous Mudstone	Slate	Amphibolite	Rhyotite	Basalt Obsidian

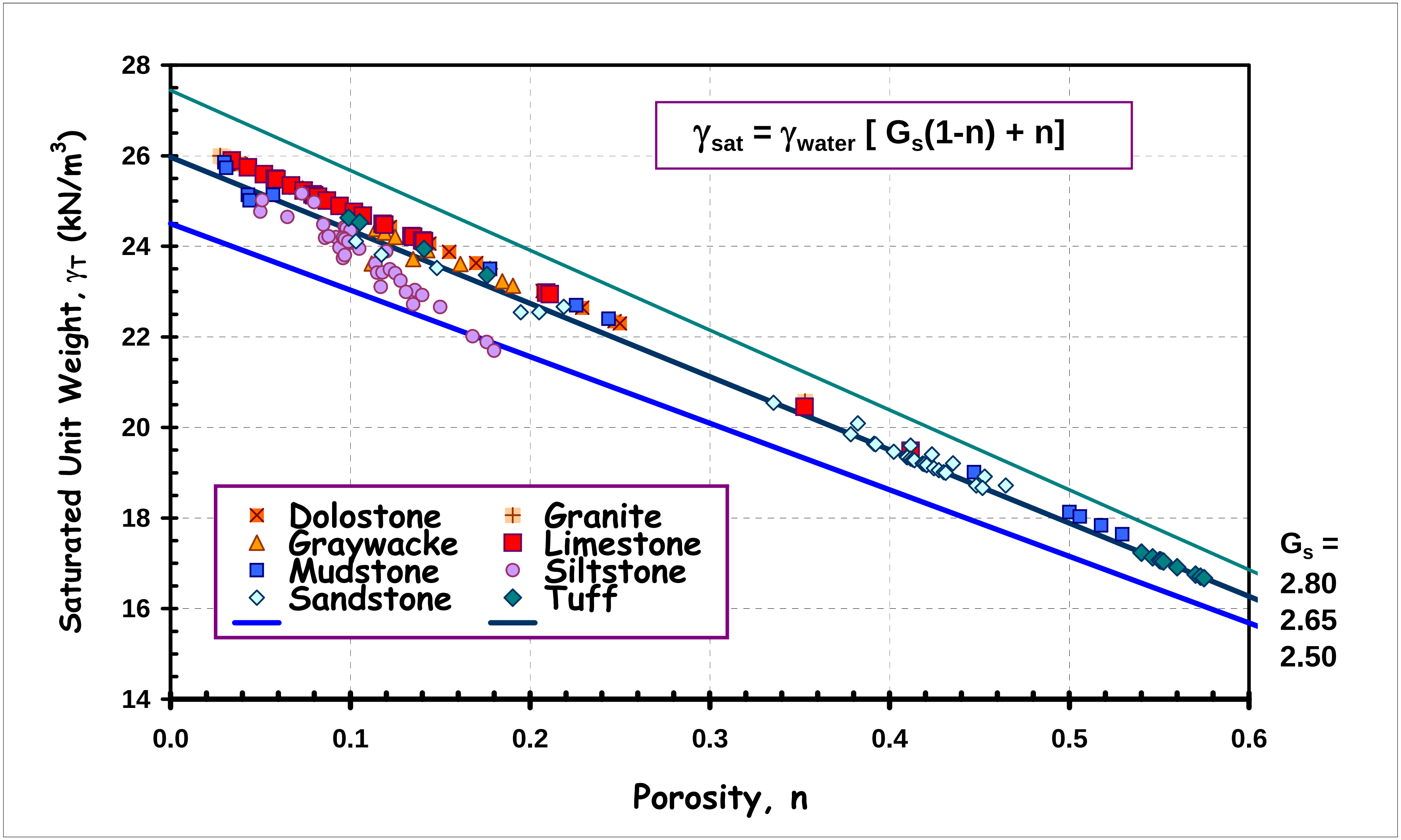
Index Properties of Intact Rock

- Specific Gravity of Solids, G_s
- Unit Weight, γ
- Porosity, n
- Ultrasonic Velocities (V_p and V_s)
- Compressive Strength, q_u
- Tensile Strength, T_0
- Elastic Modulus, E_R (at 50% of q_u)

Specific Gravity of Rock Minerals



Unit Weights of Rocks



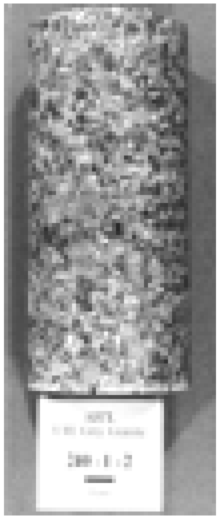
CHILE

CONTINUOUS

HOMOGENEOUS

ISOTROPIC

LINEAR ELASTIC



DIANE

DISCONTINUOUS

➡ pores/microfractures - vugs, joints - faults, caverns

INHOMOGENEOUS

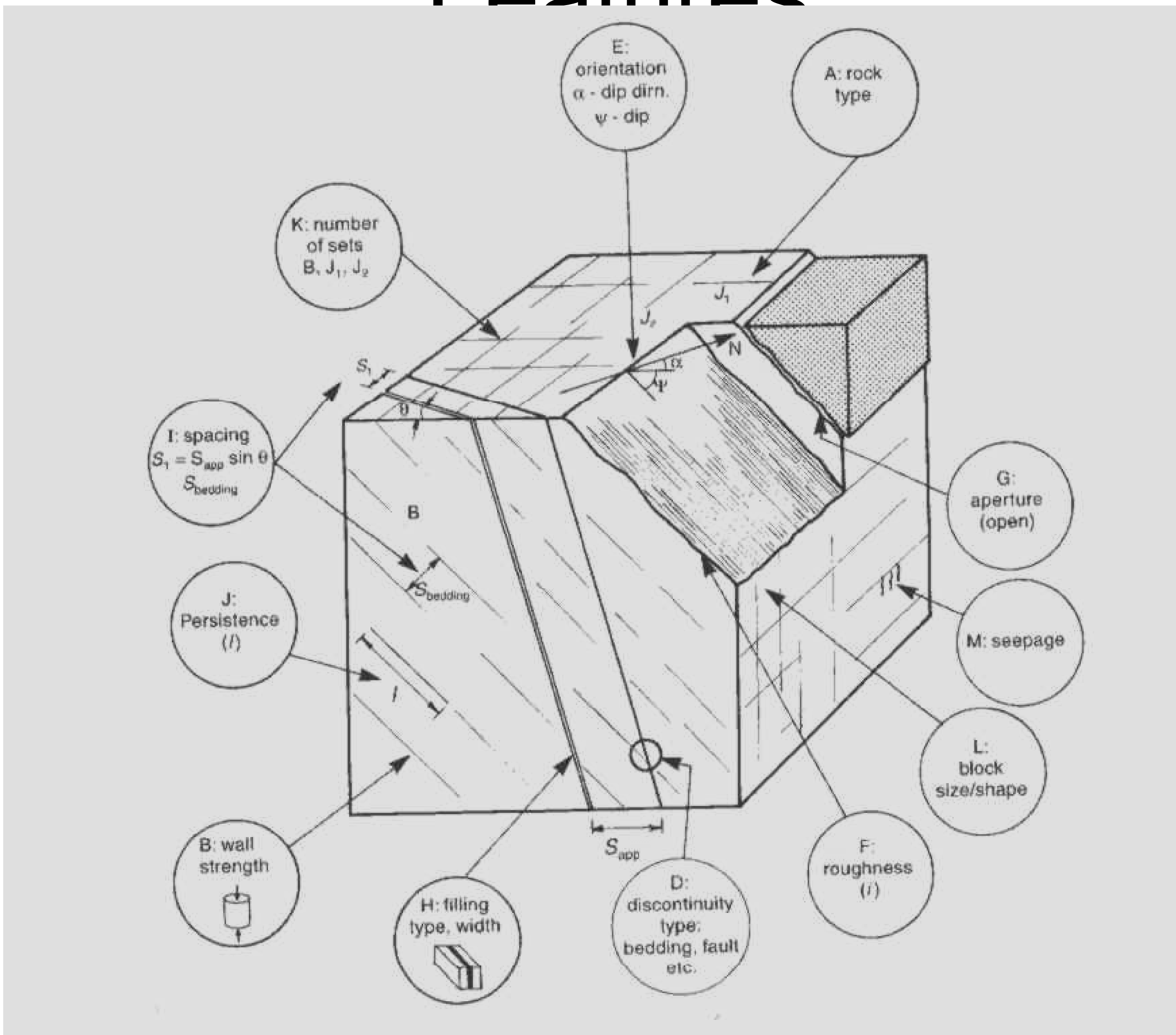
➡ mineralogy-layering-facies

ANISOTROPIC

➡ fabric - mineral alignment-discontinuity sets

NON ELASTIC

Geologic Mapping of Rock Mass Features



THE MECHANICAL CLASSIFICATION OF ROCKS

Goodman proposed a classification based on rock TEXTURE recognizing four textural groups

1. CRYSTALLINE
2. CLASTIC
3. VERY FINE GRAINED
4. ORGANIC

The mechanical strength varies considerably within each textural group.

APPLICATION OF ROCK MECHANICS

- **SURFACE STRUCTURES**
- Low rise (Housing)
- High rise (Tower blocks)
- High load (Dams, power plants, bridges)

- **TRANSPORTATION ROUTES**
- Highways, railways
- Canals
- Pipelines

- **SHALLOW EXCAVATIONS**
- Quarries
- Open pits, strip mines
- Trenches, cuttings

CRYSTALLINE TEXTURE

• *characterized by tightly interlocked texture*

A. **Evaporites** .. carbonates, sulphates, halides etc
B. **Banded Phyllosilicates** .. mica schists etc.
C. **Banded Silicates** .. some schists, gneiss etc.
D. Plutonic igneous .. granite, gabbro etc
E. **Porphyritic igneous** .. lavas etc.
F. **Highly sheared** .. serpentinite, mylonite

i. Unweathered banded silicates, plutonic and porphyritic igneous rocks tend to behave in a BRITTLE-ELASTIC manner under **normal** rock engineering conditions.
ii. Evaporites and weathered crystalline silicates behave in a PLASTIC or **VISCO- ELASTO-PLASTIC** manner.
iii. Banded phyllo- (sheet) silicates, banded silicates and highly sheared rocks often are very strongly ANISOTROPIC and ELASTO-PLASTIC.

CLASTIC TEXTURE

… Characterized by the presence of strong mineral grains in a cement or binder matrix

A. **Stably cemented** .. silica and limonite cements
B. **Slightly soluble cement**.. calcareous cement
C. **Highly soluble cement** .. gypsum cement
D. **Weakly cemented** .. friable sandstones, some tuffs
E. **Uncemented** .. clay-bound sandstones etc.

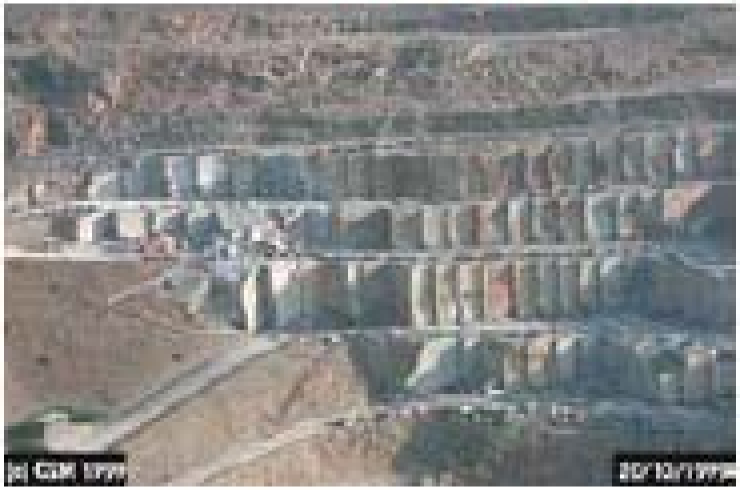
i. **Stably cemented** rocks often behave in a **BRITTLE-ELASTIC** manner
ii. Rocks with slightly-**highly soluble** cements tend to show **ELASTO-PLASTIC** behavior characteristic of the cement
iii. **Weakly cemented** or **uncemented** rocks (and B and C in the presence of water) exhibit behavior resembling **UNCONSOLIDATED SOILS**.

VERY FINE GRAINED

A. **Isotropic Hard Rocks** .. hornfels, some basalts
B. **Anisotropic thickly bedded** .. flagstones, mudstones.
C. **Anisotropic thinly bedded** .. slate phyllite
D. **Soft, soil like rocks** .. shales, chalk, marls

i. Isotropic hard rocks display BRITTLE-ELASTIC response to load.
ii. Bedded fine grained rocks are essentially BRITTLE-ELASTIC in response to stress but are strongly ANISOTROPIC and may show permanent PLASTIC strains parallel to bedding at relatively low stress levels.

VERY FINE GRAINED



ORGANIC TEXTURE

A. Soft Coals
B. Hard Coals
C. Oil Shales
D. Bituminous shale
E. Tar sands

i. Hard coals and oil shales may display BRITTLE-ELASTIC behavior
ii. Both hard and soft coals are frequently HEAVILY FISSURED and may behave as GRANULAR MATERIALS
iii. Tar sands can behave as VISCOUS FLUIDS and bituminous shales and soft coals sometimes exhibit extreme PLASTICITY
iv. PORE FLUID content can often control mechanical behavior.

INHERENT COMPLEXITIES

1. Rock fracture
   – under compressive stresses
2. Size effects
   – response of rock to loading affected by the size of the loaded volume” (joints & fractures)
3. Tensile strength
   – is low (similar to concrete); HOWEVER a rock mass can have even less tensile strength

COMPLEXITIES….

4. Groundwater effects

- **water in joints:** if under pressure, reduces normal stress (less resistance along joints)
- water in permeable rocks (e.g. sandstone) → *soil like response*
- *softening* of clay seams & argillaceous rocks (e.g. shales)

COMPLEXITIES….

5. **Weathering**
   - chemical/physical alteration, *reduction of engineering properties*
   - limestone caverns, sinkholes: ”Karst”
   - basic rocks with olivine (e.g. basalt) and pyroxene minerals are reduced to montmorillonite by hydrolysis

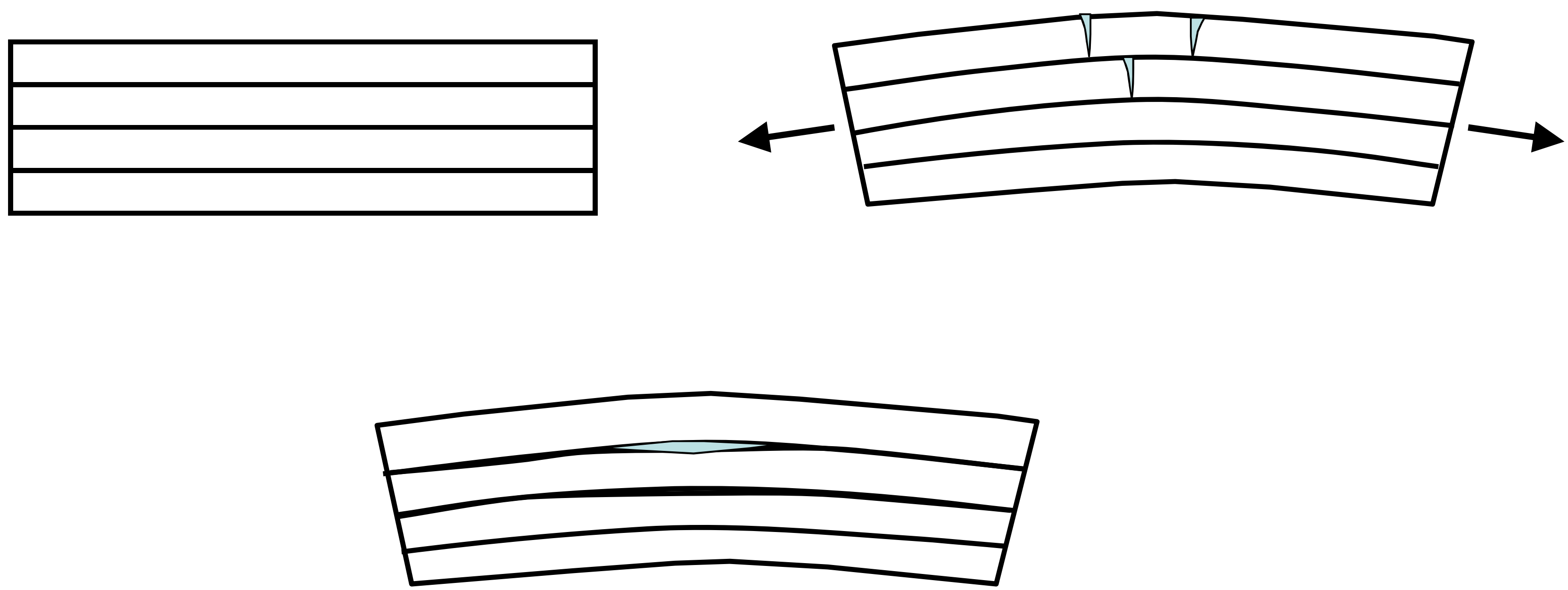
Cavernous limestone

Coffin
Bay

STRUCTURAL FEATURES or DISCONTINUITIES

1) **Bedding planes**
2) **Folds**
   - tension joints at the crest of a fold (strike, dip & shear joints)
   - folding may cause shear failure along bedding planes (axial plane or fracture cleavage)

Folding



DISCONTINUITIES

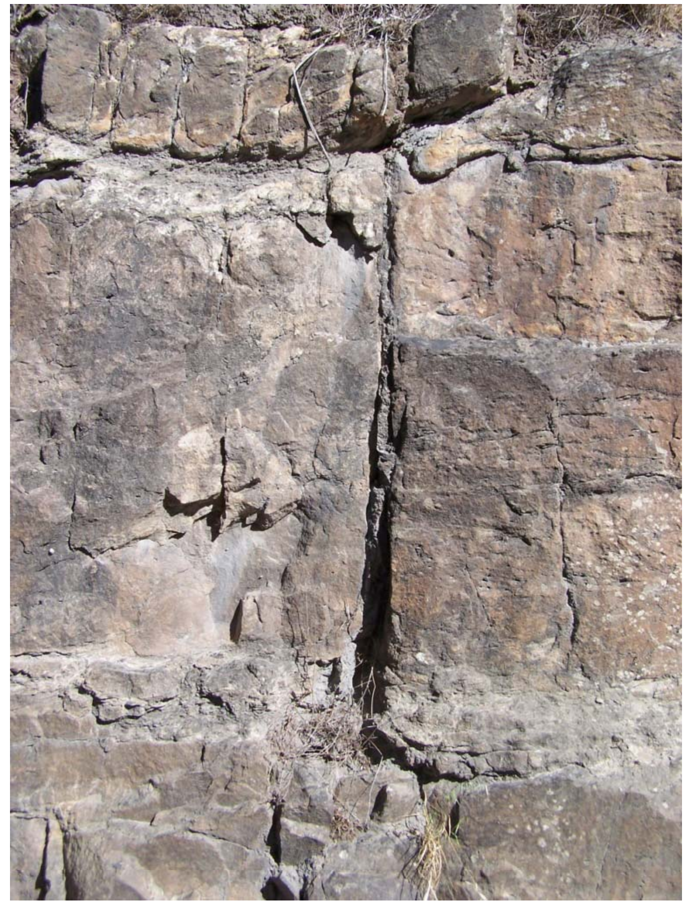
3) Faults

- shear displacement zones - sliding

Faults may contain

- Fault gouge (clay) – weak
- Fault breccia (re-cemented rock) – weak
- Rock flour – weak
- Angular fragments – may be strong

Defects

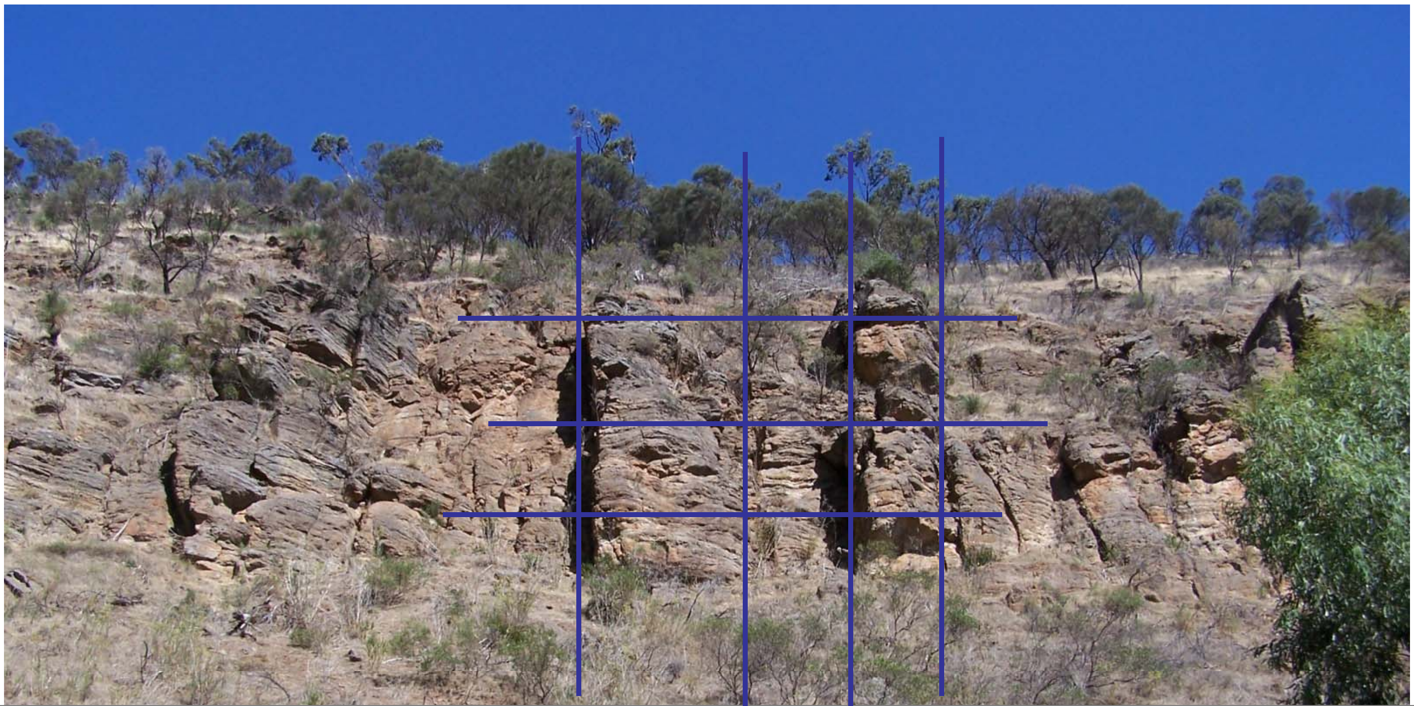


Defects

DISCONTINUITIES

4) **Shear zones**
   - bands of materials - local shear failure
5) **Dykes**
   - igneous intrusions (near vertical)
   - weathered dykes, e.g. *dolerite weathers to montmorillonite*
   - unweathered dykes *attract high stresses*
6) **Joints**
   - breaks with no visible displacement

Joint Patterns



sedimentary rocks usually contain 2 sets of joints, orthogonal to each other and the bedding plane

JOINTS

1) Open

Filled

Healed (*or closed*)

2) Stepped

Undulating

Planar

2B) each of the above can be Rough

Smooth

Slickensided

JOINT CLASSES
(AS 1726-1993)

I II II	Stepped	Rough *Smooth* Slickensided
IV V VI	Undulating	Rough *Smooth* Slickensided
VII VIII IX	Planar	Rough *Smooth* Slickensided

Order of Description of Rocks (AS 1726-1993)

ROCK MATERIAL COMPOSITION	rock name grain size (Table A6) texture and fabric (Table A7) colour

e.g. Basalt, fine, massive, vesicular, dark grey to black

Order of Description of Rocks (AS 1726-1993)

ROCK MATERIAL CONDITION	strength (Table A8) weathering (Table A9)

e.g. VL strength, XW

OR EH strength, FR

Order of Description of Rocks (AS 1726-1993)

ROCK **MASS** PROPERTIES	structure defects (much information required) weathering of joints

Structure:

sedimentary rocks	– bedded, laminated
metamorphic	– foliated, banded, cleaved
igneous rocks	– massive, flow banded

DEFECTS – information needed

- tightness
- cementation or infill
- smoothness or irregularity of surfaces
  - **class of joint**
- water in joints
- joint orientation
- joint spacing

DESIGN IN ROCK

<u>Take into account:</u>

- Local geological structure
- Shear strength of **the rock mass**
- Impact of water on stability
- Rock anchoring?
- Drilling and blasting procedures
- Monitoring of stability
  - ***the observational method***

Intact Rock

- Heterogeneous
- Anisotropic (soils less so)
- Spatial variability (soils the same)
- Yield mechanisms are non-linear & depend on stress level and rock type
- Failures are often brittle (soils strain soften or harden past the peak strength)

Rock Masses

- Contain discontinuities with little tensile strength
- Scale effect
  - response is dependent on stressed volume
- Affected by groundwater & weathering
- In-situ stresses difficult to estimate

Rock Masses

DEFINITIONS

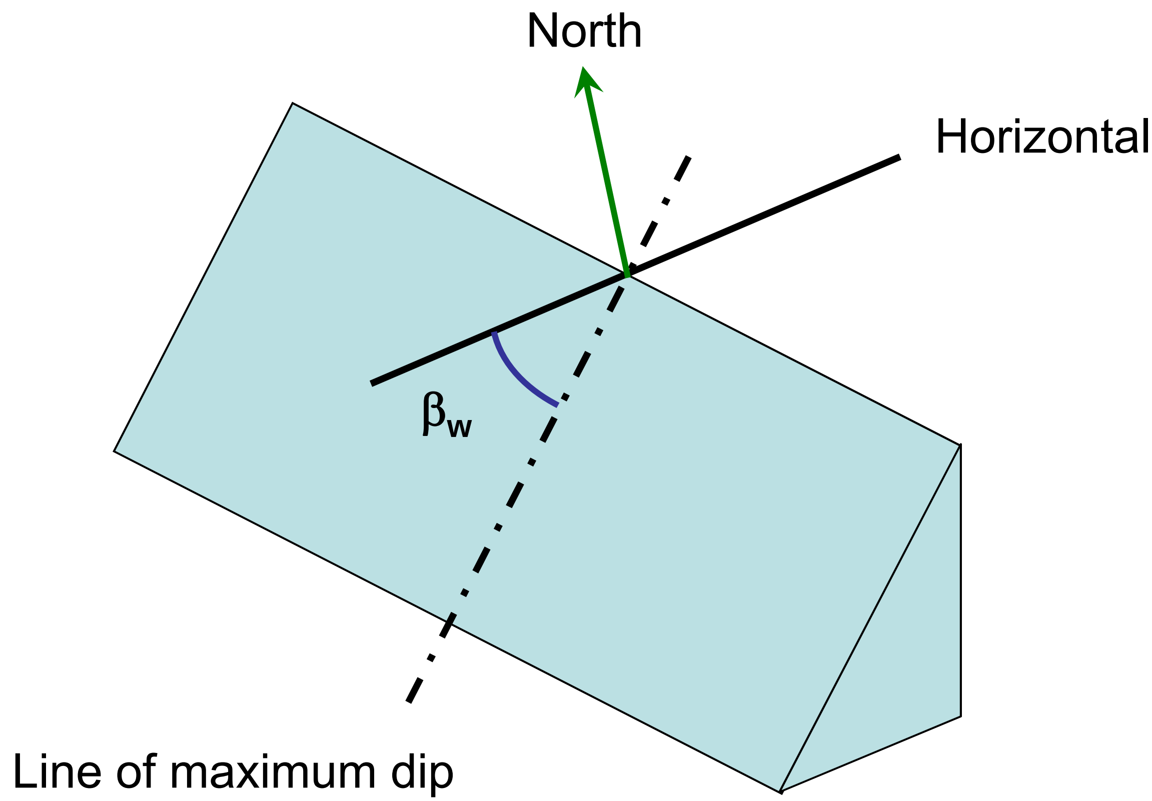
- **Dip angle, β_w:**

  the acute angle measured in a vertical plane between the line of maximum dip in a non-horizontal plane and the horizontal plane

  i.e. $0° \leq \beta_w \leq 90°$

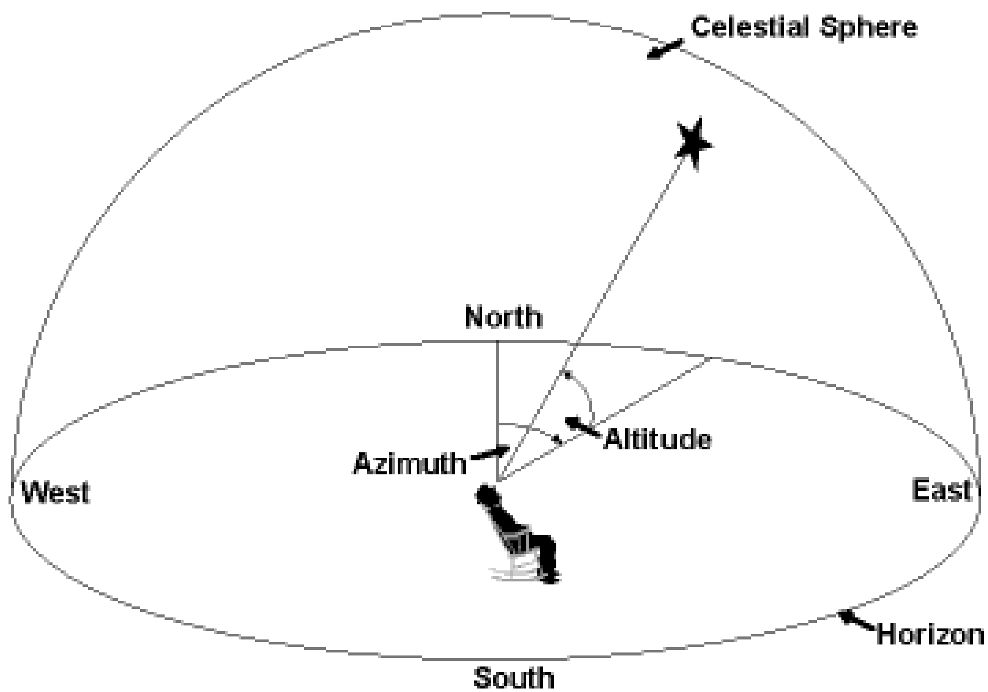
- **Dip direction, α_w:** the geographical azimuth measured in a clockwise direction from north (0°) of the vertical plane in which the dip angle is measured i.e. $0° \leq \alpha_w \leq 360°$

Dip Angle

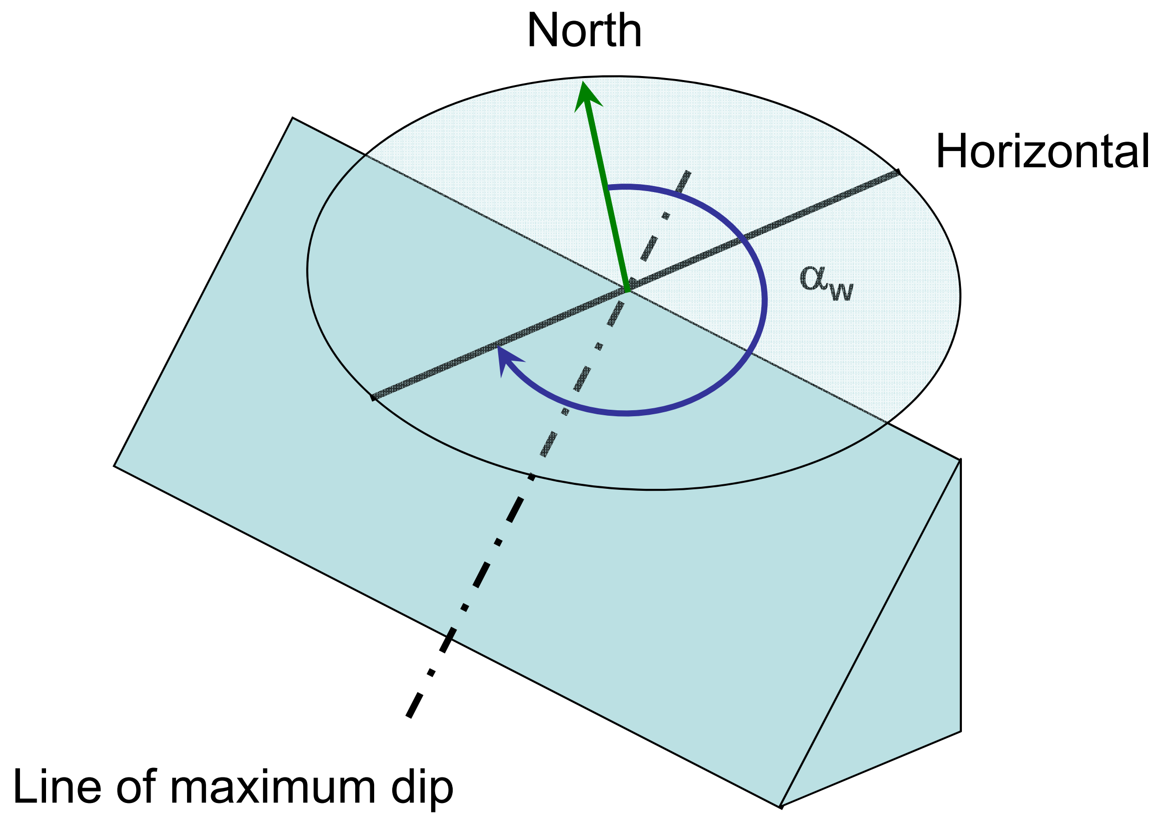


Dip direction

Azimuth is the direction of an object, measured clockwise around the observer's horizon from North, i.e. an object due north has an azimuth of 0°



Dip Direction



Quantitative Classification of Rock Mass

- Description of Joints:

  Orientation, Persistence, Roughness, Wall Strength, Aperture, Filling, Seepage, Number of sets, Block size, spacing.

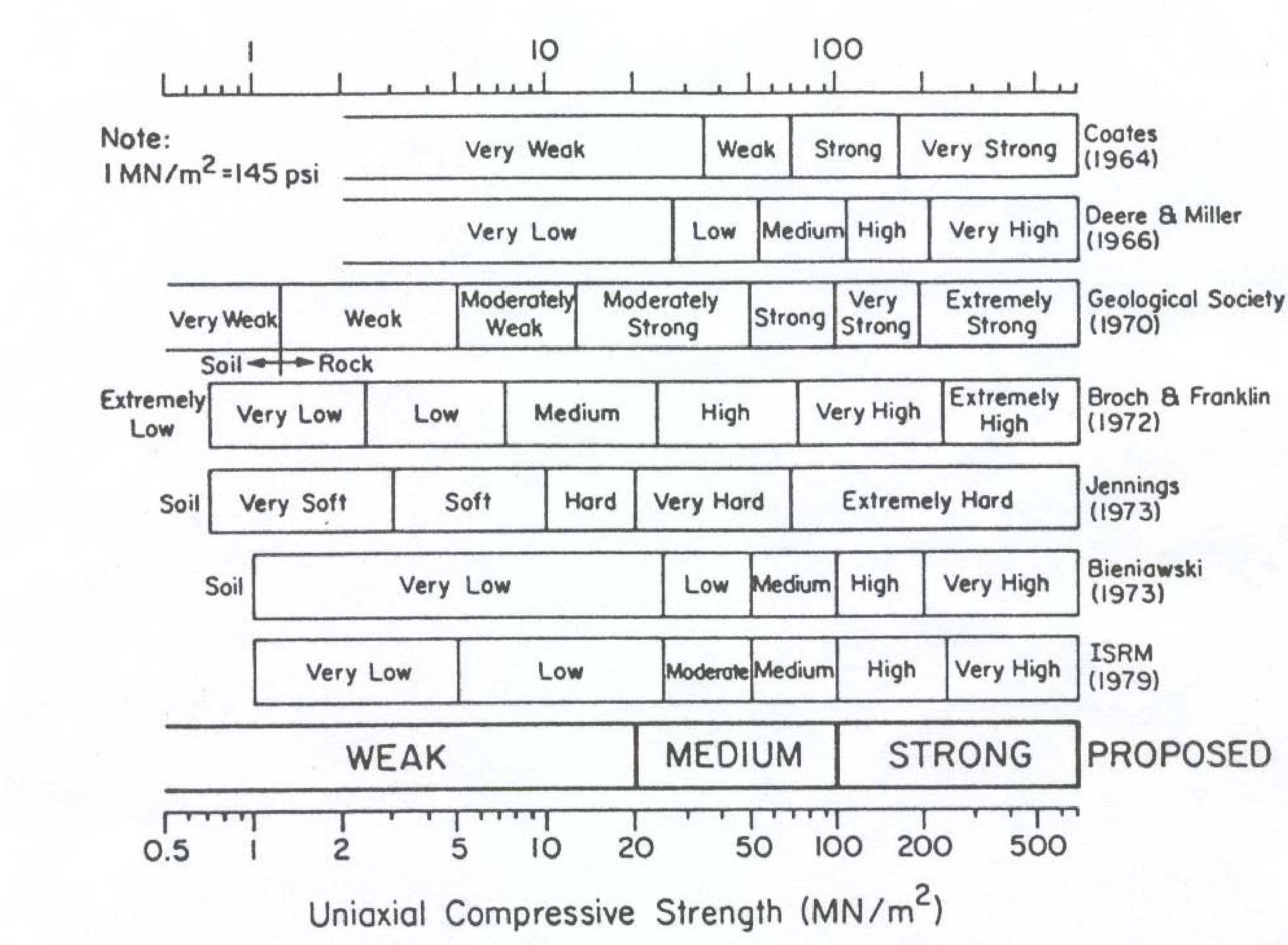
  ISRM commission's report

  Classification of Rock Material

  Based on Uniaxial Compressive Strength

Uniaxial Compressive Strength		Ranges for some Common Rock Material
Term	Kg/cm^2	Schist, Silt stone VW-W, Sand Stone, Lime stone –VW-M,Granite, Basalt, Gneiss, Quartzite, Marble –MS-VS
Very Weak- VW Weak- W Medium Strong-MS Strong- S Very Strong- VS	< 70 70-200 200-700 700-1400 > 1400	

Classification for Rock Material Strength



Intact Rock Classification

- Rock Type
- Geologic Formation and Age
- Indices:
  - Specific Gravity, Porosity, Unit Weight, Wave Velocities
  - Strength (compressive, tensile, shear)
  - Elastic Modulus

- **What is Rock Mechanics?**

Rock mechanics is a discipline that uses the principles of *mechanics* to describe the behaviour of *rock* of engineering scale.

- How to correlate the properties of rock studied in the laboratory with in-situ properties?
- What in-situ test methods will provide actual in-situ conditions and properties of rock?
- What design parameters are to be used for rock slope design?
- How to stabilize slopes and underground openings?