

Rock mass characterisation and site investigation for engineering design

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Course goals

Course Goals

- Recognize the importance of performing an adequate subsurface investigation.
- Plan and execute a subsurface exploration program for a typical geotechnical project.
- Use existing information in planning the investigation program.
- Apply appropriate in-situ testing procedures based upon the expected subsurface conditions and obtain high-quality soil and rock samples for laboratory testing.
- Assign appropriate laboratory testing procedures for determining soil and rock design parameters.
- Interpret the results of laboratory tests and determine soil and rock parameters to be used in design.
- Summarize results of subsurface investigation in a concise geotechnical investigation **report**.

Why perform a good quality subsurface exploration program?



Cost of Failure - Too High!



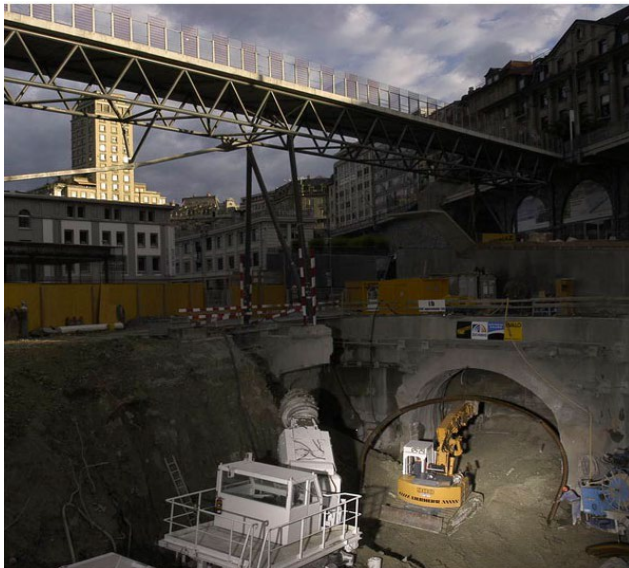
Cost of Failure - Too High!



Cost of Failure - Too High!



- Déterminer les conditions géologiques de surface
- Estimer les conditions géologiques en profondeur (par géophysique, fouille, forage)
- Minimiser le risque géologique sur l'ouvrage
- Estimer l'impact de l'ouvrage sur son environnement
- Suivi des travaux (conditions géologiques)
- etc.

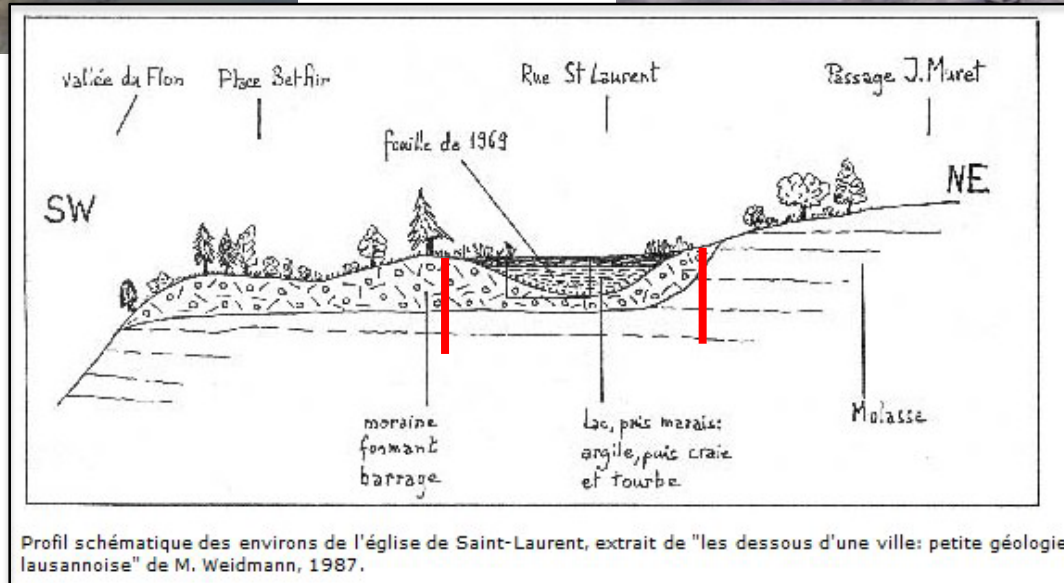


M2 à Lausanne.

Cost of Failure - Too High!

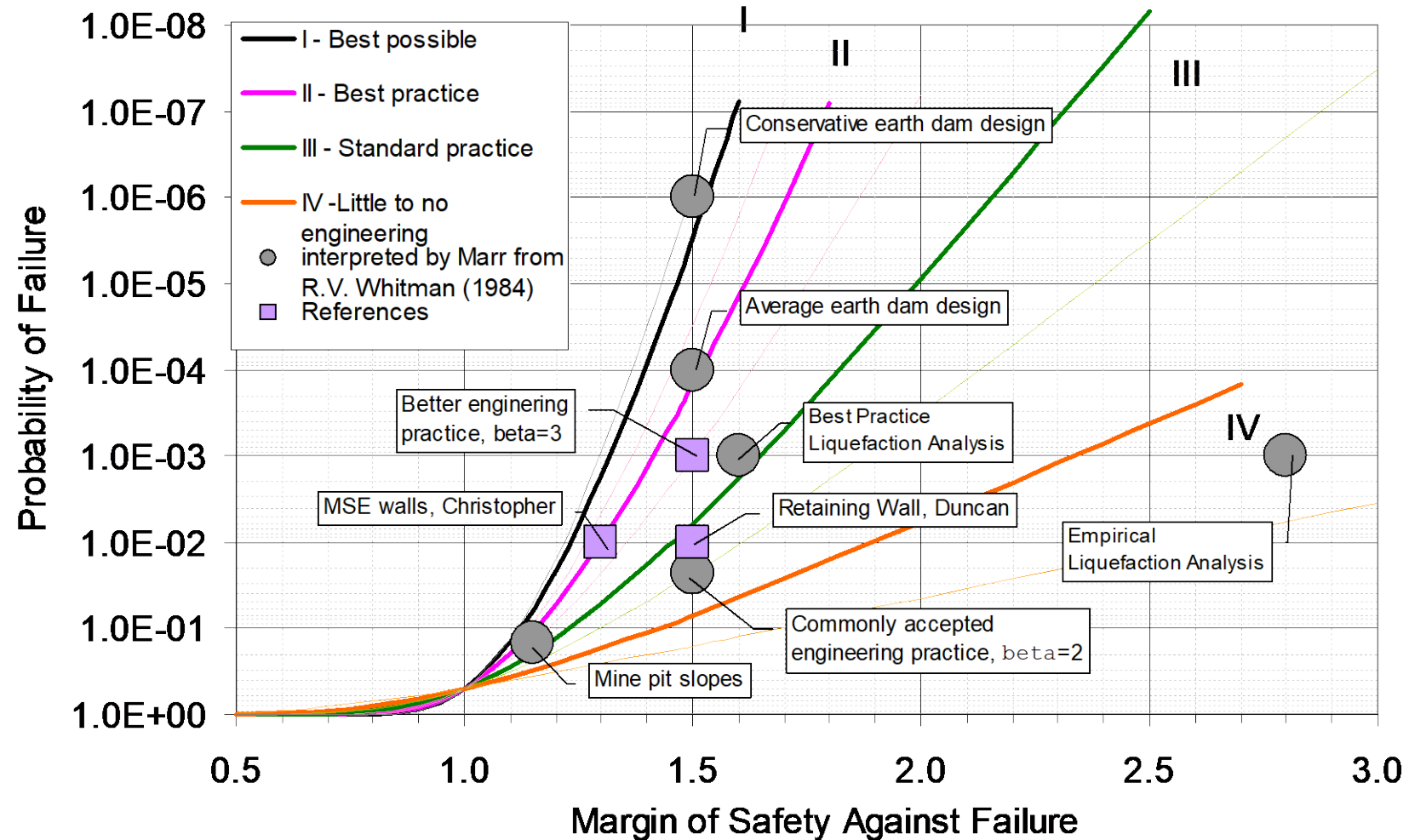


23 février 2005
Chantier du métro
M2 Place Saint-Laurent, Lausanne,
Suisse



Geotechnical Failures

based on original idea by Lambe, Marr and Silva



Why perform a good quality subsurface exploration program?

Cost of Over Design -
Too High as well!



Know what you're digging into and building on!

Identify and quantify ground conditions that may affect viability, design, and construction.

Objectives:

- Establish viability of the site in terms of its geological, geotechnical, and geoenvironmental conditions
- Establish which sites or corridors offer the most favourable conditions for development
- Identify any geological hazards and instability problems
- Determine geotechnical properties needed for structural design, construction, and environmental acceptability

Know what you're digging into and building on!

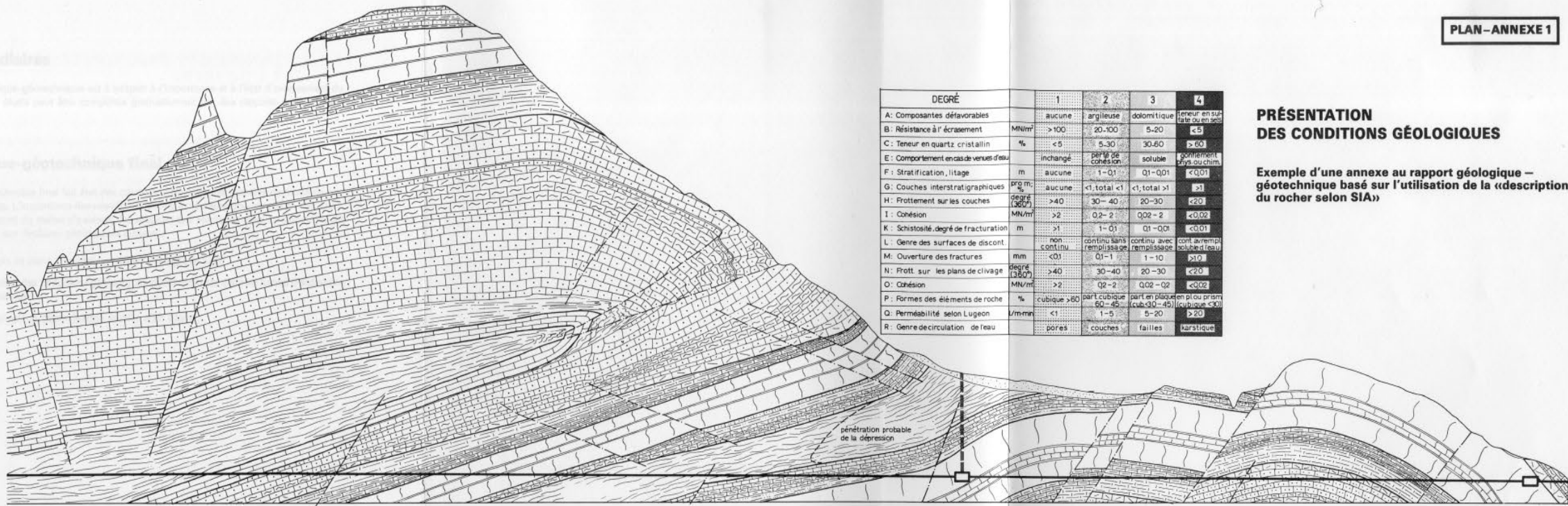
- Safety!
- Cost:
 - Up to 50% of the total cost of public works results from inadequate site investigation (González de Vallejo and Ferrer, 2011)
 - Poor site investigation leads to delays in at least a third of all projects (Tyrell et al., 1983)
 - Why? Inadequate planning and misinterpretation of data

Geological model

Rapport géotechnique

Exemple de rapport géotechnique géologique en 1 volume à l'annexe 1 (voir l'annexe 1 pour les détails de la couverture, les données et les schémas)

Rapport géotechnique géologique



DEGRÉ	1	2	3	4
A: Composantes défavorables	aucune	argileuse	dolomitique	teneur en sulfate ou en sel
B: Résistance à l'écrasement	MN/m ² >100	20-100	5-20	<5
C: Teneur en quartz cristallin	% <5	5-30	30-60	>60
E: Comportement en cas de venues d'eau	inchange	perte de cohésion	soluble	gonflement sous ou chim.
F: Stratification, litage	m aucune	1-01	01-001	<0,01
G: Couches interstratigraphiques	pro m aucune	<1, total <1	<1, total >1	>1
H: Frottement sur les couches	degré (360°) >40	30-40	20-30	<20
I: Cohésion	MN/m ² >2	0,2-2	0,02-2	<0,02
K: Schistosité, degré de fracturation	m >1	1-01	01-001	<0,01
L: Genre des surfaces de discont.	non continu	continu sans remplissage	continu avec remplissage	cont. av rempl. soluble (eau)
M: Ouverture des fractures	mm <01	01-1	1-10	>10
N: Proft. sur les plans de clivage	degré (360°) >40	30-40	20-30	<20
O: Cohésion	MN/m ² >2	0,2-2	0,02-0,2	<0,02
P: Formes des éléments de roche	% cubique >60	part cubique 50-45	part en plaques (cub 30-45)	part en plaques (cub 30-45)
Q: Perméabilité selon Lugeon	l/mm <1	1-5	5-20	>20
R: Genre de circulation de l'eau	poros	couches	failles	karstique

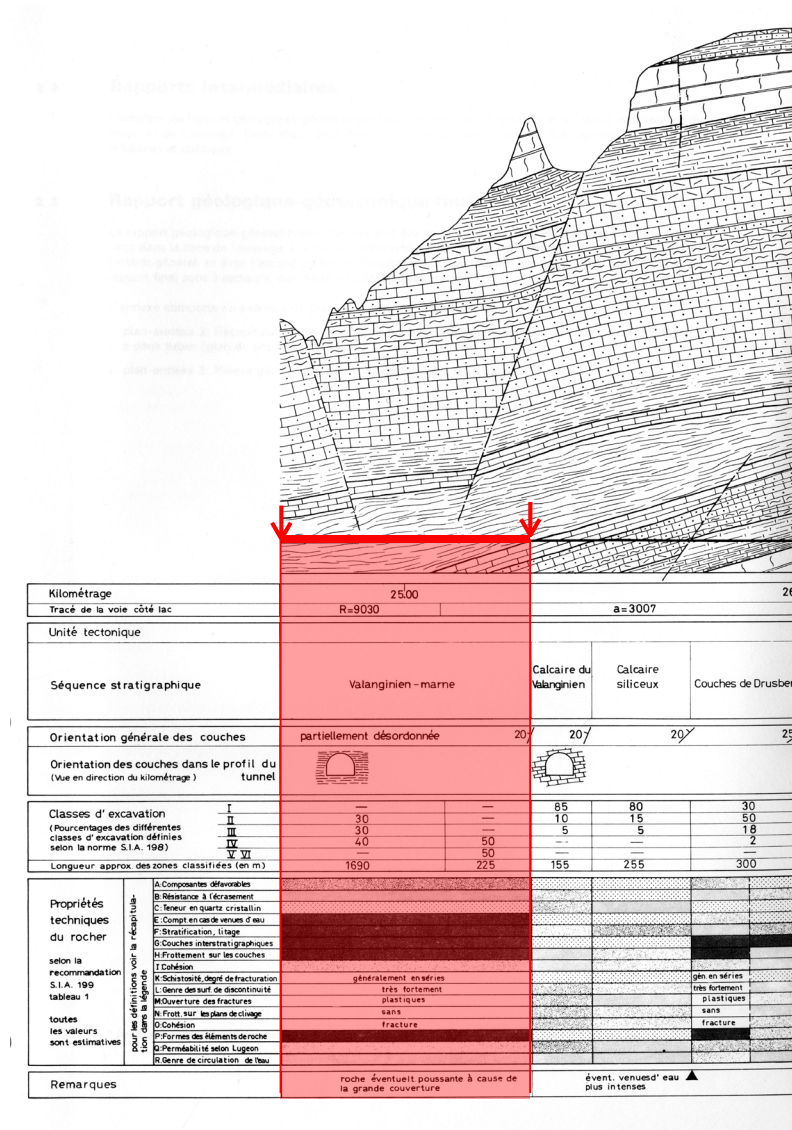
PRÉSENTATION
DES CONDITIONS GÉOLOGIQUES

Exemple d'une annexe au rapport géologique – géotechnique basé sur l'utilisation de la «description du rocher selon SIA»

Kilométrage		2500		2600		2700		2800		2900		29.66																	
Tracé de la voie côté lac		R=9030		a=3007		ligne droite		a=1011		R=2030		a=1011		ligne droite		a=484		R=750											
Unité tectonique		Couverture de Drusberg																											
Séquence stratigraphique		Valanginien - marne		Calcaire du Valanginien		Calcaire siliceux		Couches de Drusberg		'Schrattenkalk'		Calcaire de Gault et Seewer		Marne d' Amden		Calcaire de Gault et Seewer		'Schrattenkalk'		Couches de Drusberg		Calcaire siliceux		Couches de Drusberg		'Schrattenkalk'		Gault	
Orientation générale des couches		partiellement désordonnée		20/		20/		20/		25/		40/		40/		30/		25/		10/		20/		30/		45/		60/75/	
Orientation des couches dans le profil du tunnel (Vue en direction du kilométrage)																													
Classes d' excavation		I		—		—		85		80		30		85		65		—		85		30		80		50			
(Pourcentages des différentes classes d' excavation définies selon la norme S.I.A. 198)		II		30		—		10		15		50		10		25		30		25		10		45		10		40	
		III		30		—		5		5		18		5		10		30		10		5		23		5		10	
		IV		40		—		50		—		2		—		—		50		—		—		2		—		—	
		V		—		50		—		—		—		—		—		50		—		—		—		—		—	
Longueur approx. des zones classifiées (en m)		1690		225		155		255		300		375		80		375		200		460		575		455		500		85	
Propriétés techniques du rocher		A Composantes défavorables																											
		B Résistance à l'écrasement																											
		C Teneur en quartz cristallin																											
		E Compt en cas de venues d' eau																											
		F Stratification, litage																											
		G Couches interstratigraphiques																											
		H Frottement sur les couches																											
		I Cohésion																											
		K Schistosité, degré de fracturation		généralement en séries																									
		L Genre des surf. de discontinuité																											
		M Ouverture des fractures																											
		N Frott. sur les plans de clivage																											
		O Cohésion																											
		P Formes des éléments de roche																											
		Q Perméabilité selon Lugeon																											
		R Genre de circulation de l' eau																											
Remarques		roche éventuelit poussante à cause de la grande couverture		évent. venues d' eau plus intenses ▲		possibilité de rencontrer des cavités remplies d' eau et de matières désagrégées		▲ évent. surface de contact avec venues d' eau plus intenses		possibilité de rencontrer des cavités remplies d' eau et de matières désagrégées		▲ évent. venues d' eau plus intenses		évent. venues d' eau ▲		possibilité de rencontrer des cavités remplies d' eau et de matières désagrégées													

Rock mass characterization

- Location data
(measurement)
- Geological data (tectonic
unit, lithostratigraphy)
- Structural data (dip, dip
direction)
- Excavation classes
(stability of the structure)
- Technical properties of the
rock

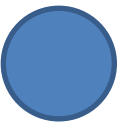


Rock mass characterization

Kilométrage		25.00		26.00		
Tracé de la voie côté lac		R=9030		a=3007		
Unité tectonique						
Séquence stratigraphique		Valanginien - marne		Calcaire du Valanginien	Calcaire siliceux	Couches de Drusberg
Orientation générale des couches		partiellement désordonnée		20/	20/	20/ 25/
Orientation des couches dans le profil du tunnel (Vue en direction du kilométrage)						
Classes d'excavation		I	—	85	80	30
(Pourcentages des différentes classes d'excavation définies selon la norme S.I.A. 198)		II	30	10	15	50
		III	30	5	5	18
		IV	40	—	—	2
		V VI	—	—	—	—
Longueur approx. des zones classifiées (en m)		1690	225	155	255	300
Propriétés techniques du rocher selon la recommandation S.I.A. 199 tableau 1 toutes les valeurs sont estimatives	pour les définitions voir la récapitulation dans la légende	A: Composantes défavorables				
		B: Résistance à l'écrasement				
		C: Teneur en quartz cristallin				
		E: Compt. en cas de venues d'eau				
		F: Stratification, litage				
		G: Couches interstratigraphiques				
		H: Frottement sur les couches				
		I Cohésion				
		K: Schistosité, degré de fracturation	généralement en séries			gén. en séries
		L: Genre des surf. de discontinuité	très fortement			très fortement
		M: Ouverture des fractures	plastiques			plastiques
		N: Frott. sur les plans de clivage	sans			sans
		O: Cohésion	fracture			fracture
		P: Formes des éléments de roche				
		Q: Perméabilité selon Lugeon				
		R: Genre de circulation de l'eau				
Remarques		roche éventuel. poussante à cause de la grande couverture		évent. venues d'eau plus intenses ▲		

How, what and when?

How?



- No general rules: case by case!.
- But considering: Information from previous studies.
- The design of the structure (e.g. depth of foundations).
- Forces exerted on the terrain.
- Local and regional geological information (considering risks, expansive soils, karstic areas).
- Groundwater table level.
- Site access and geographical characteristics.
- Construction methods.

Site Investigation



What?

Description of the Rock (SIA - SN 531 199)

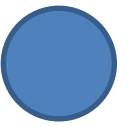
4 property groups and 4 intensity levels:

- Rock:** unfavorable components, compressive strength, quartz content, drillability for a tunnel boring machine, behavior in case of water ingress and humidity
- Stratigraphic discontinuities of the rock mass:** stratification/lamination, clay/mica interlayers, friction on layers (sliding friction), cohesion (in case of sliding)
- Tectonic discontinuities of the rock mass:** schistosity (distance between discontinuities)/fracturing degree, nature of the discontinuity surface, fracture openings, friction on cleavage planes (sliding friction), cohesion (in case of sliding), shapes of rock elements
- Water circulation:** permeability according to Lugeon, type of water circulation

What?

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E: Comportement en cas de venues d'eau		inchangé	perte de cohésion	soluble	gonflement phys. ou chim.
F: Stratification, litage	m	aucune	1-0,1	0,1-0,01	< 0,01
G: Couches interstratigraphiques	pro m; %	aucune	<1; total <1	<1; total >1	>1
H: Frottement sur les couches	degré (360°)	> 40	30-40	20-30	< 20
I: Cohésion	MN/m ²	> 2	0,2-2	0,02-2	< 0,02
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O: Cohésion	MN/m ²	> 2	0,2-2	0,02-0,2	< 0,02
P: Formes des éléments de roche	%	cubique > 60	part. cubique 60-45	part. en plaque (cub. < 30-45)	en pl. ou prism (cubique < 30)
Q: Perméabilité selon Lugeon	L/m-min	< 1	1-5	5-20	> 20
R: Genre de circulation de l'eau		pores	couches	failles	karstique

When?



During project definition:

- Geological risks
- Understanding of geotechnical conditions
- Geological factors that could affect project viability

Initial design

- Site selection
- Geo-mechanical classification of subsurface

Final design

- Detailed geo-mechanical properties
- Measurement of properties (e.g. stresses) useful for excavation or foundation design

Construction

- Site monitoring
- On-site design and solutions
- Soil-structure response

Control site surveillance

When should you do site investigations?

Table 5.1 AIMS OF SITE INVESTIGATION AND RELATED ENGINEERING GEOLOGICAL STUDIES

Project stage	Objectives
Preliminary studies	– Identification of geological hazards. – Preliminary assessment of geological-geotechnical conditions. – Identification of geological factors that may affect project viability.
Preliminary design	– Site selection. – Geomechanical classification of materials. – Preliminary geotechnical solutions.
Design	– Detailed geomechanical characterization. – Geomechanical parameters for design of excavations, foundations, etc.
Construction	– Monitoring and ground control. – On-site design and remedial measures.
Operation	– Ground-structure response control. – Monitoring.

Geological Engineering, González de Vallejo and Ferrer (2011)

What's involved?

Table 5.2 SITE INVESTIGATION PROCEDURES

Project stages	Main activities	Site investigations
Preliminary studies	Literature review and desk-based study	- Topography, relief and land use. - Hydrology and hydrogeology. - Regional geological maps. - Geological history. - Seismicity and other geological hazards.
	Aerial and remote sensing interpretation	- Aerial photographs and remote sensing. - Geomorphology. - Lithological and structural characterisation. - Geo-hazards. - Geological mapping.
	Walk-over survey and preliminary geological reconnaissance	- Identification of soils and rocks. - Faults and structures. - Hydrogeological data and drainage. - Geomorphology, slope stability, subsidence, collapses, flooding, land use, etc. - Geo-environmental problems. - Accesses and sites for borehole drilling, trial excavations and geophysical surveys.
Preliminary design	Engineering geological mapping (scales 1:5,000–1:10,000)	- Lithostratigraphy and structure. - Geomorphology and Hydrogeology. - Classification and properties of materials.
	Hydrological and hydrogeological data	- Identification of karstic areas and areas susceptible to flooding and runoff. - Regional and local hydrological data.
	Basic site investigations ⁽¹⁾	- Boreholes and trial excavations. - Geophysical prospecting. - Laboratory tests.
Design	Detailed site investigations ⁽²⁾	- Boreholes <i>In situ</i> and laboratory testing.
	Detailed geotechnical mapping (scales 1:500–1:2,000)	- Detailed geological-geotechnical mapping. - Geomechanical properties, classification and zoning.
Construction	Geotechnical validation	- Detailed geotechnical mapping. - Stability of excavations and tunnels. - Ground control and improvements. - Foundations and ground reinforcement work.
	Ground structure monitoring and control	- Monitoring equipment installation and instrumental readings. <i>In situ</i> testing. - Quality control.
Operation	Monitoring	Ground-structure behaviour monitoring.

⁽¹⁾ Basic investigations refer mainly to exploratory investigations and identification tests.

⁽²⁾ Detailed investigation involves intrusive investigations for each structure and for the whole area affected by the project, followed by *in situ* and laboratory testing.

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Preliminary studies:

- Literature review and “desk-based” study
 - What’s already been done?
- Aerial and remote sensing interpretation
 - What aerial and satellite information exist?
- Walk-over survey
 - Geomorphology, slope stability, subsidence, collapses, flooding, land use, etc.
 - Environmental concerns
 - Suitability for geophysics and borehole investigations
- Preliminary geological reconnaissance
 - Rock/soil identification
 - Discontinuities
 - Hydrogeological data

What's involved?

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Preliminary design:

- Engineering geological mapping
 - Detailed lithostratigraphic and structural characterization
 - Geomorphology
 - **Material characterisation**
- Hydrological and hydrogeological data
 - Identify areas susceptible to flooding and runoff
 - Regional and local hydrological data
- Basic site investigation
 - Boreholes and trial excavations
 - Geophysics
 - **Laboratory characterisation**

What's involved?

Design:

- Detailed site investigation
 - Boreholes
 - ***In situ* and laboratory testing**
- Detailed geotechnical mapping
 - Geomechanical properties, classification and zoning

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Construction:

- Geotechnical validation
 - Stability of excavations and tunnels
 - Ground control and improvements
 - Foundations and ground reinforcement work
- Ground structure monitoring and control
 - Installation of monitoring equipment
 - Quality testing
 - *In situ* testing

What's involved?

Operation:

- Monitoring
 - Ground-structure behaviour

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	Walk-over survey and preliminary geological reconnaissance	— Identification of soils and rocks. — Faults and structures. — Hydrogeological data and drainage. — Geomorphology, slope stability, subsidence, collapses, flooding, land use, etc. — Geo-environmental problems. — Accesses and sites for borehole drilling, trial excavations and geophysical surveys.
Preliminary design	Engineering geological mapping (scales 1:5,000–1:10,000)	— Lithostratigraphy and structure. — Geomorphology and Hydrogeology. — Classification and properties of materials.
	Hydrological and hydrogeological data	— Identification of karstic areas and areas susceptible to flooding and runoff. — Regional and local hydrological data.
	Basic site investigations ⁽¹⁾	— Boreholes and trial excavations. — Geophysical prospecting. — Laboratory tests.
Design	Detailed site investigations ⁽²⁾	— Boreholes — <i>In situ</i> and laboratory testing.
	Detailed geotechnical mapping (scales 1:500–1:2,000)	— Detailed geological-geotechnical mapping. — Geomechanical properties, classification and zoning.
Construction	Geotechnical validation	— Detailed geotechnical mapping. — Stability of excavations and tunnels. — Ground control and improvements. — Foundations and ground reinforcement work.
	Ground structure monitoring and control	— Monitoring equipment installation and instrumental readings. — <i>In situ</i> testing. — Quality control.
Operation	Monitoring	— Ground-structure behaviour monitoring.

⁽¹⁾ Basic investigations refer mainly to exploratory investigations and identification tests.

⁽²⁾ Detailed investigation involves intrusive investigations for each structure and for the whole area affected by the project, followed by *in situ* and laboratory testing.

What's involved?

Table 5.2 SITE INVESTIGATION PROCEDURES

Project stages	Main activities	Site investigations
Preliminary studies	Literature review and desk-based study	- Topography, relief and land use. - Hydrology and hydrogeology. - Regional geological maps. - Geological history. - Seismicity and other geological hazards.
	Aerial and remote sensing interpretation	- Aerial photographs and remote sensing. - Geomorphology. - Lithological and structural characterisation. - Geo-hazards. - Geological mapping.
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⁽¹⁾ Basic investigations refer mainly to exploratory investigations and identification tests.
⁽²⁾ Detailed investigation involves intrusive investigations for each structure and for the whole area affected by the project, followed by *in situ* and laboratory testing.

What should you consider when planning site investigation?

- Aims of the project
- Structural loads acting on the ground
- Information already available (previous studies)
- Regional and local geological conditions
- Site access and physiographical characteristics
- Suitable site investigation methods
- Cost estimates and completion deadlines

Interpretation of Rock Properties

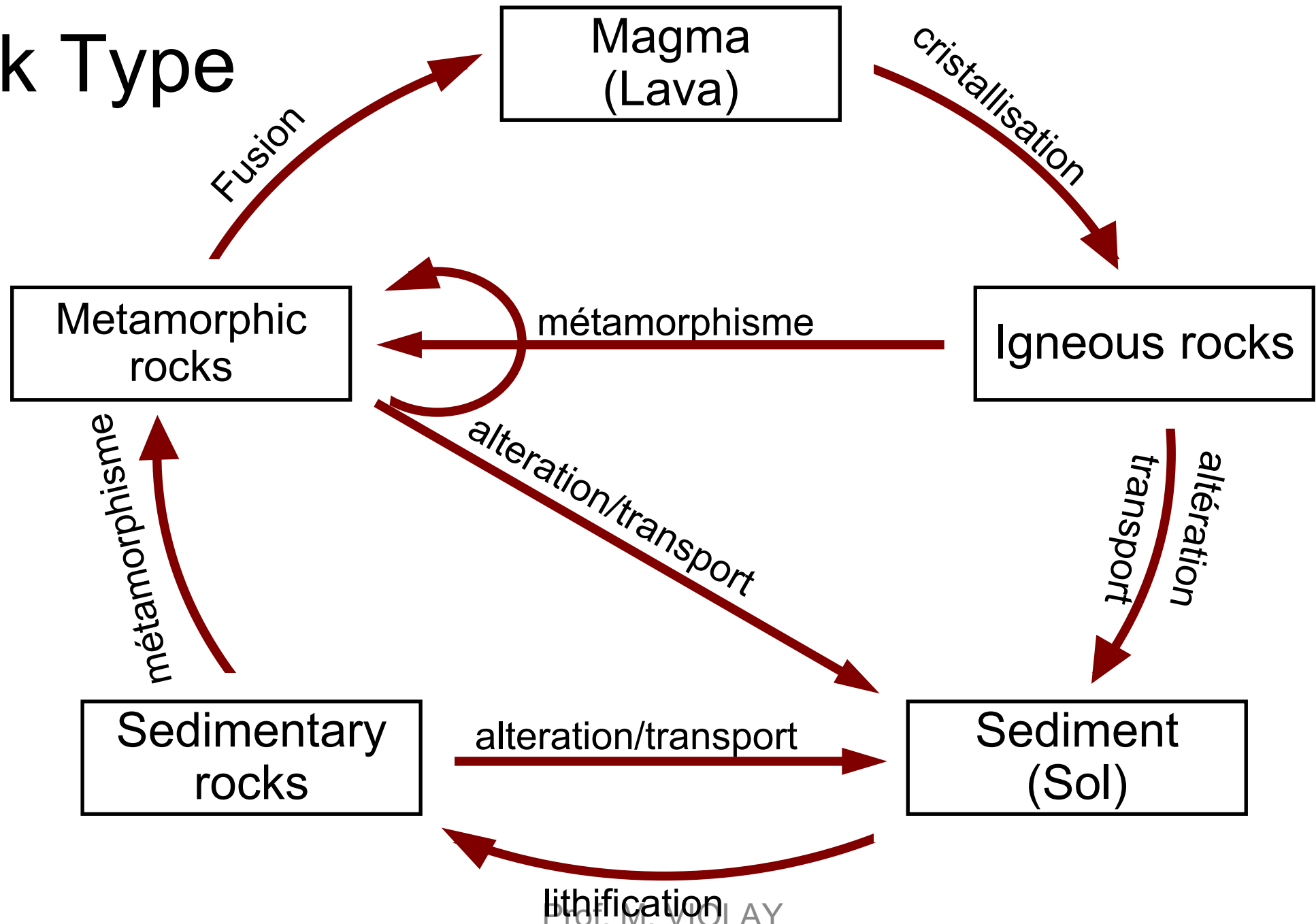
- **For, foundations, slopes, tunnels, and cuts:**
- **Two levels of rock classification:**
 - Intact Rock (origin, type, age, minerals)
 - Rock Mass (discontinuities, joints, fissures)
- **Combined lab and field test program**

Intact rock classification (recap)

Intact Rock Classification

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

Rock Type



ROCK FORMATION

Rocks are natural (solid) materials formed primarily or entirely by an assembly of minerals, sometimes containing fossils (sedimentary rocks), glass (volcanism, friction), or aggregates of other rocks.

The formation of rocks depends on three origins: igneous rocks, sedimentary rocks from the lithification of sediments, and metamorphic rocks from metamorphism, as illustrated by the rock cycle.

Minerals

Rocks are primarily composed of minerals.

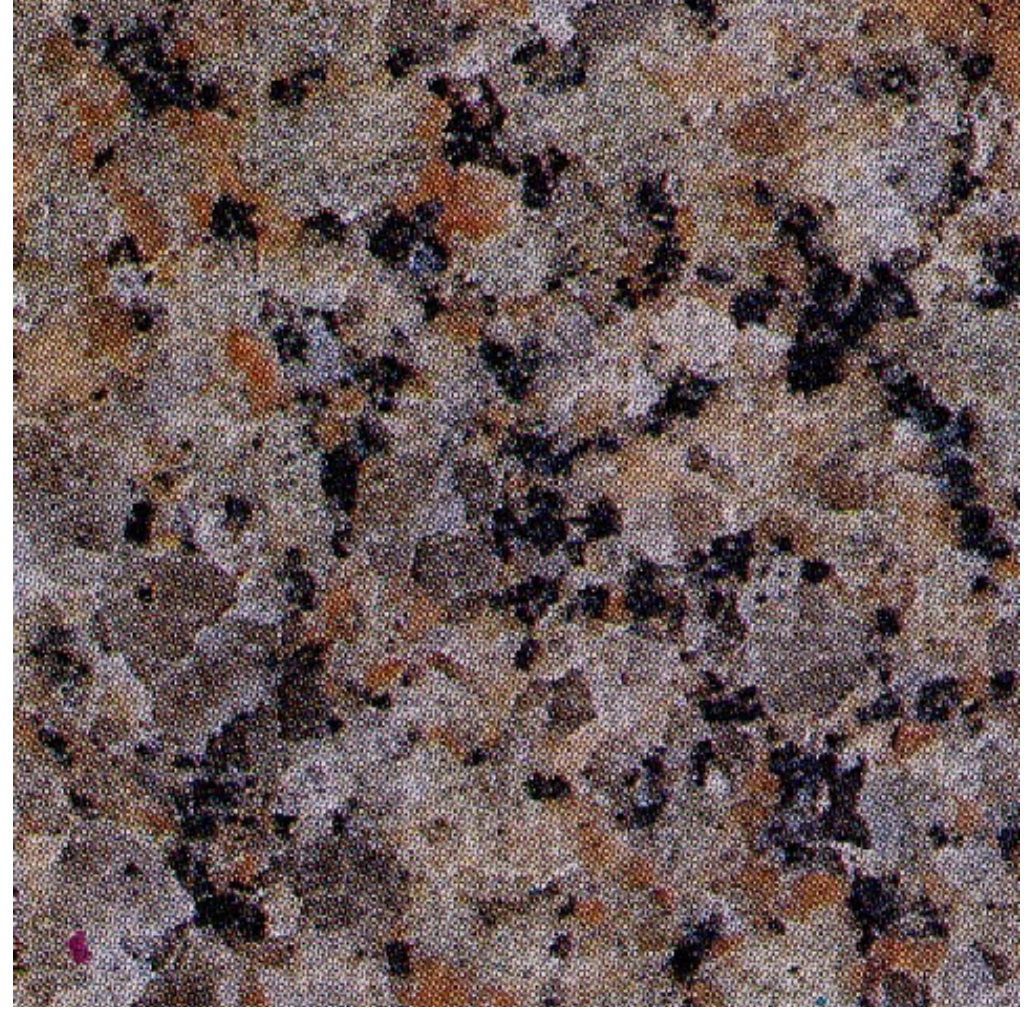
Silicates are important constituents of rocks: feldspars, quartz, olivine, pyroxene, amphibole, garnet, and mica.

Minerals have different properties; their crystalline structure, hardness, and cleavage influence the properties of the rock.

Rock formation



A well-developed quartz crystal



Quartz in a granite

Igneous rocks

Igneous rocks are formed when molten (or partially molten) rock cools and solidifies, with or without crystallization.

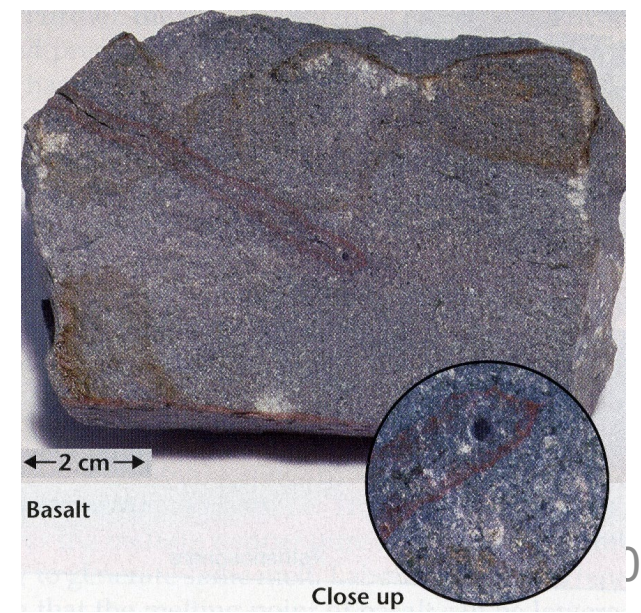
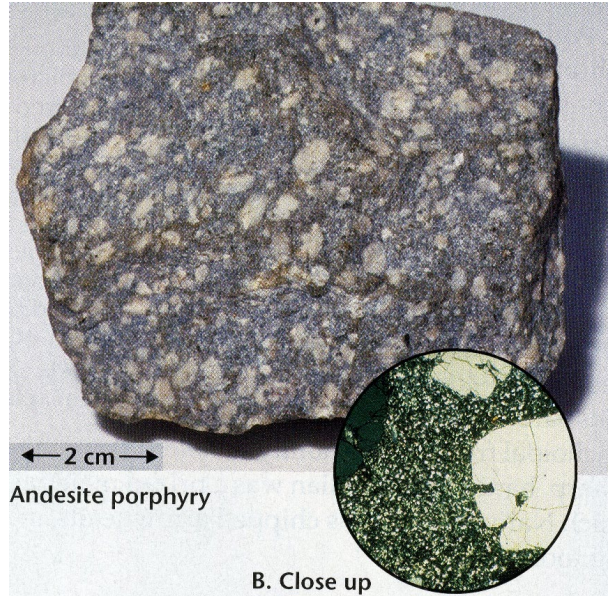
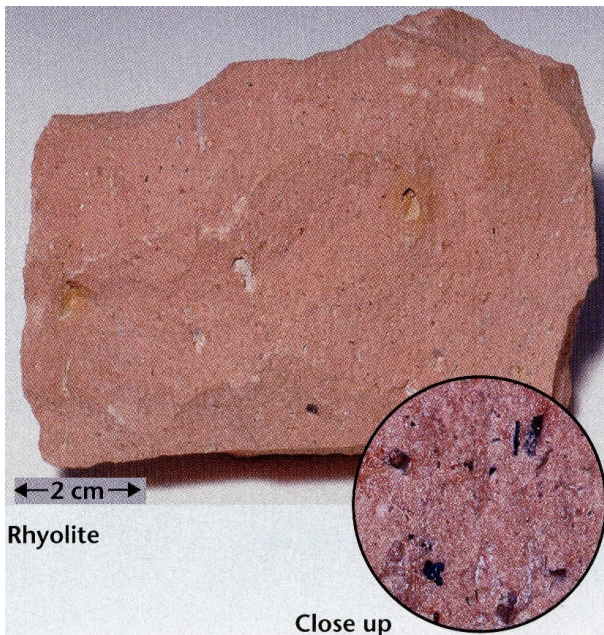
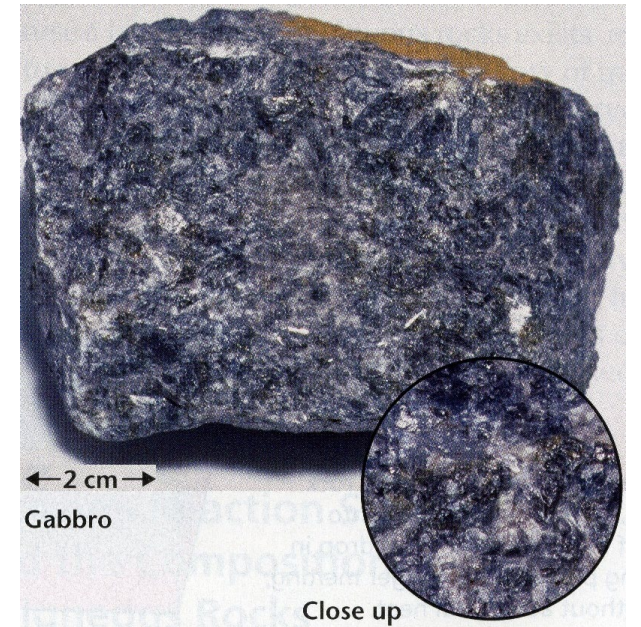
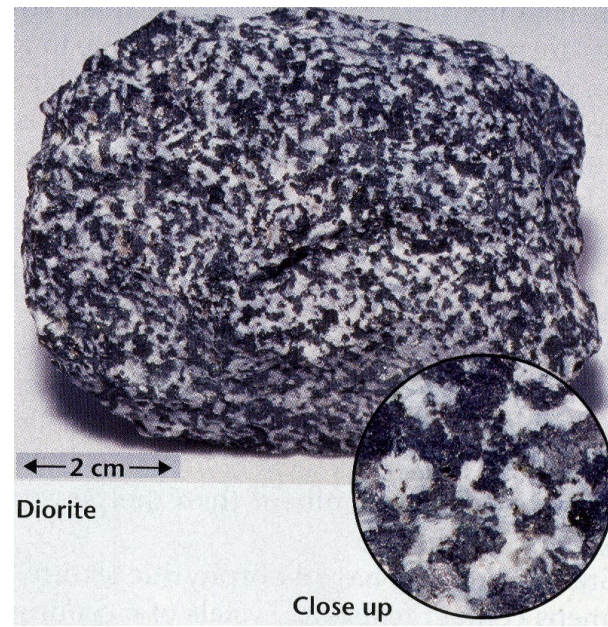
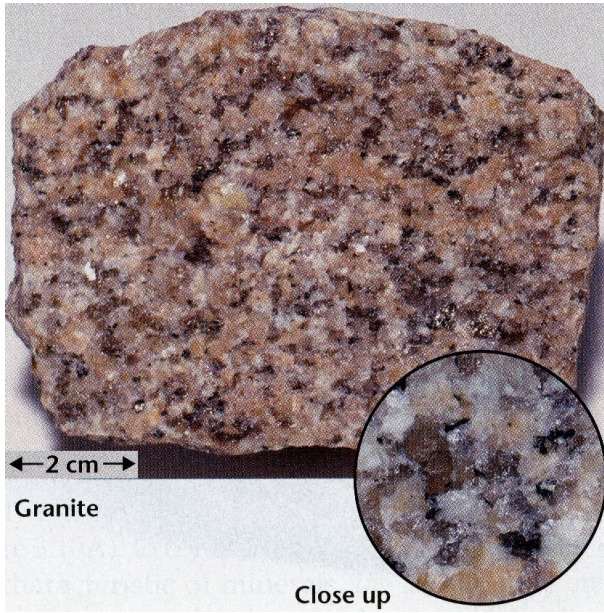
They can be formed

- In deep underground as intrusive (plutonic) rocks,
- At the surface as extrusive (volcanic) rocks.

Intrusive rocks typically have a coarse grain, while extrusive rocks have a fine grain.

They can also have different mineralogical arrangements.

	Granitique (acide)(felsique)	Andésitique (intermédiaire)	Basaltique (basique)(mafique)	Ultramafique (ultrabasique)
Intrusive (grain grossier)	Granite	Diorite	Gabbro	Péridotite
Extrusive (grain fin)	Rhyolite	Andésite	Basalte	Aucune
Pourcentage de silice	>65% de silice	50-65% de silice	40-50% de silice	<40% de silice
Composition minérale principale	Quartz Orthose N-Plagioclase	Amphibole Plagioclase Biotite	Ca-Plagioclase Pyroxène	Olivine Pyroxène
Composition minérale mineure	Muscovite Biotite Amphibole	Pyroxène	Olivine Amphibole	Ca-Plagioclase
Couleur	Claire	Foncée		



Sedimentary rocks

Sedimentary rocks are formed in three main ways:

- through the deposition of residues resulting from the weathering of other rocks (clastic sedimentary rocks);
- through deposition resulting from biogenic activity;
- And through the precipitation of a solution (evaporite).

Clastic sedimentary rocks are generally classified according to their grain size.

Sedimentary rocks

Detrital sedimentary rocks

SEDIMENTARY ROCK ANALYSIS AND CLASSIFICATION						
STEP 1: What is the rock's composition?		STEP 2: What are the rock's textural and other distinctive properties?			STEP 3: Rock Name(s)	
DETRITAL (CLASTIC)	Mainly rock fragments or mineral grains (quartz, feldspar, clay) weathered from other rocks	Mainly gravel (≥ 2 mm)		Rounded grains	CONGLOMERATE	
				Angular grains	BRECCIA	
		Mainly sand ($1/16 - 2$ mm)		Mostly quartz grains	QUARTZ SANDSTONE	SANDSTONE
				Mainly feldspar and quartz	ARKOSE	
				Sand is mixed with much silt and/or clay (mud)	GRAYWACKE	
		Mainly Mud ($< 1/16$ mm)	Mostly silt ($1/256 - 1/16$ mm)	Breaks into blocks or layers	SILTSTONE	MUDSTONE
			Mostly clay ($< 1/256$ mm)	Crumbles or breaks into blocks	CLAYSTONE	
				Fissile (splits easily)	SHALE	

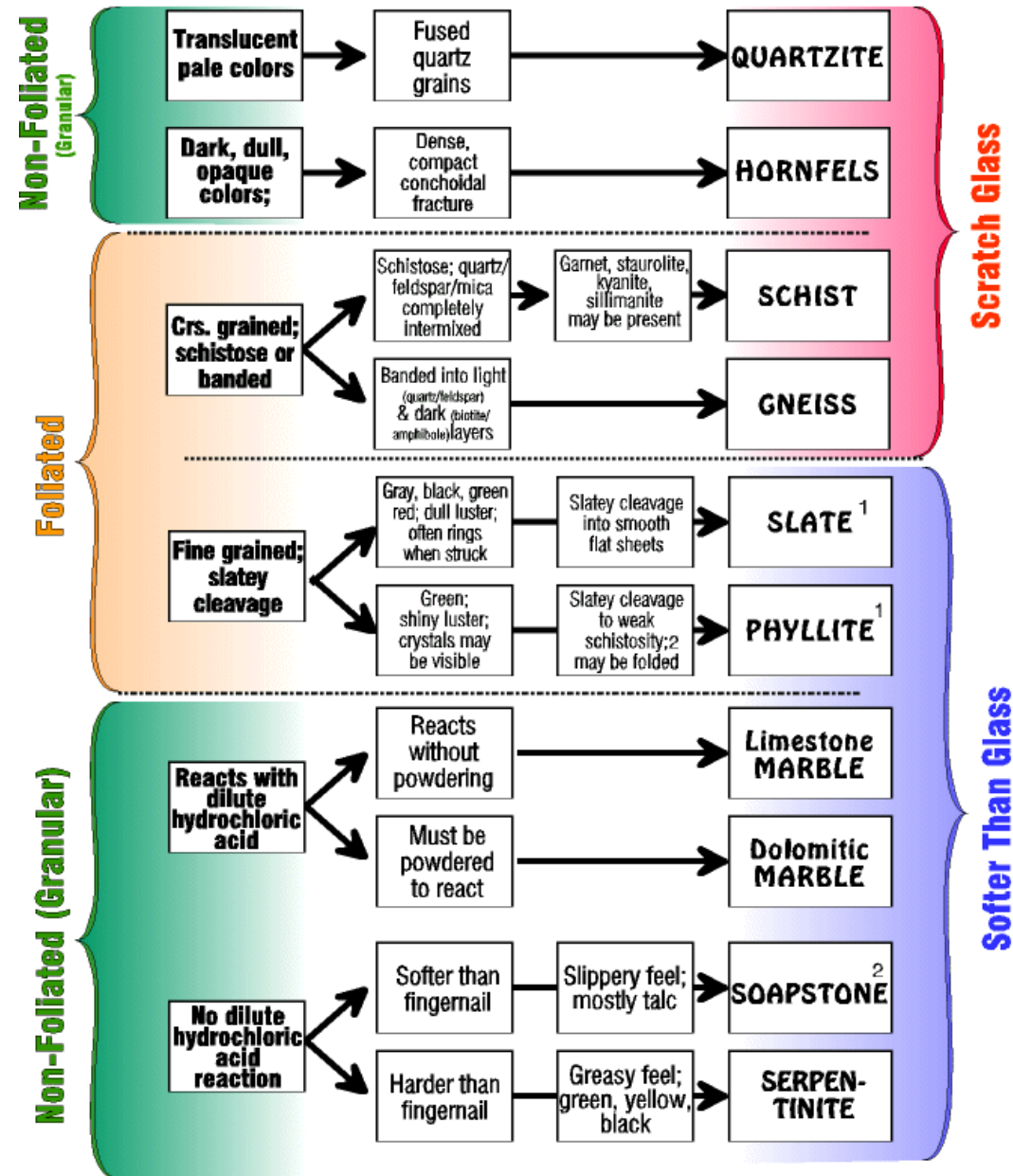
Metamorphic rocks

Metamorphic rock is a new rock transformed from an existing rock through metamorphism - changes due to heat and pressure (in the solid state).

Metamorphic rocks may have a layered structure or not. Foliation is due to the reorientation of certain minerals, creating a cleavage plane or a visible alignment of minerals.



Key to Common Metamorphic Rocks



¹ (Shale), slate, and phyllite complete intergrade with each other. Distinctions may be difficult.

² Soapstone may be weakly foliated.



Slate



Phyllite

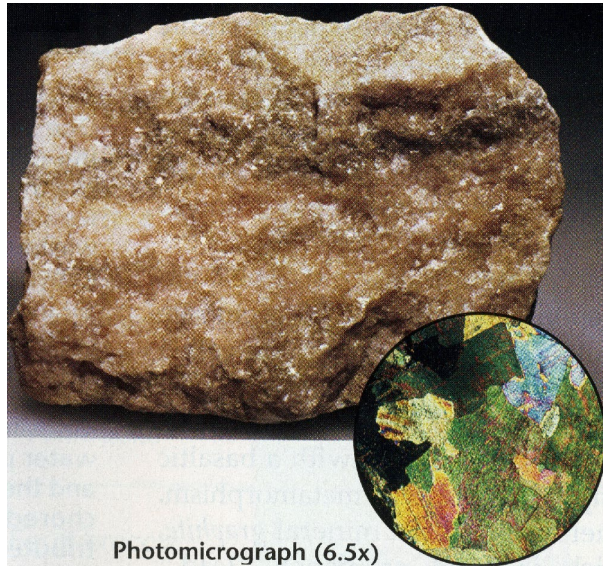


Schist

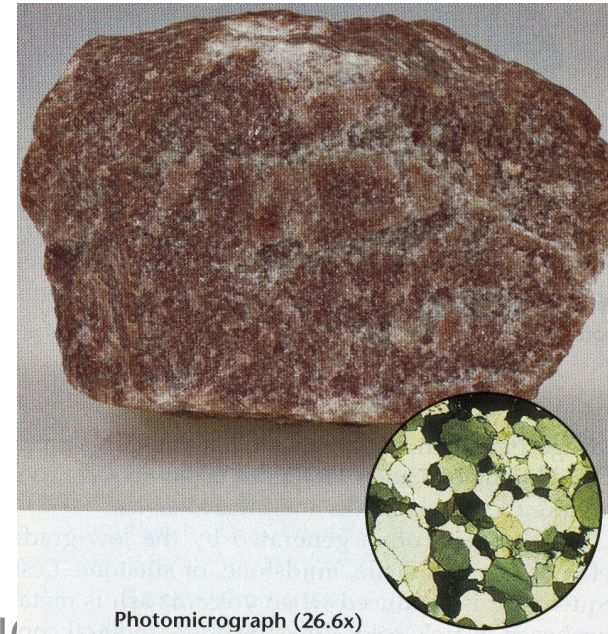


Gneiss

Low ————— High
metamorphism



Marbre



Quartzite

Rock texture

Sedimentary, igneous, and metamorphic rocks have different textures due to their different origins.

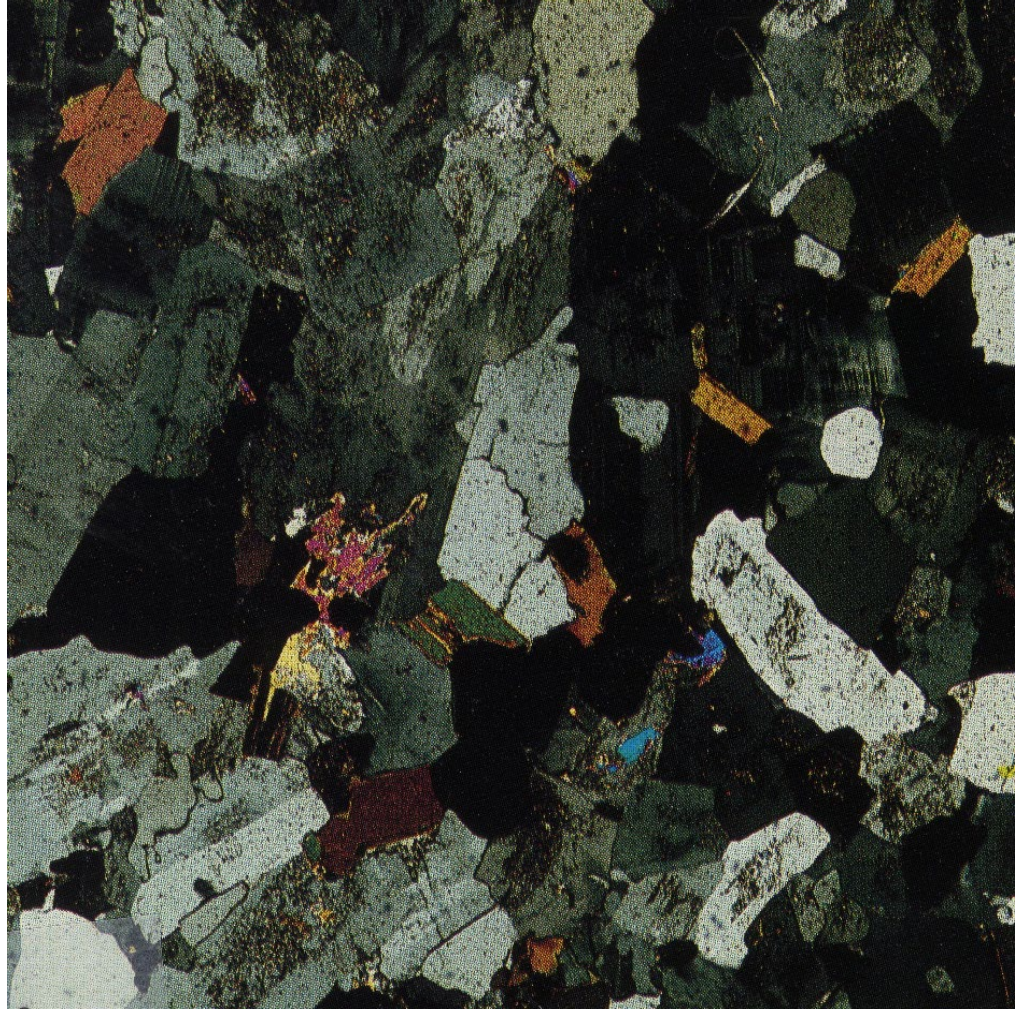
The two main forms of texture are clastic and foliated.

The rock's strength is a structural resistance of mineral composition.

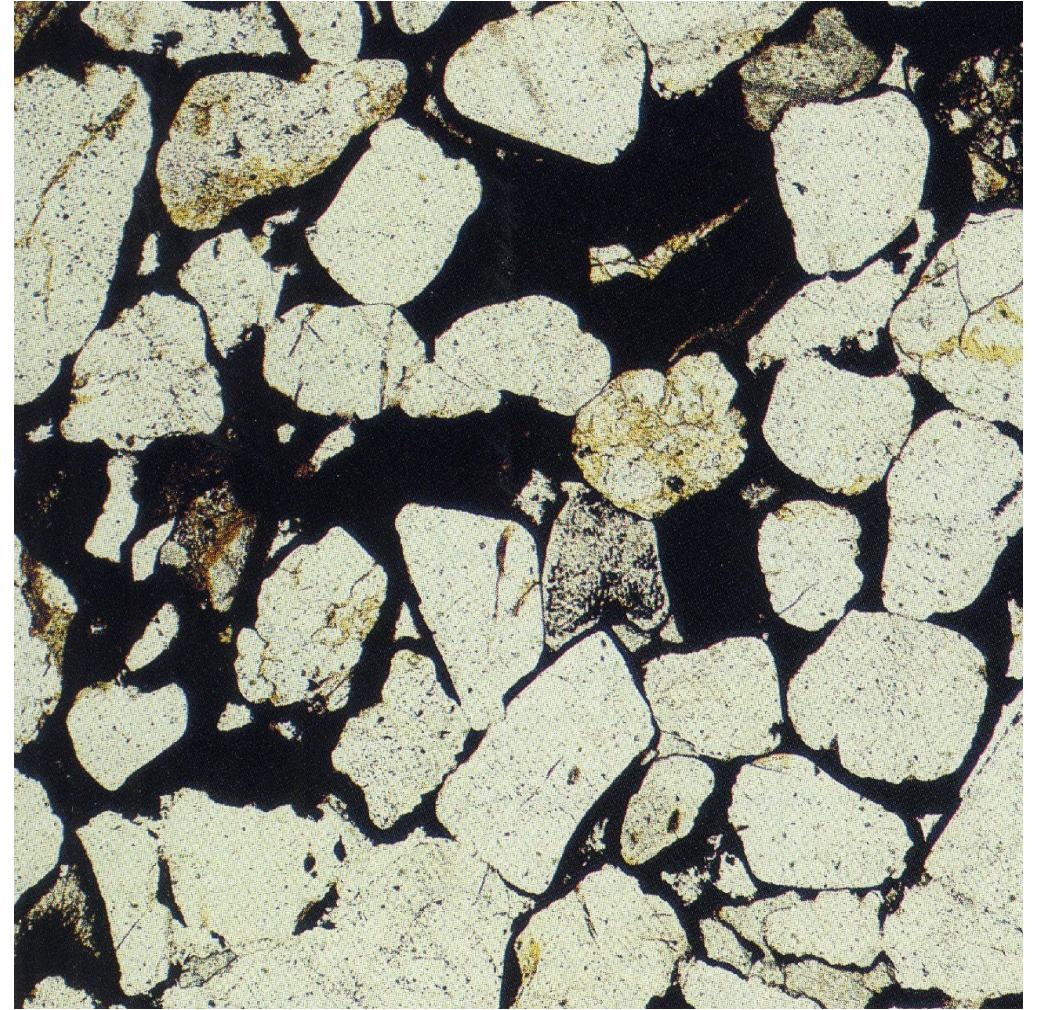
This is governed by:

- Mineral strength, and
- The bond between minerals.

Rock texture



Interlocking texture of a granite



Clastic texture of a sandstone

Rock texture

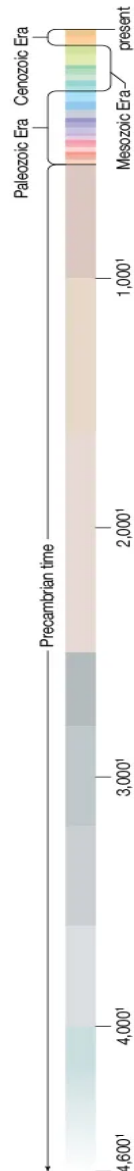
The interlocking microstructures of igneous and metamorphic rocks typically lead to high-strength rock material, while the microstructures of sedimentary rocks often result in low-strength rock material, especially when cementation is weak.

Any existing weaknesses in a rock material matrix (microfissures, pores, weak grains, and cementation) also weaken the rock material.

Primary grain aspect by Geologic Origin

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

Geologic Time Scale



Geologic time scale

Eonothem/ Eon	Erathem/ Era	System/ Period	Series/ Epoch	Stage/ Age	mya ¹
Phanerozoic	Cenozoic	Quaternary	Anthropocene ⁵ Holocene		1950 CE
				Upper	0.0117
			Pleistocene	Middle	0.126
				Calabrian	0.781
				Gelasian	1.80
		Neogene	Pliocene	Placenzian	2.58
				Zanclean	3.600
			Miocene	Messinian	5.833
				Tortonian	7.246
				Serravallian	11.63
		Paleogene	Oligocene	Langhian	13.82
				Burdigalian	15.97
				Aquitania	20.44
				Chattian	23.03
				Rupelian	27.82
			Eocene	Priabonian	33.9
				Bartonian	37.8
				Lutetian	41.2
			Paleocene	Ypresian	47.8
				Thanetian	56.0
	Mesozoic	Cretaceous	Upper	Selandian	59.2
				Danian	61.6
				Maastrichtian	66.0
				Campanian	72.1 ± 0.2
				Santonian	83.6 ± 0.2
			Lower	Coniacian	86.3 ± 0.5
				Turonian	89.8 ± 0.3
				Cenomanian	93.9
		Jurassic	Upper	Albian	100.5
				Aptian	113
				Barremian	125.0
			Lower	Hauterivian	129.4
				Valanginian	132.9
				Valanginian	139.8
				Berriasian	145.0

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¹ Millions of years ago.

² Both the Mississippian and Pennsylvanian time units are formally designated as subperiods within the Carboniferous Period.

³ Several Cambrian unit age boundaries are informal and are awaiting ratified definitions.

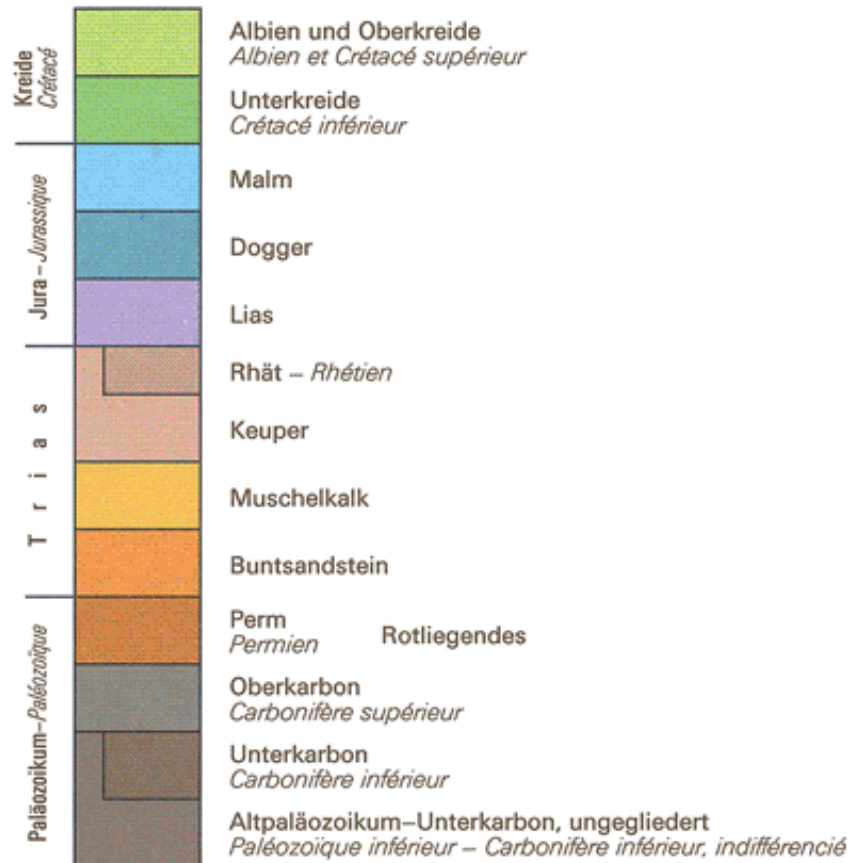
⁴ The Hadean Eon is an informal interval of geologic time.

⁵ The Anthropocene Epoch was declared a formal interval of geologic time by the Anthropocene Working Group (AWG), International Commission on Stratigraphy (ICS), in August 2016. The formalization of the interval still awaits confirmation by ICS and the greater International Union of Geological Sciences (IUGS).

Published with permission from the International Commission on Stratigraphy (ICS). International chronostratigraphic units, ranks, names, and formal status are approved by the ICS and ratified by the International Union of Geological Sciences (IUGS). Source: 2016 International Chronostratigraphic Chart produced by the ICS.

Geologic Time Scale

Ausseralpine paläozoische und mesozoische Sedimente *Sédiments paléozoïques et mésozoïques extra-alpins*



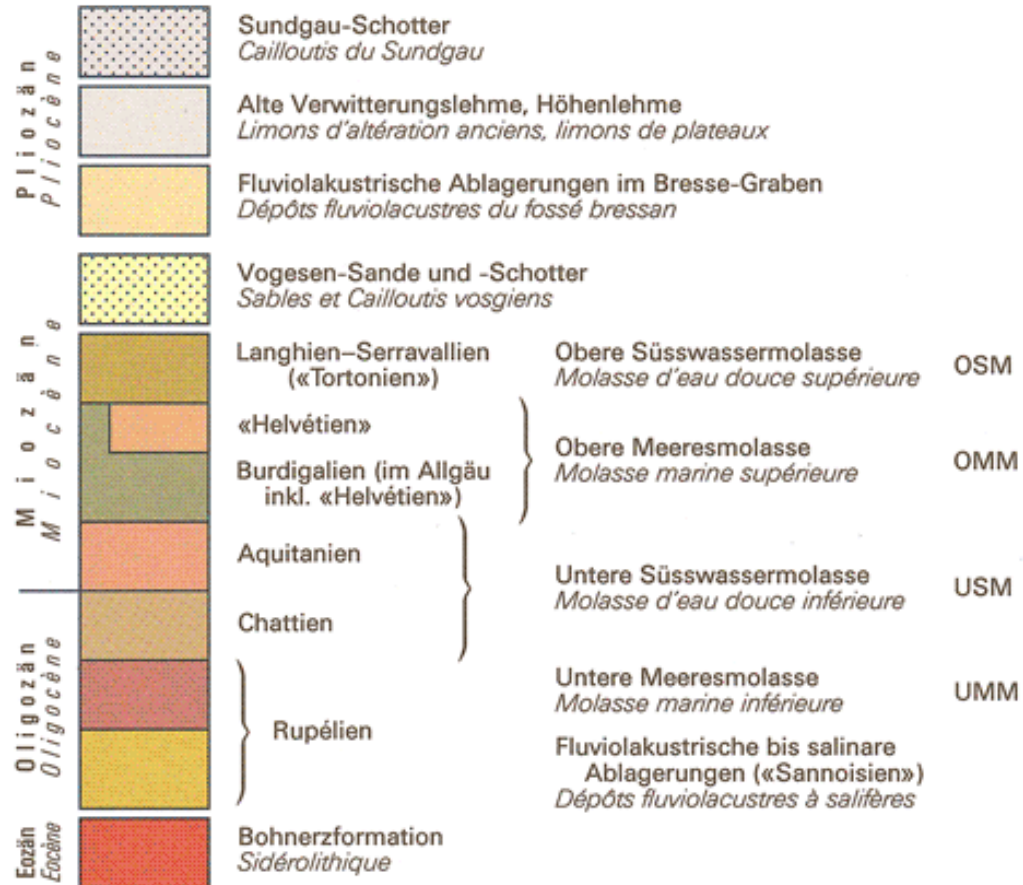
Color code of 'pre-Tertiary' geological formations.

Source: 1:500'000 (Swisstopo)

Geologic Time Scale

Ausseralpine tertiäre Sedimente *Sédiments tertiaires extra-alpins*

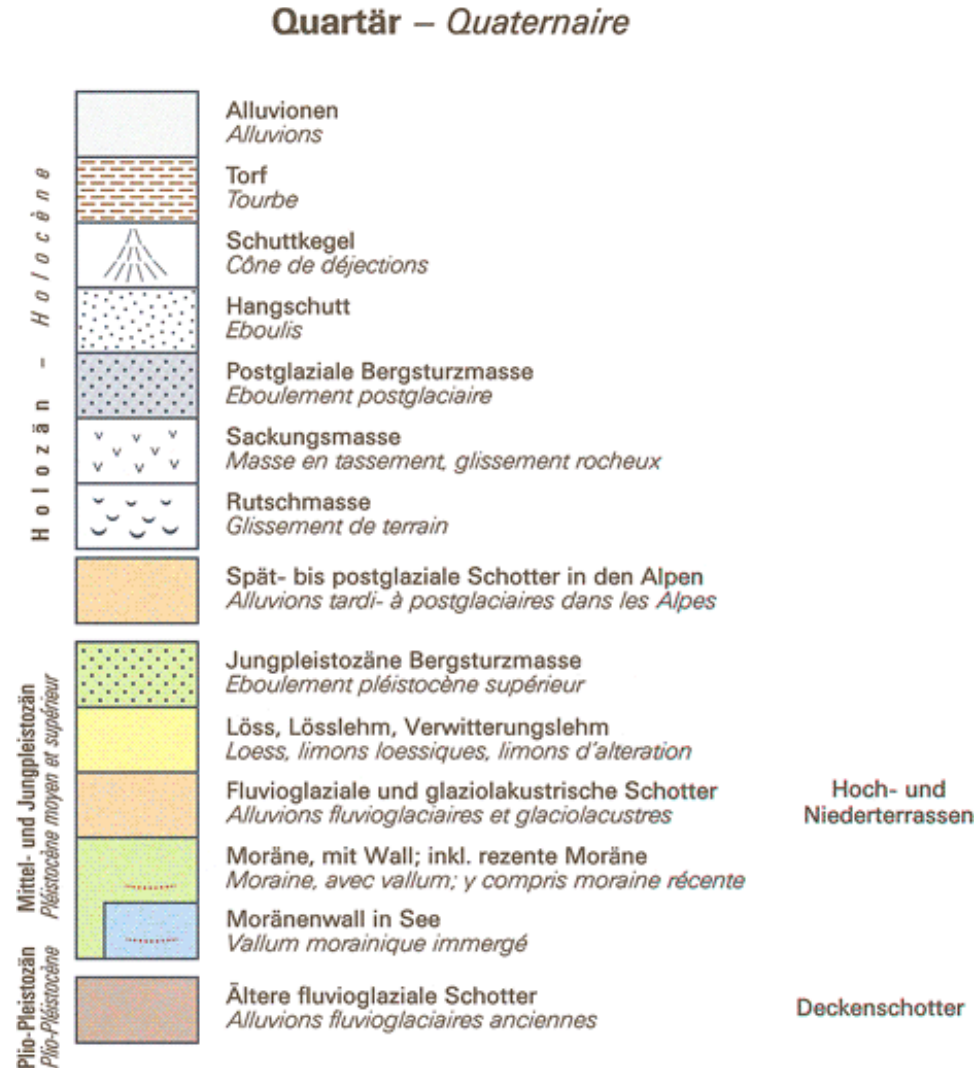
Nordalpines Vorland – Avant-pays nord-alpin



Color code and symbols of
Tertiary geological
formations

Source: 1:500'000 (Swisstopo)

Geologic Time Scale



Color code of pre-Tertiary geological formations.

Source: 1:500'000 (Swisstopo)

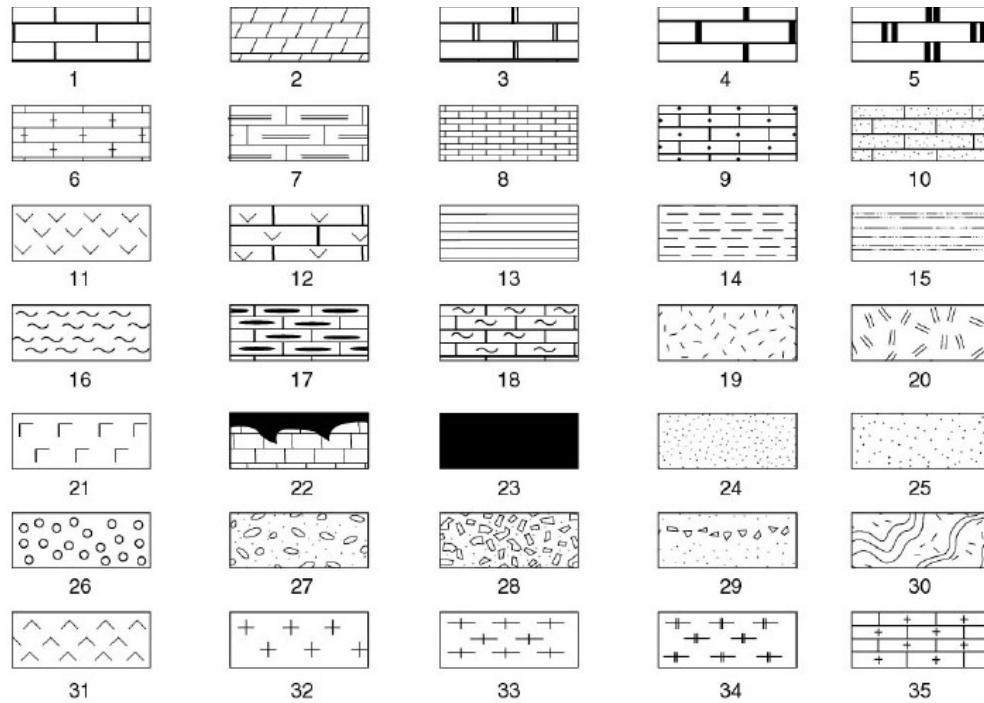
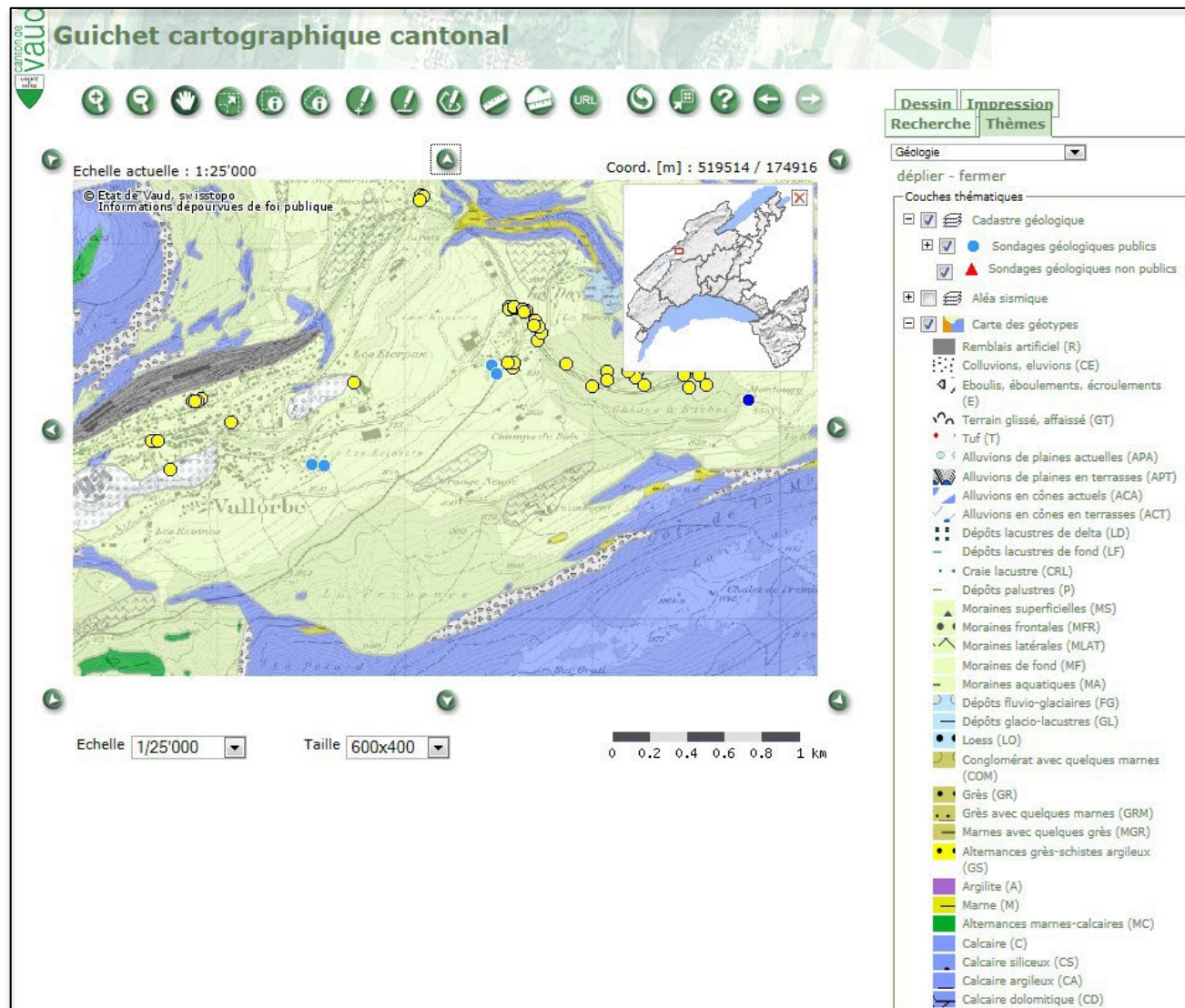


Figure 4

- 1 à 10 : calcaires (1 à 5, en bancs ; 6 : marneux ; 7 : à silex ; 8 : en plaquettes ; 9 : conglomératiques ; 10 : gréseux) ; 11 et 12 : dolomies et calcaires dolomitiques ;
- 13 à 18 : argiles et marnes (15 : sableuses ; 17, 18 : marno-calcaires) ; 19 et 20 : roches massives ;
- 21 : roches salines ; 22 : dépôts en poches ; 23 : couche de faible épaisseur ou épaisseur variable ;
- 24 à 29 : roches détritiques (24 : sables ; 25 : grès ; 26 et 27 : conglomérats ; 28 et 29 : brèches ;
- 30 : socle plissé ;
- 31 : roche éruptives basiques ; 32 : roches intrusives acides ;
- 33 à 35 : roches métamorphiques (33 et 34 : schistes cristallins ; 35 : calcaires métamorphiques).

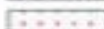
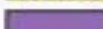
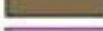
General symbols of rock geological formations on cross-sections.



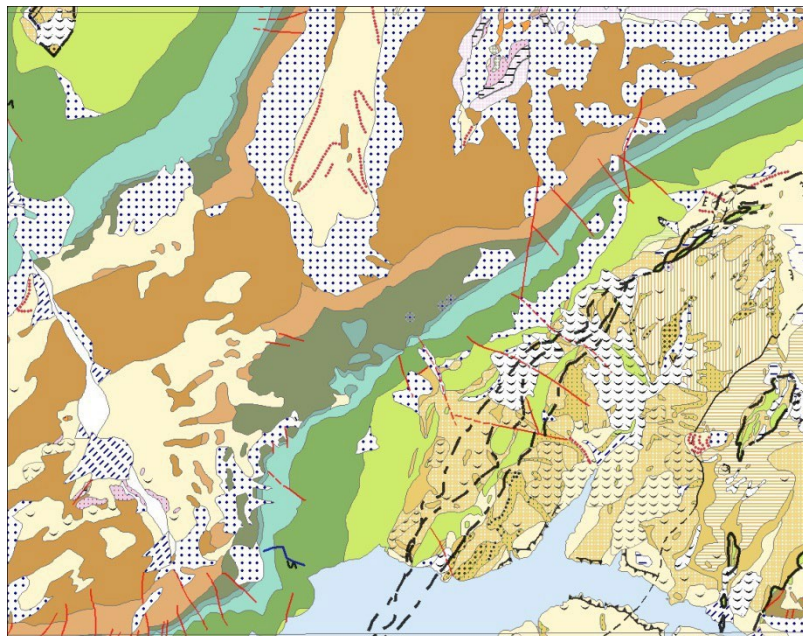
[http://www.geo.vd.ch
/theme/geologie_thm](http://www.geo.vd.ch/theme/geologie_thm)

Légende

Géotypes

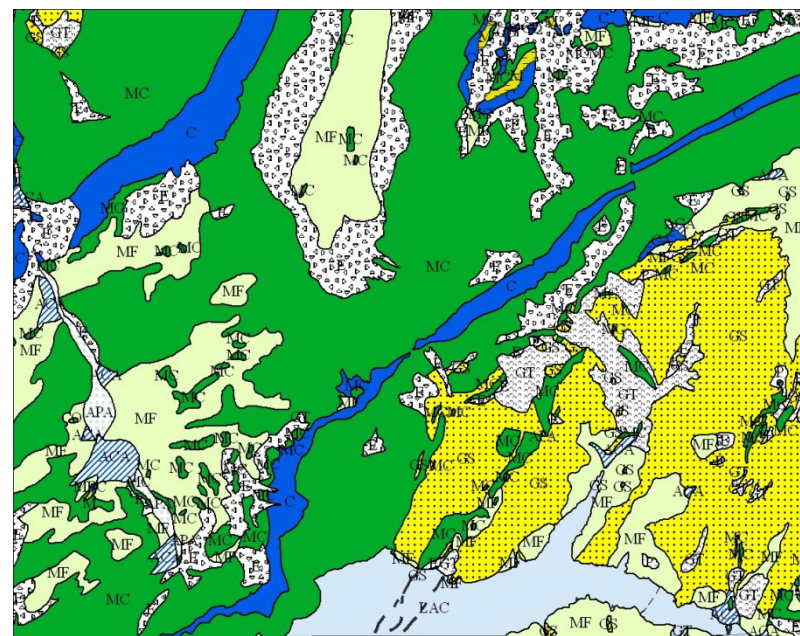
Code	Surface [%]		Surface [%]		
	Remblais artificiels (R)-----	0.6		Conglomérat avec quelques marnes (COM)-----	0.7
	Colluvions, eluvions (CE)-----	0.9		Grès (GR)-----	3.7
	Eboulis, éboulements, écroulements (E)-----	4.2		Grès avec quelques marnes (GRM)-----	3.3
	Terrain glissé, affaissé (GT)-----	2.0		Marnes avec quelques grès (MGR)-----	3.0
	Tuf (T)-----	0.1		Alternances grès-schistes argileux (GS)-----	2.0
	Alluvions de plaines actuelles (APA)-----	2.4		Argilite (A)-----	0.0
	Alluvions de plaines en terrasses (APT)-----	0.1		Marnes (M)-----	0.5
	Alluvions en cônes actuelles (ACA)-----	3.4		Alternances marnes-calcaires (MC)-----	2.6
	Alluvions en cônes en terrasses (ACT)-----	0.0		Calcaire (C)-----	16.9
	Dépôts lacustres de delta (LD)-----	1.0		Calcaire siliceux (CS)-----	0.4
	Dépôts lacustres de fond (LF)-----	0.7		Calcaire argileux (CA)-----	0.1
	Craie lacustre (CRL)-----	0.0		Calcaire dolomitique (CD)-----	0.1
	Dépôts palustres (P)-----	3.9		Dolomie (D)-----	0.0
	Moraines superficielles (MS)-----	0.1		Gypse (G)-----	0.2
	Moraines frontales (MFR)-----	1.9		Cornieule (CO)-----	0.1
	Moraines latérales (MLAT)-----	3.5		Anhydrite (AN)-----	0.0
	Moraines de fond (MF)-----	36.9		Roche salifère (RS)-----	0.0
	Moraines aquatiques (MA)-----	0.1		Quartzite (Q)-----	0.0
	Dépôts fluvio-glaciaires (FG)-----	1.9		Gneiss (GN)-----	0.1
	Dépôts glacio-lacustres (GL)-----	0.4		Granite (GA)-----	0.0
	Loess (LO)-----	0.0		Roche indéterminée (RO)-----	2.0

Autres (glacier, étang)----- 0.2



Extrait de la carte 1265 de l'Atlas géologique de la Suisse au 1:25'000 (légendes non indiquées)

Carte 1265 (Les Mosses)



Extrait de la carte nationale 1265

Carte 1265 (Les Mosses)

Carte des géotypes

Index Properties of Intact Rock

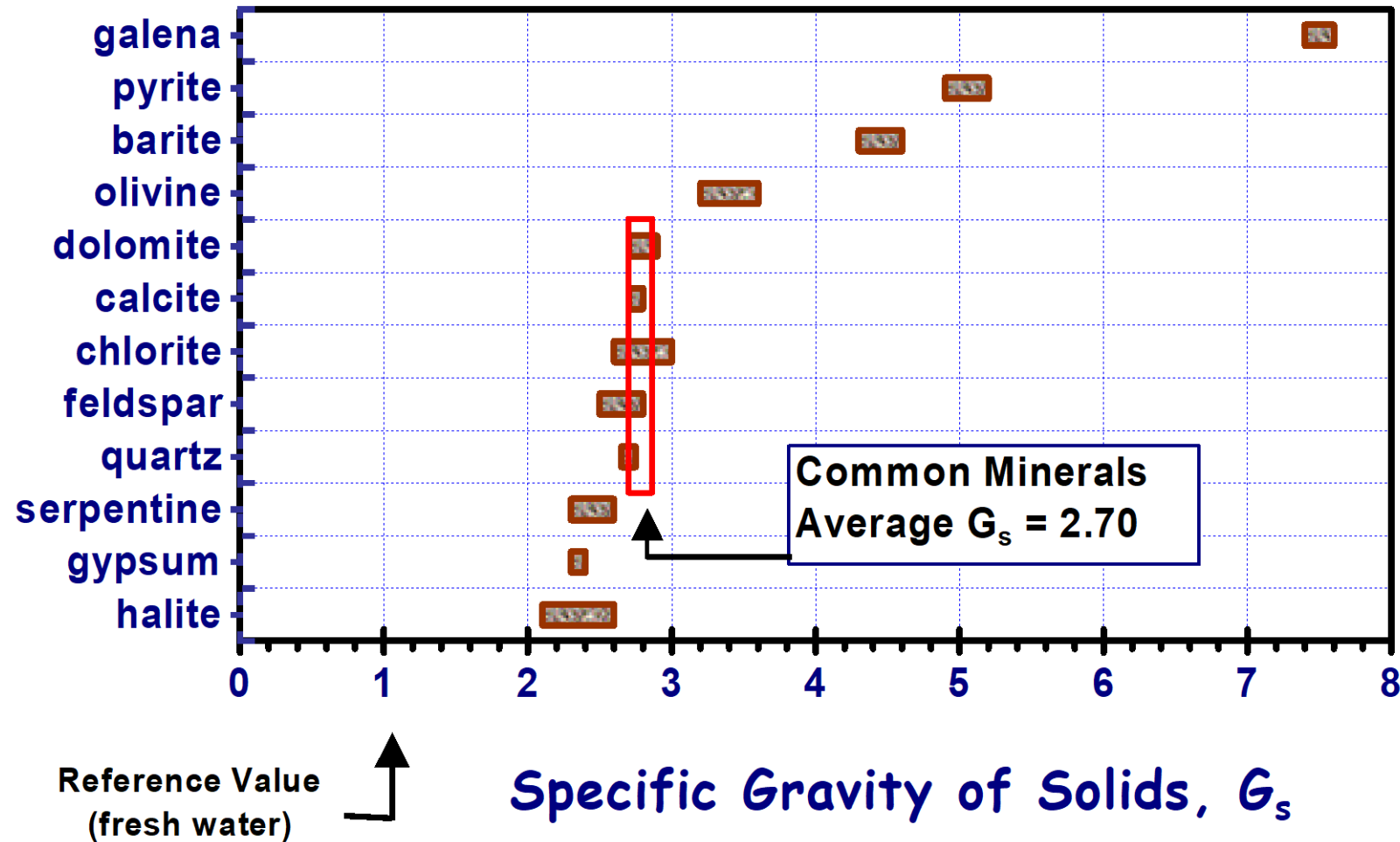
- Specific Gravity of Solids, G_s
- Unit Weight, γ
- Porosity, Φ
- Ultrasonic Velocities (V_p and V_s)

specific courses and tps will be provided on these properties

- Compressive Strength, q_u
- Tensile Strength, T_0
- Elastic Modulus, E_R (at 50% of q_u)

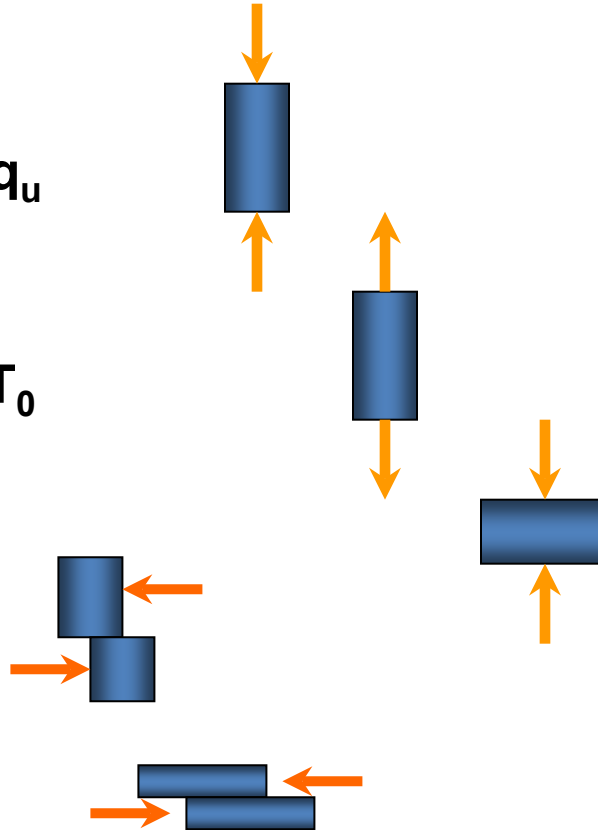
You received detailed courses on these properties during your bachelor's degree; we will only focus on practical sessions (TPs). Refer to the annex for bachelor's courses if needed.

Specific Gravity of Rock Minerals

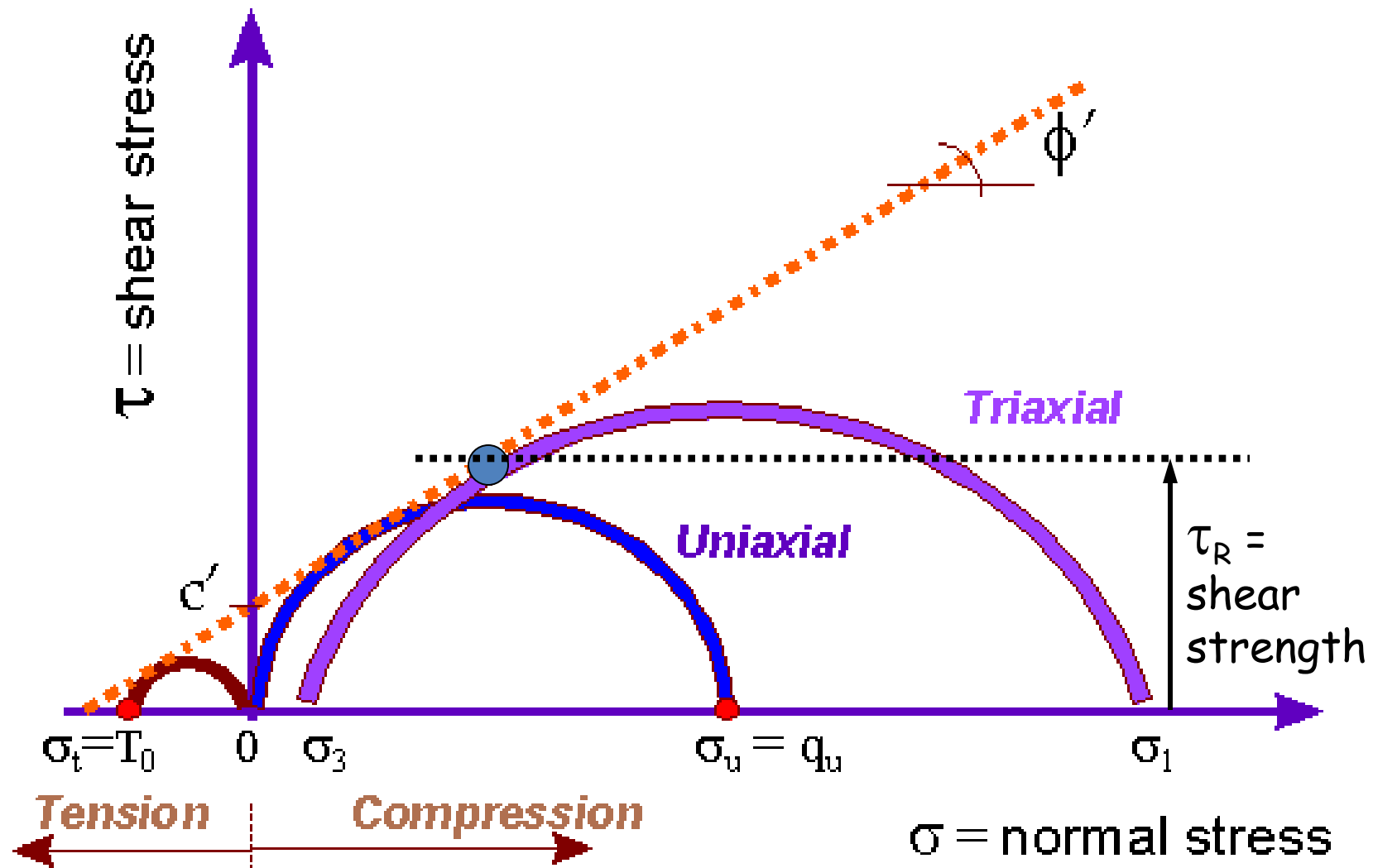


Strength of Intact Rocks

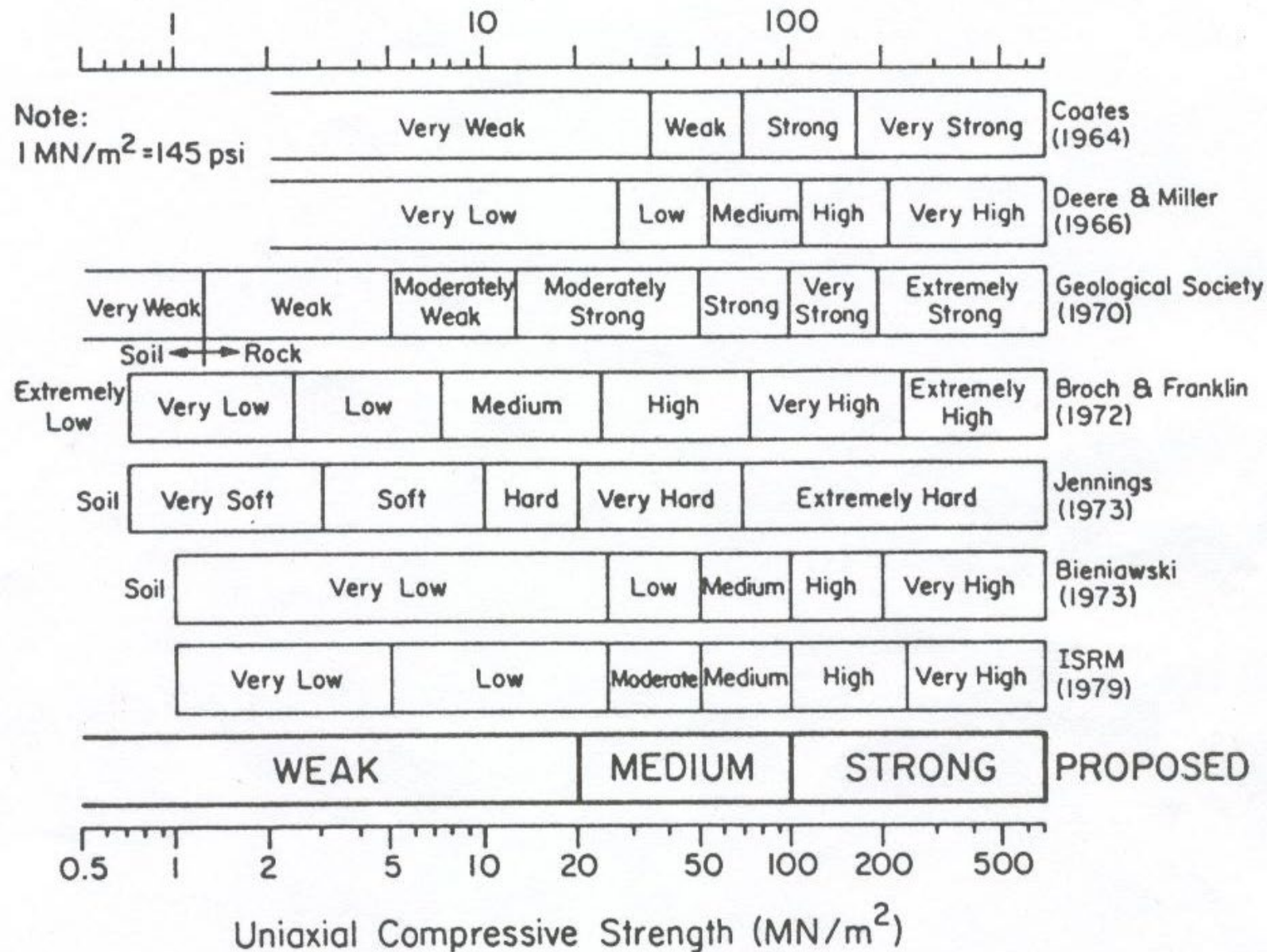
- **Compressive Strength, $\sigma_u = q_u$**
- **(Direct) Tensile Strength, σ_t**
- **(Indirect) Brazilian Strength, σ_{bt}**
- **Shear Strength, τ**
 - Across the intact rock
 - Along the planar surface (joints)



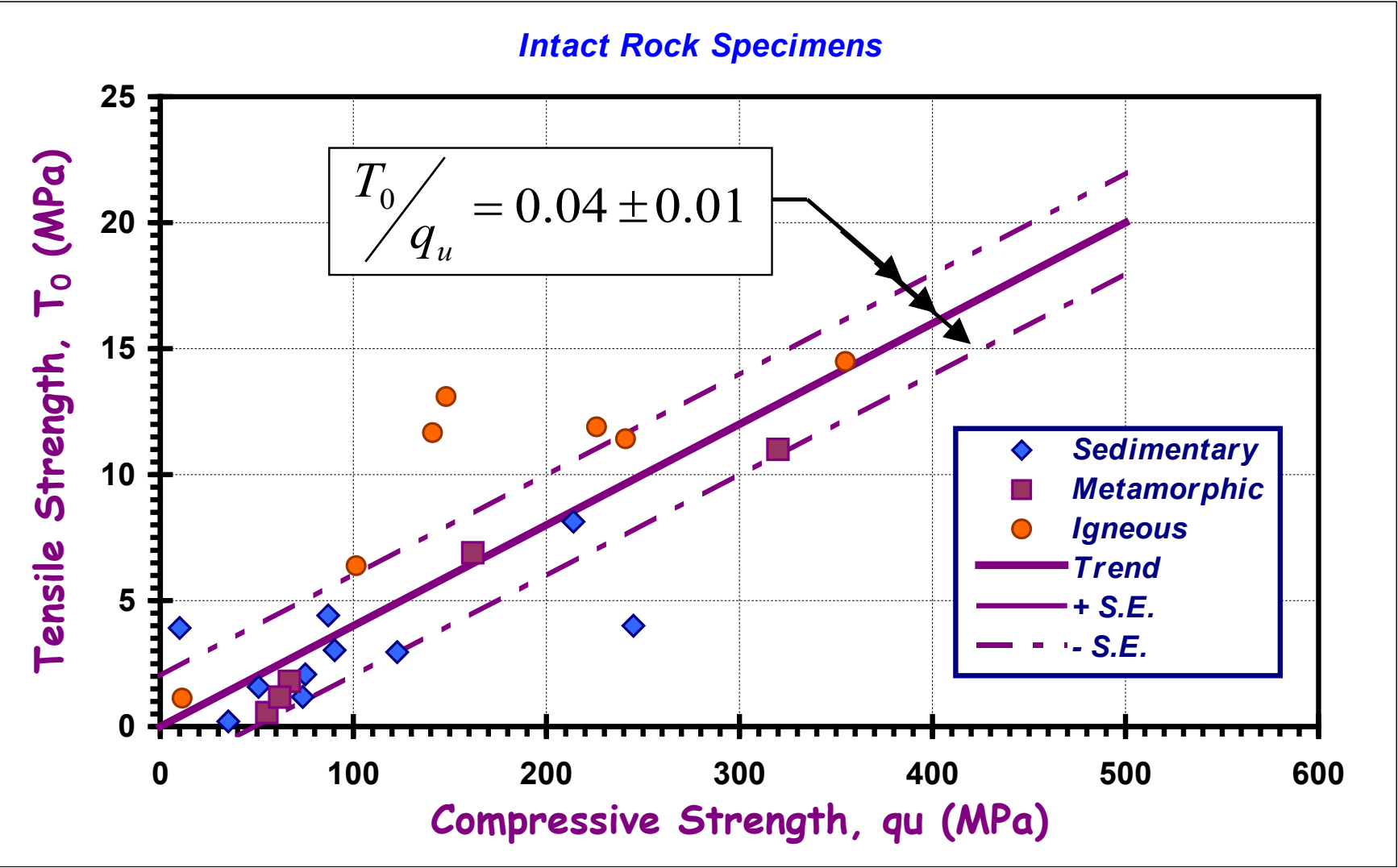
Rock Strength Interrelationships



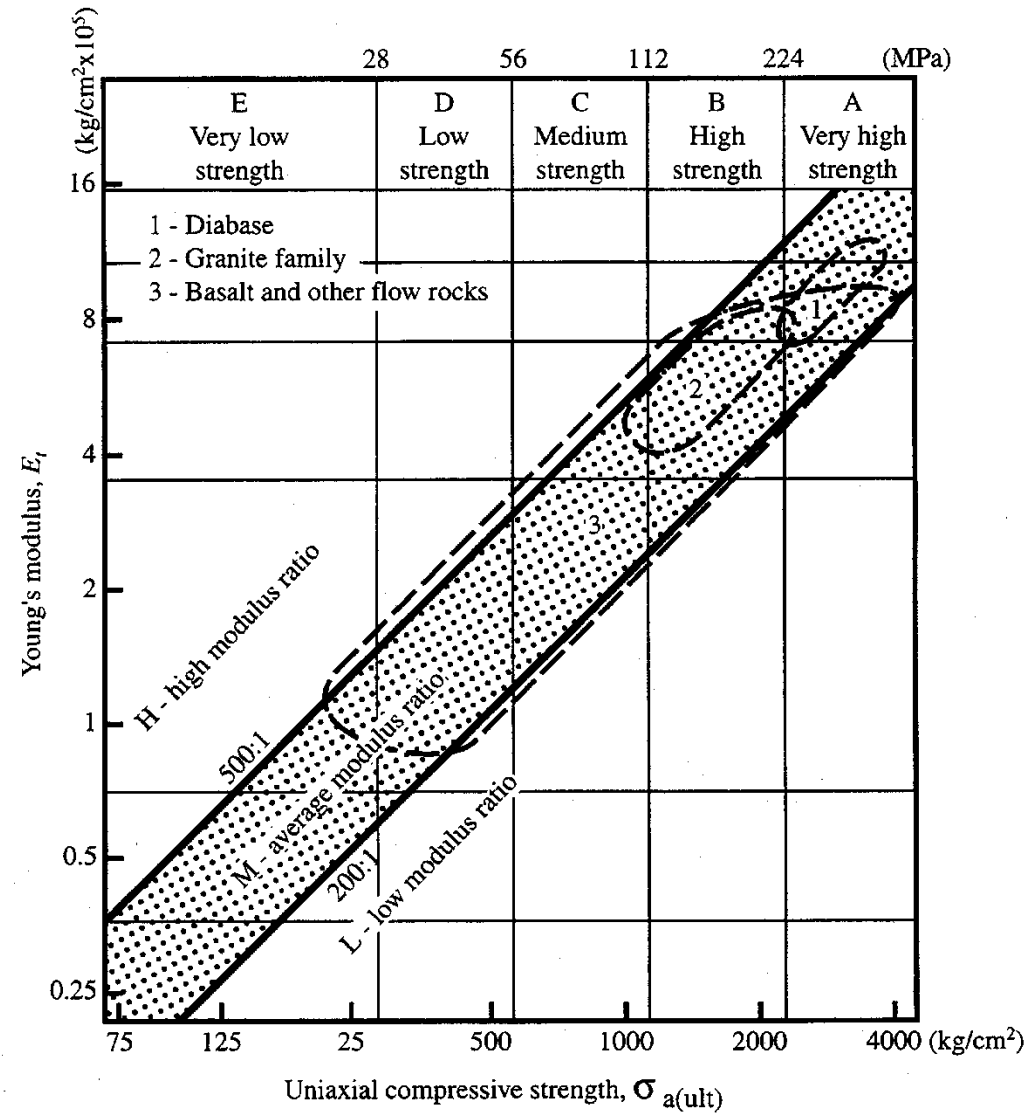
Classification for Rock Material Strength



Intact Rock Strength Interrelationships

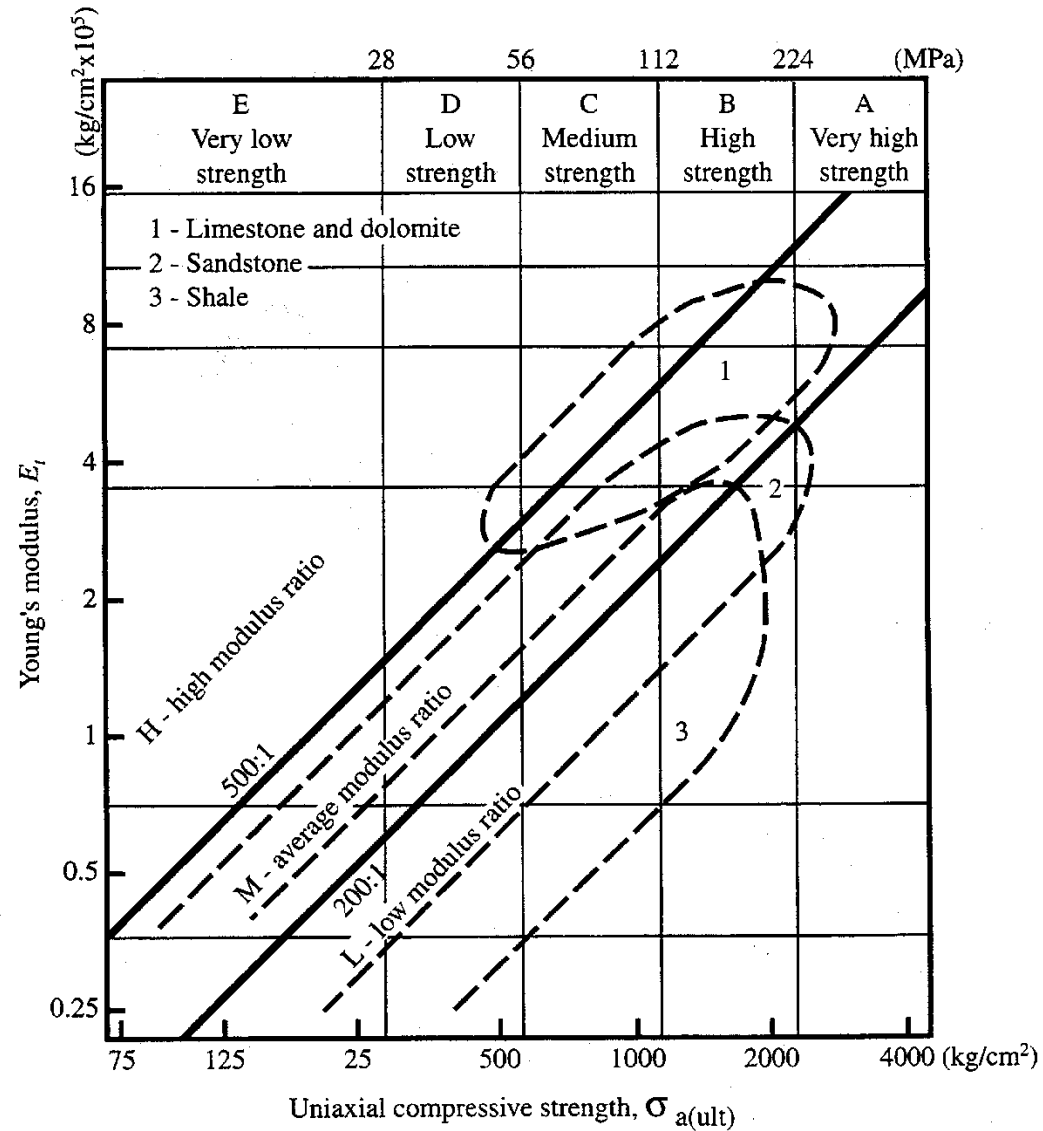


E_R -UCS Groups for Igneous Rocks



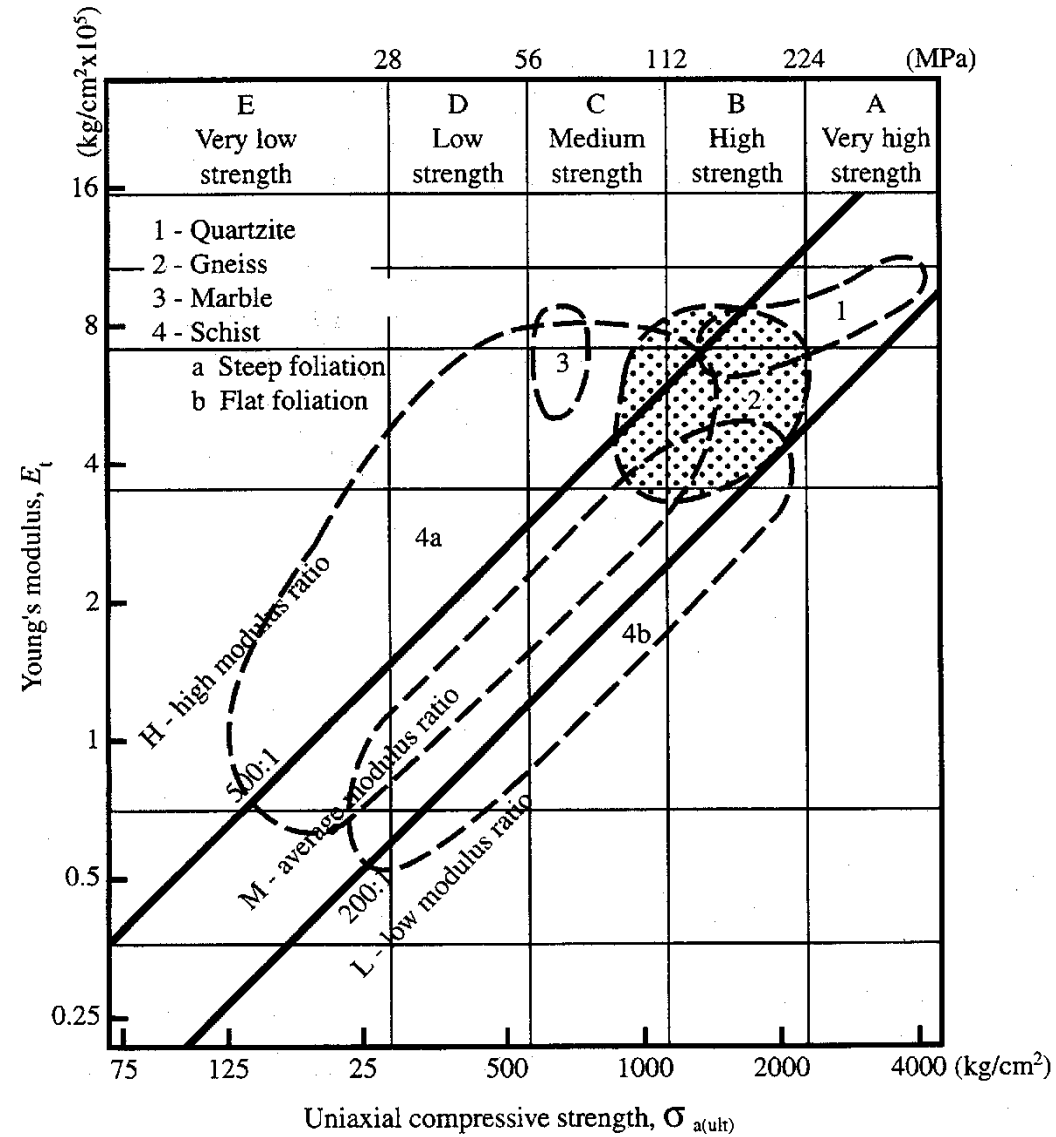
Deere
and
Miller
(1966)

E_R -UCS Groups for Sedimentary Rocks



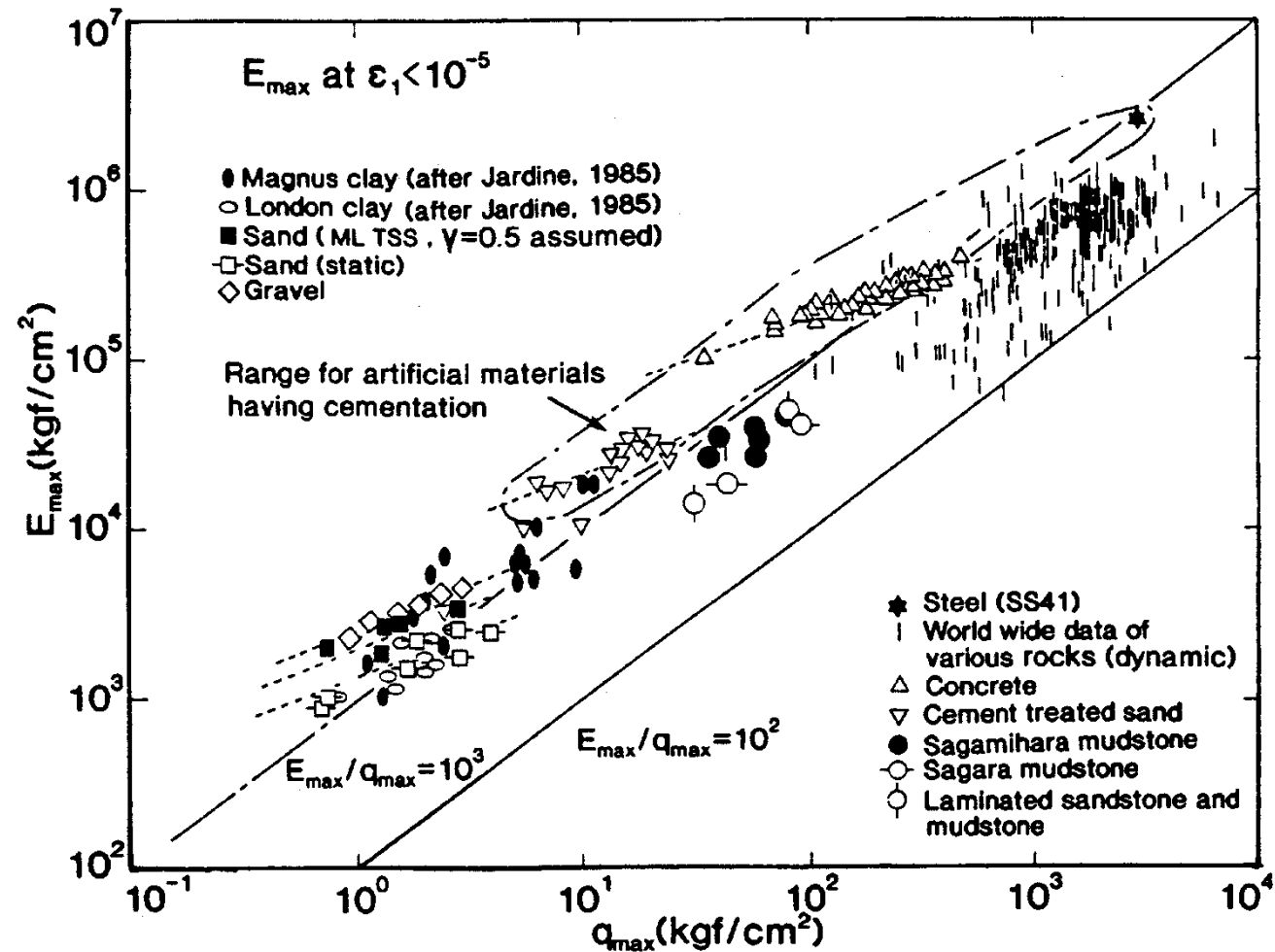
Deere
and
Miller
(1966)

E_R -UCS Groups for Metamorphic Rocks



Deere
and
Miller
(1966)

E_{MAX} -UCS Groups for All Types of Geomaterials



(Tatsuoka and Shibuya, 1992)

- Classification by Uniaxial Compressive Strength, σ_{ar}
- Categorize Rock by its Strength and Modulus Ratio (E_R/σ_u)
- Summary plots for Igneous, Sedimentary, and Metamorphic Rock Types
- Check on reasonableness of your lab measurements and tests

Rock mass classification

Rock discontinuties

Joints are the main discontinuities in rocks.

They are typically arranged in parallel systems. They are generally considered as elements of the rock mass.

The spacing of joints is usually on the order of a few centimeters to a few tens of centimeters.

For engineering purposes, joints are constant elements of the rock mass.

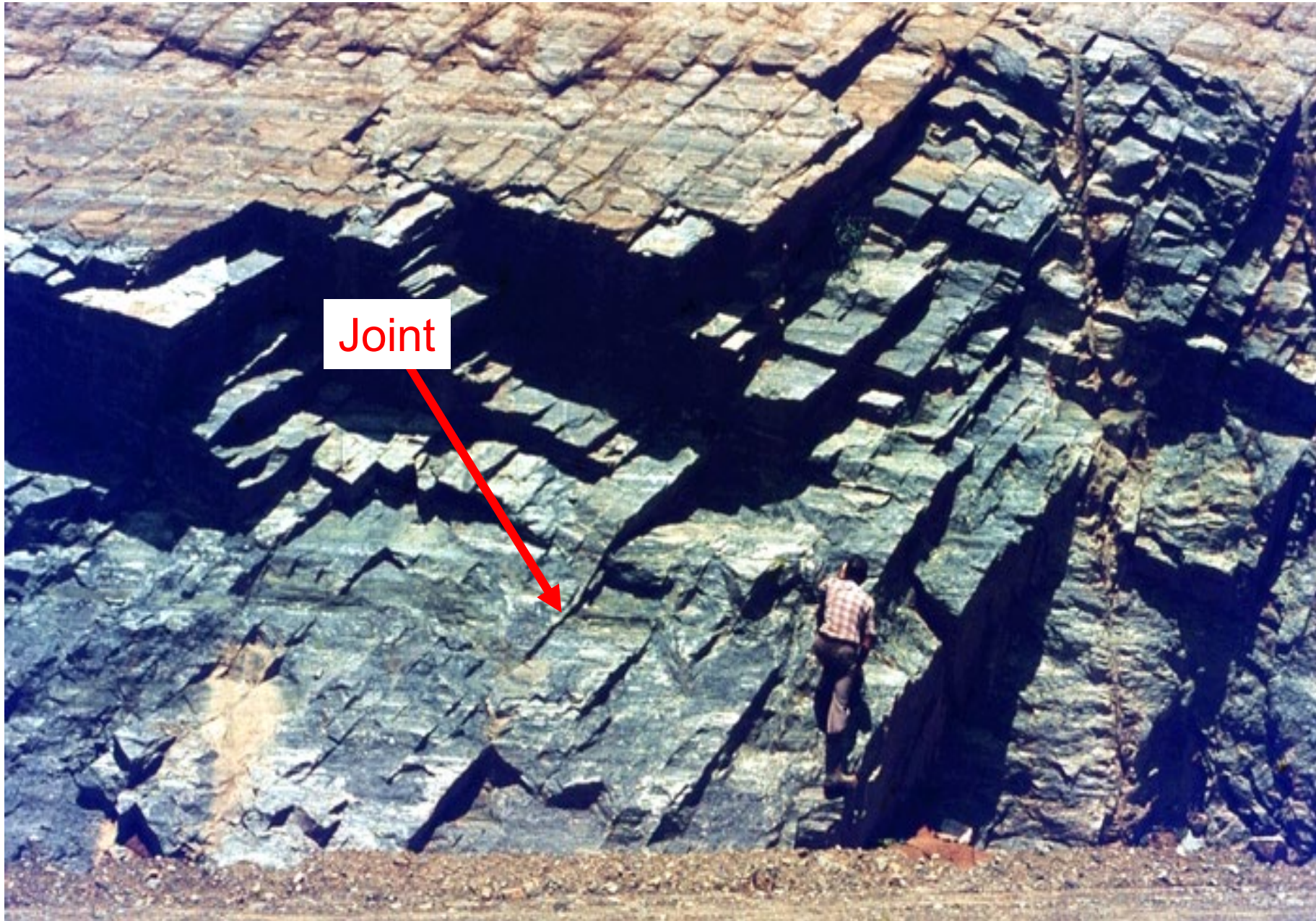


PHOTO BY MICHAEL

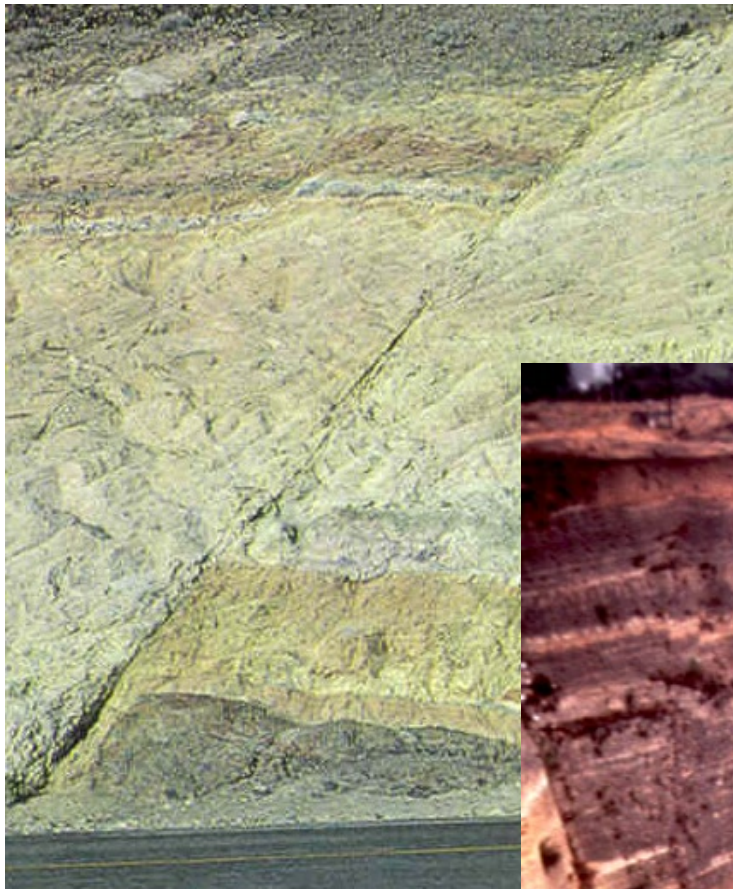
Faults

Faults are planar fractures in rock that indicate relative movement.

Faults occur at different scales; the largest ones are at the boundaries of tectonic plates (e.g., the San Andreas Fault).

Faults generally do not consist of a single, clean fracture; they often form fault zones.

Large-scale faults, fault zones, and shear zones are significant and have important localized influence. They are often treated separately from the rock mass.



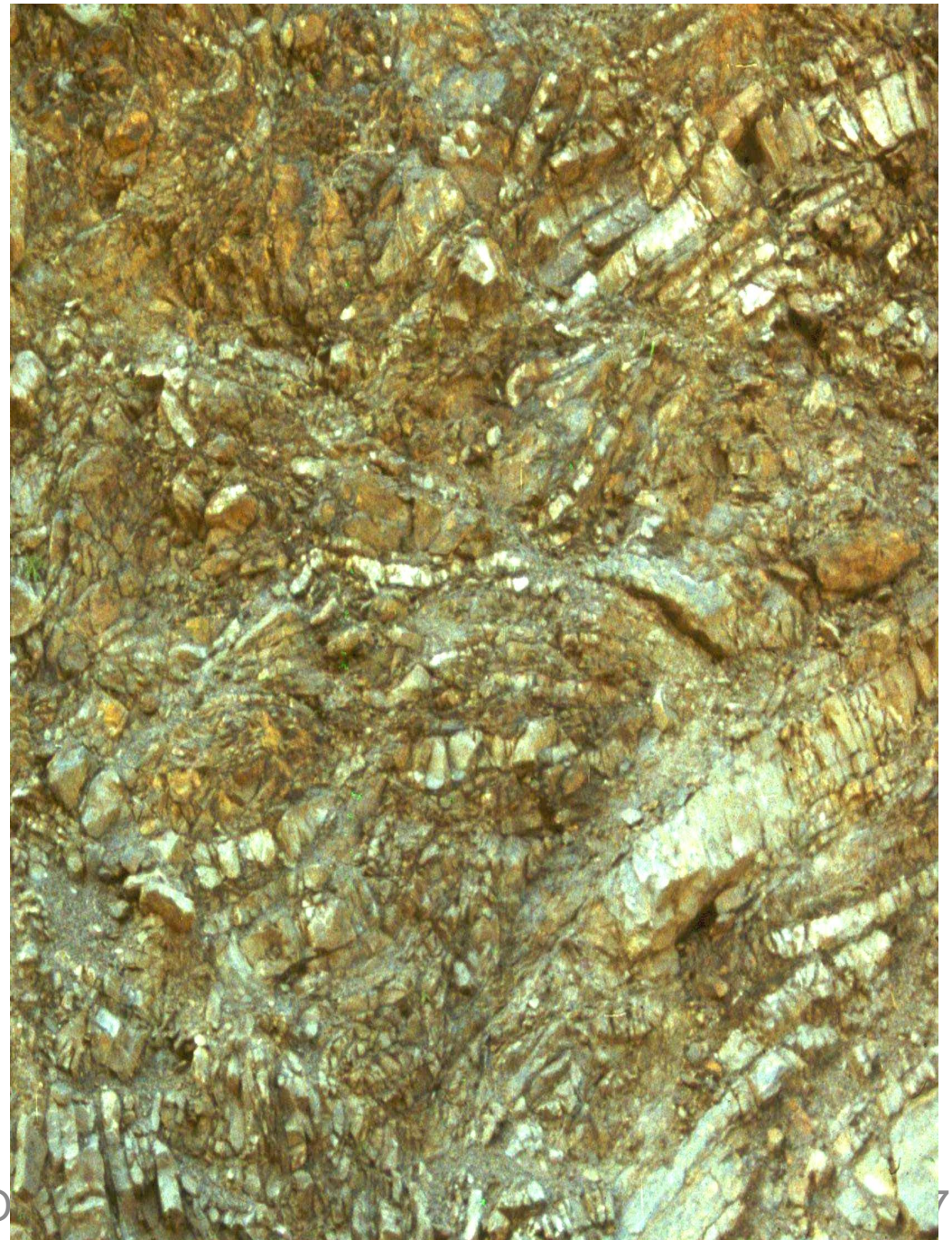
Folds

The fold is the result of the bending of a rock layer under the influence of tectonic forces or movement.

Folds are generally not considered as elements of the rock mass. They are often associated with a high degree of fracturing and relatively weak and soft rocks.



VIO



75

Stratifications

Stratification is the interface between layers of sedimentary rock.

They create an interface between two rock materials. However, some bedding planes can also become potential zones of weathering and groundwater pockets.

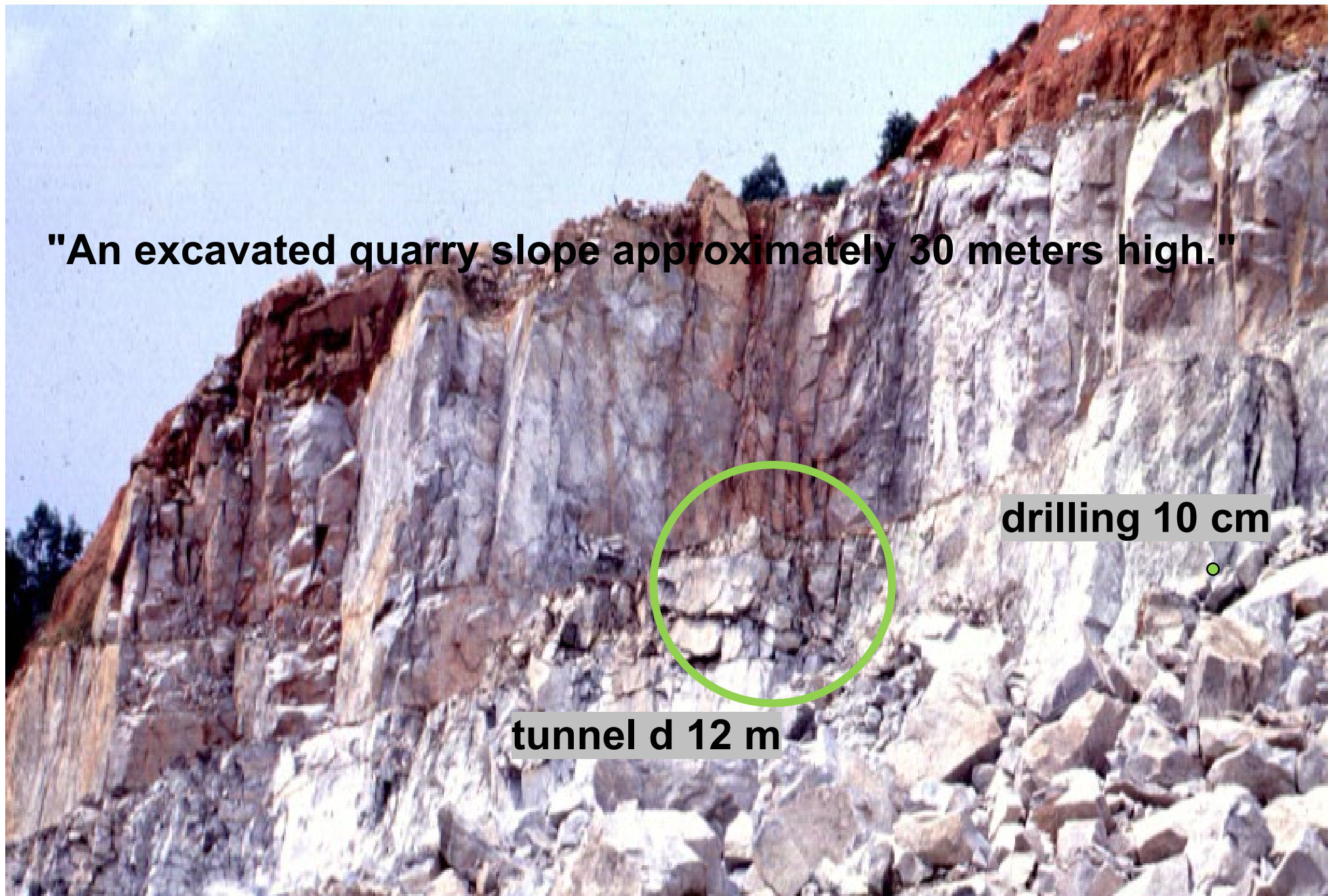


Rock mass at the engineer's scale

For civil engineering works, such as foundations, landslides, and tunnels, the scale of projects generally ranges from a few tens of meters to a few hundred meters.

Rock at the engineering scale is typically an in-place mass. This mass, often referred to as a rock mass, comprises all the rock in situ. It consists of intact rock and discontinuities (joints, faults, etc.).

"An excavated quarry slope approximately 30 meters high."



drilling 10 cm

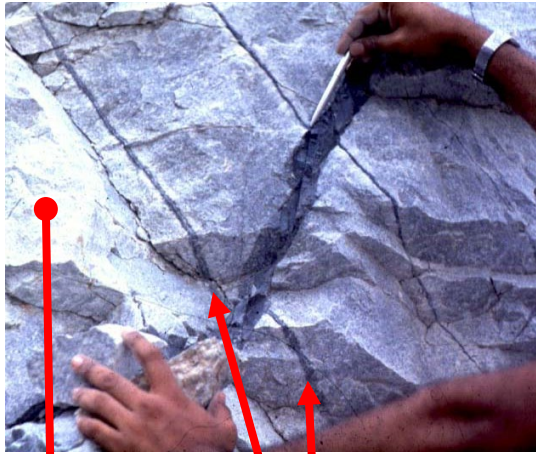
tunnel d 12 m

Rock mass at the engineer's scale

A rock mass contains

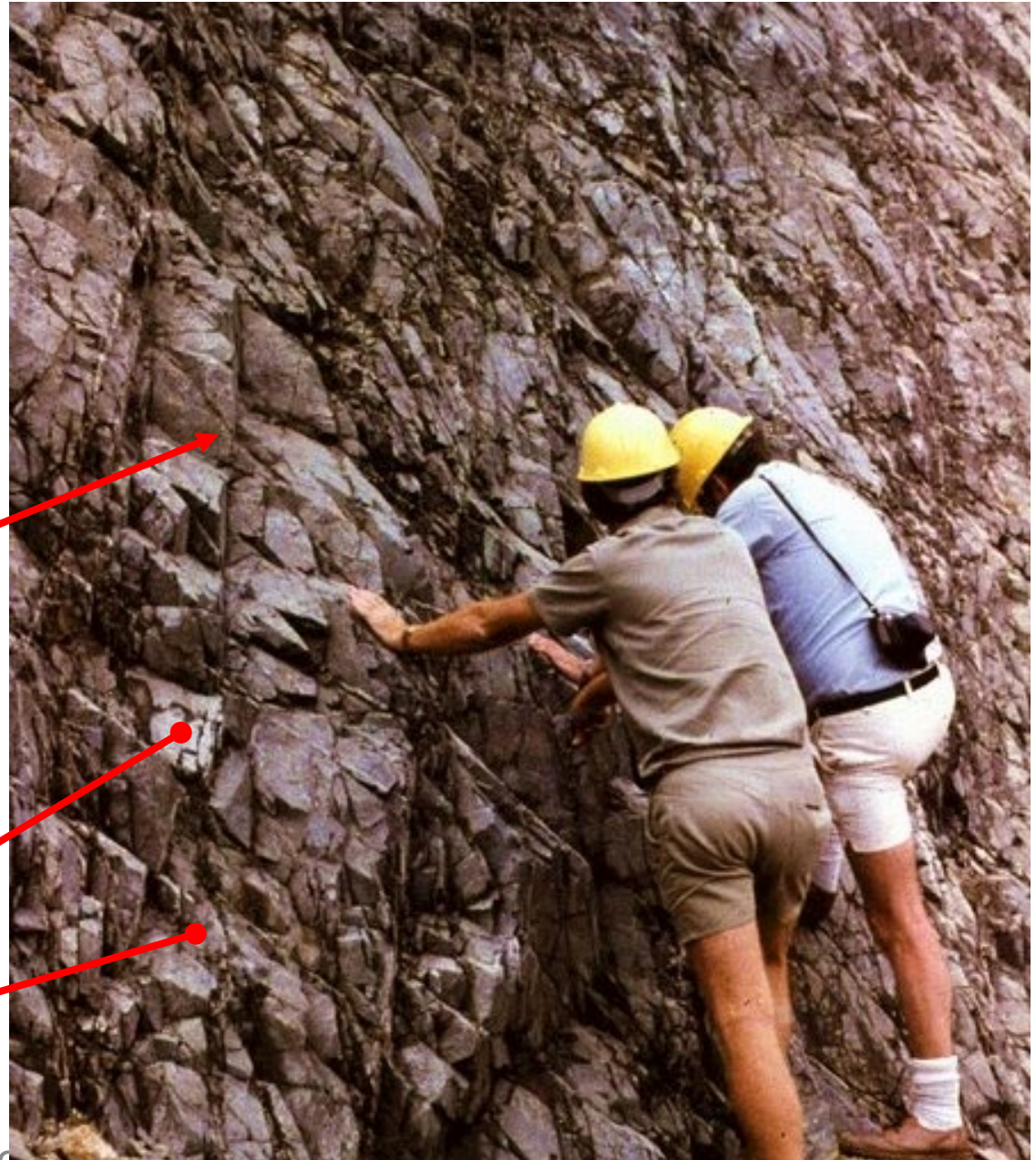
- (i) rock material in the form of intact rock blocks of various sizes, and
- (ii) discontinuities that cut through the mass in the form of fractures, joints, faults, bedding planes, and dykes.

Rock mass = Rock matrix + Discontinuities

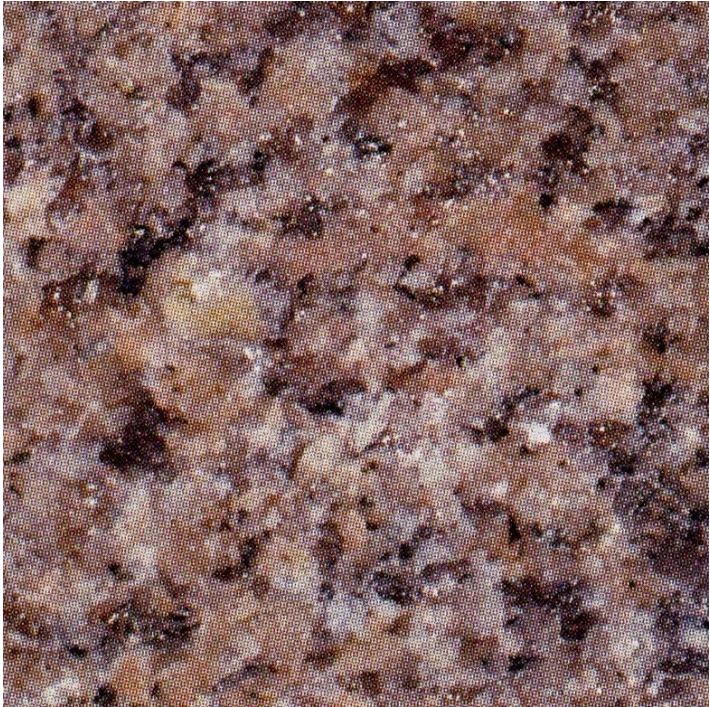


Discontinuités

Roche



Heterogeneity



Granite



Sandstone



Gneiss

Heterogeneity

Inhomogeneity is the cause of crack initiation leading to the rupture of the rock matrix.

If certain elements of the rock matrix are very weak, they begin to break earlier and often result in a decrease in the total strength of the rock.



Anisotropy

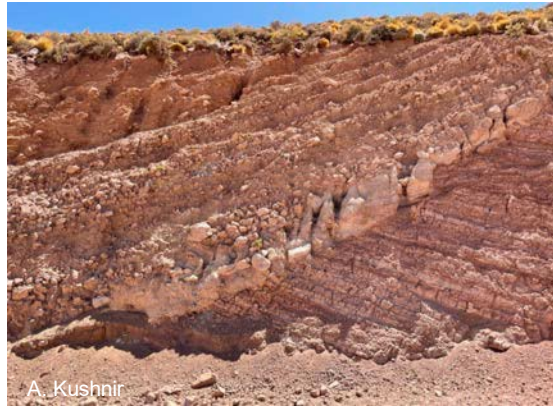
Anisotropy is defined as a property that varies depending on the direction.

Anisotropy is observed in both rocks and rock masses.

Slate is a highly anisotropic rock.

Phyllites, metamorphic schists, and sedimentary argillites also exhibit anisotropy.







<https://hardscape.co.uk/granite-facts-geology/>

Components of rock masses



<https://hardscape.co.uk/granite-facts-geology/>

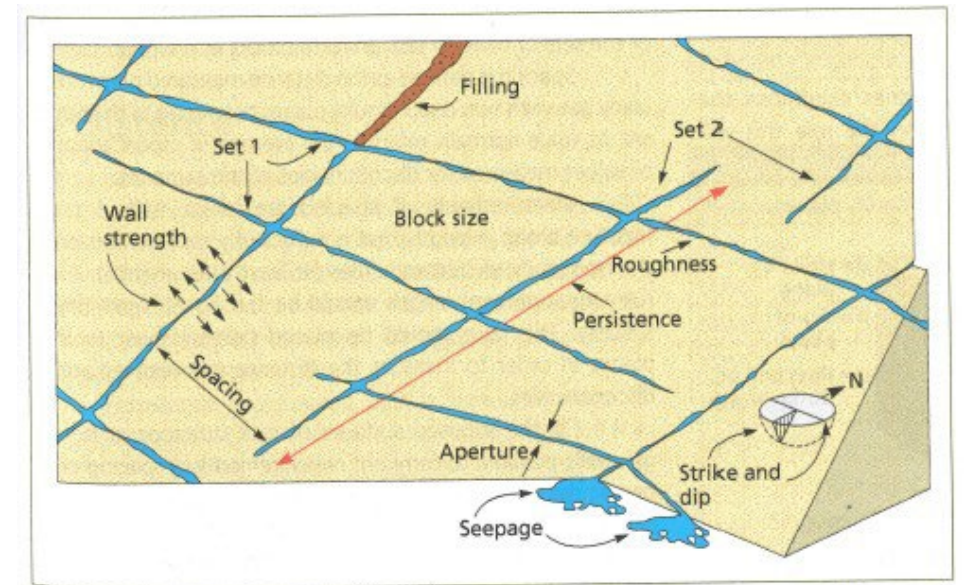


Figure 6.4 Diagram of the geometric properties of discontinuities (Hudson, 1989).

Components of rock masses

Table 6.1 FIELD DESCRIPTION FOR ROCK MASS CHARACTERIZATION

Scope of study	Characteristic or property	Method	Classification
Intact rock	Identification	Direct observation or with a magnifying glass	Geological and geotechnical classification
	Weathering	Direct observation	Standard indices
	Strength	Indices and <i>in situ</i> tests	Empirical strength classifications
Discontinuities	Orientation	Direct measurement with geological compass	
	Spacing	Field measurements	Standard classifications and indices
	Persistence		
	Roughness	Observations and field measurements	Comparison with standard profiles
	Wall strength	Schmidt hammer Field indices	Empirical strength classifications
	Aperture	Observations and field measurements	Standard indices
	Infilling		
	Seepage		
Rock mass	Number of sets of discontinuities	Field measurements	Standard indices and classifications
	Block size		
	Intensity of jointing		
	Extent of weathering	Field observations	Standard classifications

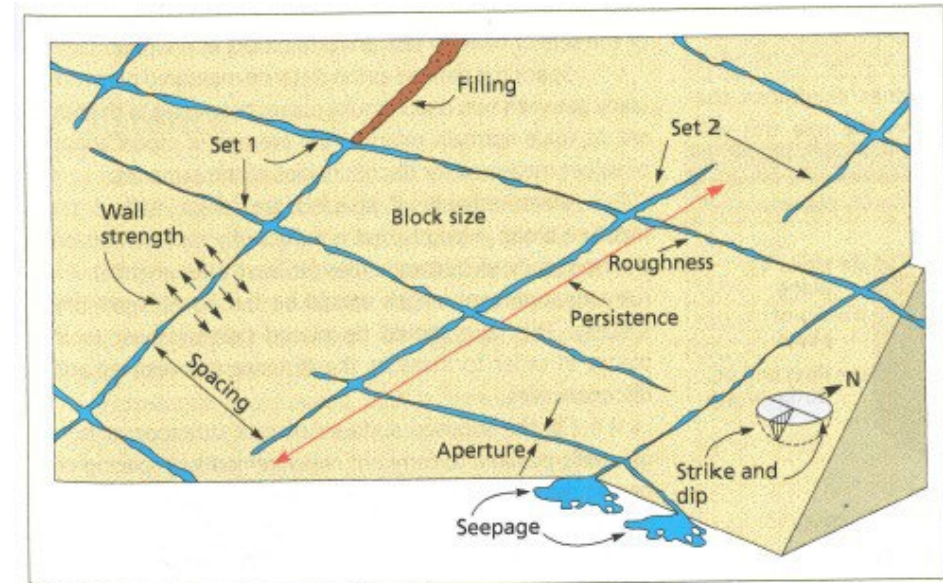
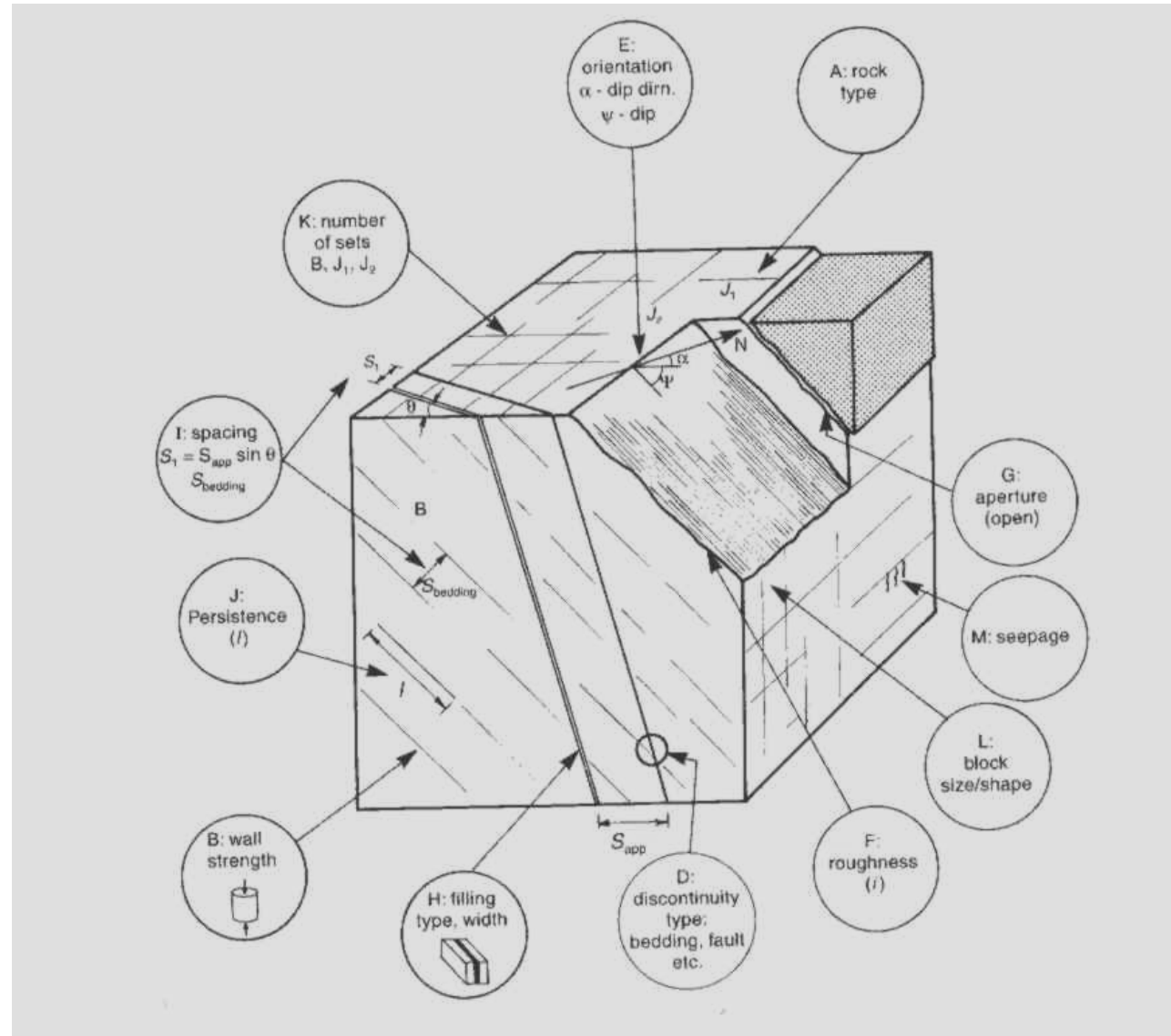


Figure 6.4 Diagram of the geometric properties of discontinuities (Hudson, 1989).

Geologic Mapping of Rock Mass Features





Modèle empirique de Barton (1973)

La résistance au cisaillement de pic τ_p pour un joint rugueux réel peut être exprimée par la relation empirique :

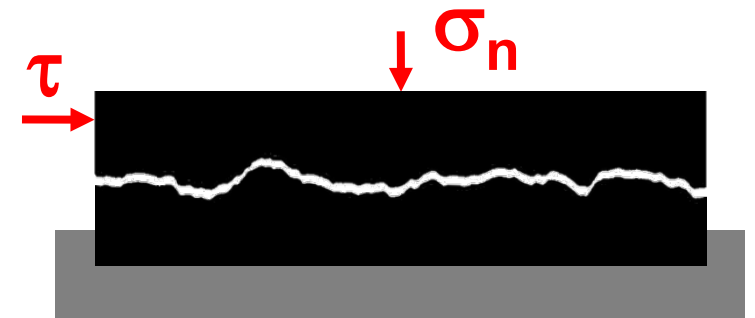
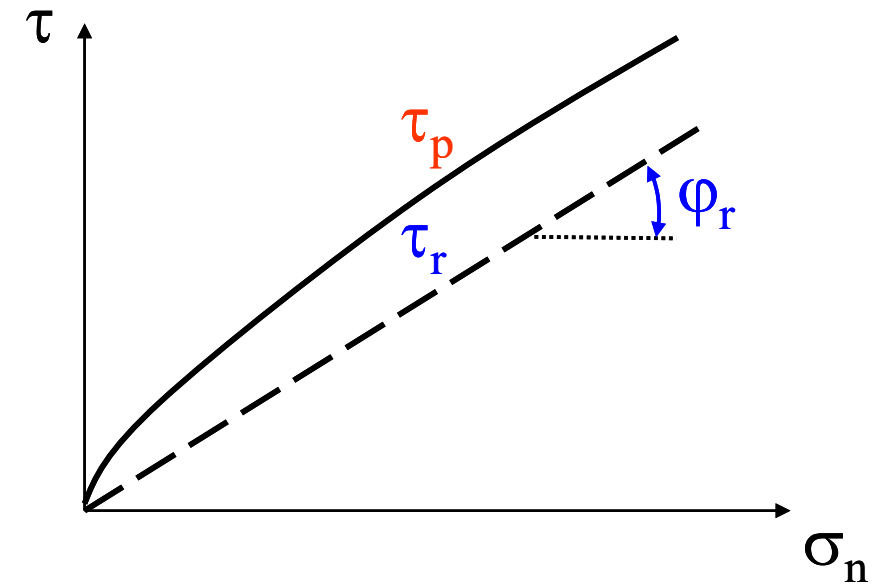
$$\tau_p = \sigma_n \tan \left(\text{JRC} \cdot \log_{10} \frac{\text{JCS}}{\sigma_n} + \phi_r \right)$$

avec:

- JRC = Coefficient de rugosité du joint
- JCS = Résistance à la compression du joint

La résistance au cisaillement résiduelle τ_r est donnée par:

$$\tau_r = \sigma_n \tan \phi_r$$



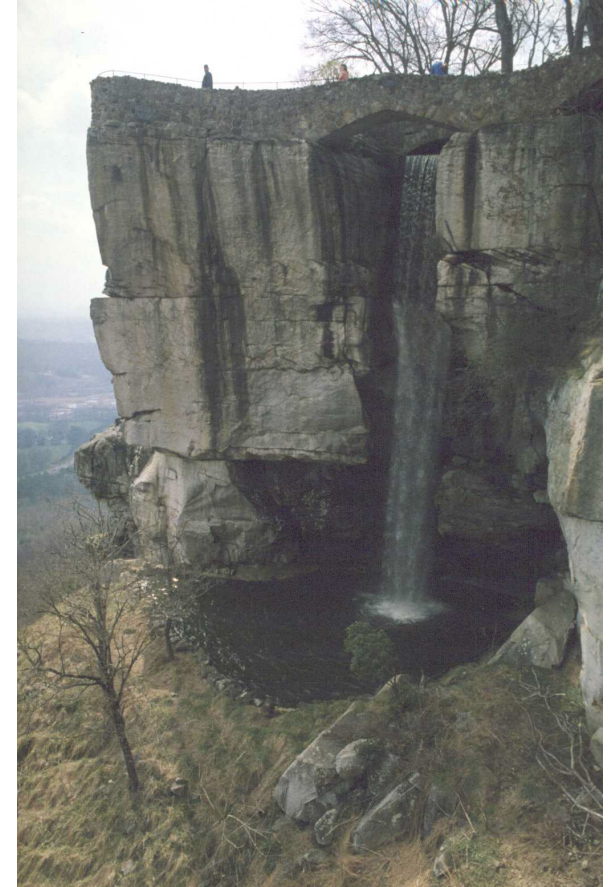
- Be familiar with charts, equations, and tables for evaluation of rock mass properties
 - Determine validity of rock test results
 - Selection of appropriate values
 - Perform preliminary design evaluation
- Recognize that cracks & fissure in rock mass are as important as intact material between the discontinuities.

Rock Mass Classifications

- RQD - early form of rating rock mass
- Geomechanics System - Rock Mass Rating (RMR) by Bieniawski (1984, 1989)
- Q-System - Norwegian Geotechnical Institute (Barton, et al. 1974)
- Geological Strength Index, GSI (Hoek, et al., 1995)

Rock Mass Rating (RMR)

- **RMR based on five parameters:**
 - Uniaxial strength, q_u
 - Rock Quality Designation, RQD
 - Spacing of Discontinuities
 - Condition of the Discontinuities
 - Groundwater Conditions
- **$RMR = R_1 + R_2 + R_3 + R_4 + R_5$**
- **Adjustment for Joint Orientation relative to construction**



NGI- Q Rating of Rock Masses

- **Q-Rating based on 6 parameters:**
 - Rock Quality Designation, RQD
 - Number of Joint Sets, J_n
 - Roughness of Discontinuities, J_r
 - Discontinuity Condition/Filling, J_a
 - Groundwater Conditions, J_w
 - Stress Reduction Factor, SRF
- **Rating of Rock Formation:**

$$Q = \left(\frac{RQD}{J_n} \right) \left(\frac{J_r}{J_a} \right) \left(\frac{J_w}{SRF} \right)$$

NGI Q-System Rating for Rock Masses (Barton, Lien, & Lunde, 1974)

Norwegian Classification for Rock Masses

Q - Value	Quality of Rock Mass
< 0.01	Exceptionally Poor
0.01 to 0.1	Extremely Poor
0.1 to 1	Very Poor
1 to 4	Poor
4 to 10	Fair
10 to 40	Good
40 to 100	Very Good
100 to 400	Extremely Good
< 400	Exceptionally Good

PARAMETERS FOR THE Q-RATING of Rock Masses

1. RQD = Rock Quality Designation = sum of cored pieces
> 100 mm long, divided by total core run length

2. Number of Sets of Discontinuities (joint sets)	= J _n
Massive	0.5
One set	2
Two sets	4
Three sets	9
Four or more sets	15
Crushed rock	20

3. Roughness of Discontinuities*	= J _r
Noncontinuous joints	4
Rough, wavy	3
Smooth, wavy	2
Rough, planar	1.5
Smooth, planar	1
Slick and planar	0.5
Filled discontinuities	1

*Note: add +1 if mean joint spacing > 3 m

$$Q = \left(\frac{RQD}{J_n} \right) \left(\frac{J_r}{J_a} \right) \left(\frac{J_w}{SRF} \right)$$

4. Discontinuity Condition & Infilling = J_a

4.1 Unfilled Cases

Healed	0.75
Stained, no alteration	1
Silty or Sandy Coating	3
Clay coating	4

4.2 Filled Discontinuities

Sand or crushed rock infill	4
Stiff clay infilling < 5 mm	6
Soft clay infill < 5 mm thick	8
Swelling clay < 5 mm	12
Stiff clay infill > 5 mm thick	10
Soft clay infill > 5 mm thick	15
Swelling clay > 5 mm	20

5. Water Conditions

Dry	1
Medium Water Inflow	0.66
Large inflow in unfilled joints	0.5
Large inflow with filled joints that wash out	0.33
High transient flow	0.2 to 0.1
High continuous flow	0.1 to 0.05

6. Stress Reduction Factor** = SRF

Loose rock with clay infill	10
Loose rock with open joints	5
Shallow rock with clay infill	2.5
Rock with unfilled joints	1

**Note: Additional SRF values given
for rocks prone to bursting, squeezing
and swelling by Barton et al. (1974)

Geological Strength Index, GSI

- Developed by Hoek, Kaiser, & Bawden (1995), Hoek & Brown (1997).
- GSI from Q-system:
- GSI from Geomechanics system where RMR > 25:
- Chart approach based on structure & surface quality

$$GSI = 9 \log \left[\left(\frac{RQD}{J_n} \right) \left(\frac{J_r}{J_a} \right) \right] + 44$$

$$GSI = 10 + \sum_{i=1}^4 (R_i)$$

GSI Evaluation from Chart

GEOLOGICAL STRENGTH INDEX		DISCONTINUITY SURFACE CONDITION				
According to geological conditions, pick the appropriate box in this chart. Estimate the average value of the Geological Strength Index GSI from the contours						
STRUCTURE		VERY GOOD Very rough, unweathered surfaces	GOOD Rough, slightly weathered, iron stained surfaces	FAIR Smooth, moderately weathered or altered surfaces	POOR Slickensided, highly weathered surfaces with compact coatings or fillings containing angular rock fragments	VERY POOR Slickensided, highly weathered surfaces with soft clay coatings or fillings
	BLOCKY - very well interlocked undisturbed rock mass consisting of cubical blocks formed by three orthogonal discontinuity sets	80	70			
	VERY BLOCKY - interlocked, partially distributed rock mass with multifaceted angular blocks formed by four or more discontinuity sets		60	50		
	BLOCKY/FOLDED - folded and faulted with many intersecting discontinuities forming angular blocks			40	30	
	CRUSHED - poorly interlocked, heavily broken rock mass with a mixture of angular and rounded blocks				20	10

Hoek (2000)

Strength of Rock Masses

- Depends on Intact Rock Material and Rock Mass Jointing
- Intact Rock:
 - ❑ Uniaxial Compression Strength, UCS
 - ❑ Rock Material Type using parameter m_i
- Fractured Rock Characteristics (in terms of GSI)
- Parameters m_b and s and exponent "a"
- Obtain Strength Envelope from:

$$\sigma_1' = \sigma_3' + \sigma_{ci} \left[m_b \left(\frac{\sigma_3'}{\sigma_{ci}} \right) + s \right]^a$$

Rock Strength: m_i parameter

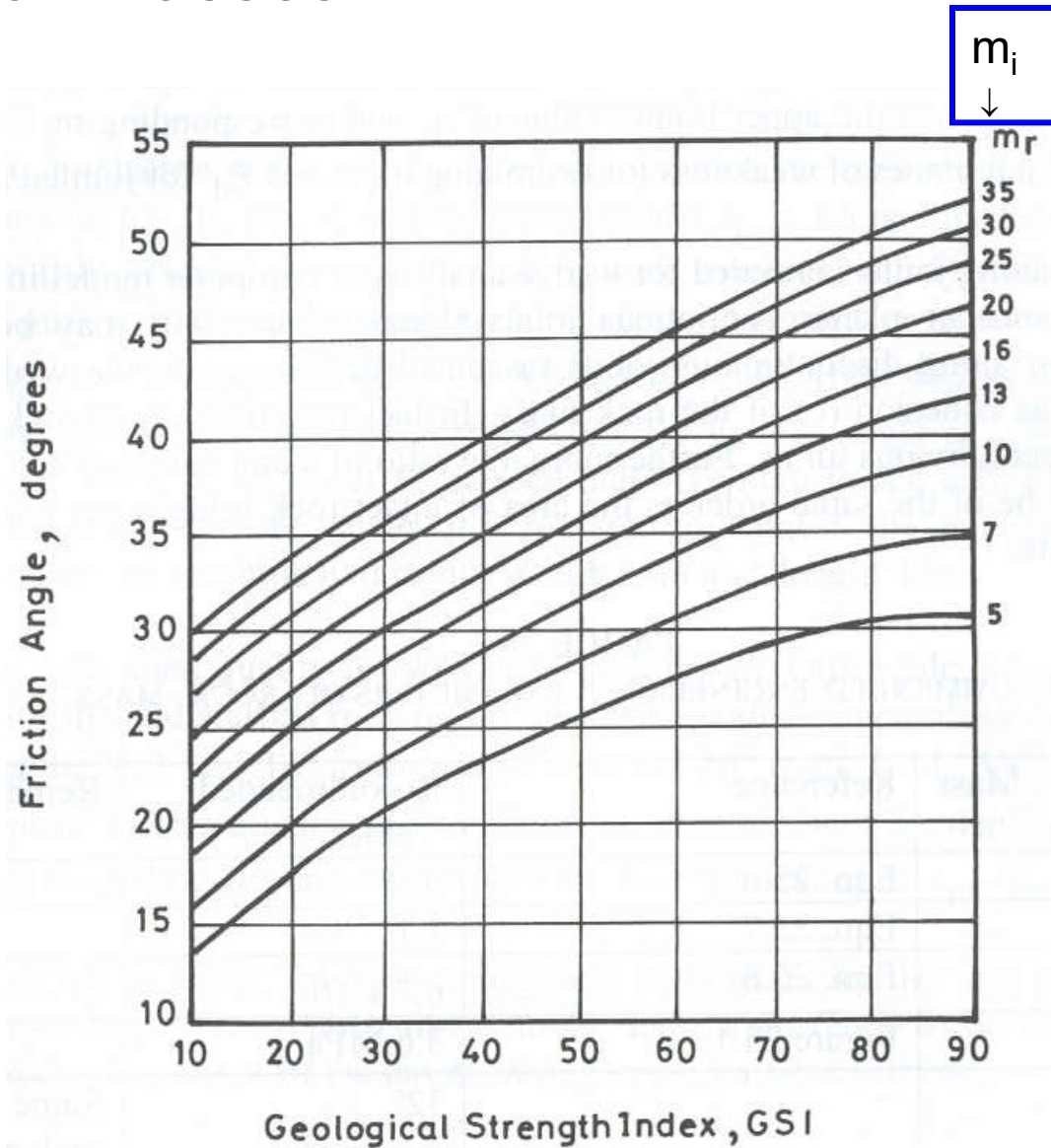
Rock type	Class	Group	Texture			
			Course	Medium	Fine	Very fine
SEDIMENTARY	Clastic		Conglomerate (22)	Sandstone 19	Siltstone 9	Claystone 4
			← Greywacke (18) →			
	Non-Clastic	Organic	← Chalk 7 →			
			← Coal (8-21) →			
		Carbonate	Breccia (20)	Sparitic Limestone (10)	Micritic Limestone 8	
Chemical			Gypstone 16	Anhydrite 13		
METAMORPHIC	Non Foliated		Marble 9	Hornfels (19)	Quartzite 24	
	Slightly foliated		Migmatite (30)	Amphibolite 31	Mylonites (6)	
	Foliated*		Gneiss 33	Schists (10)	Phyllites (10)	Slate 9
IGNEOUS	Light Dark		Granite 33		Rhyolite (16)	Obsidian (19)
			Granodiorite (30)		Dacite (17)	
			Diorite (28)		Andesite 19	
			Gabbro 27	Dolerite (19)	Basalt (17)	
			Norite 22			
Extrusive pyroclastic type		Agglomerate (20)	Breccia (18)	Tuff (15)		

Strength of Rock Masses

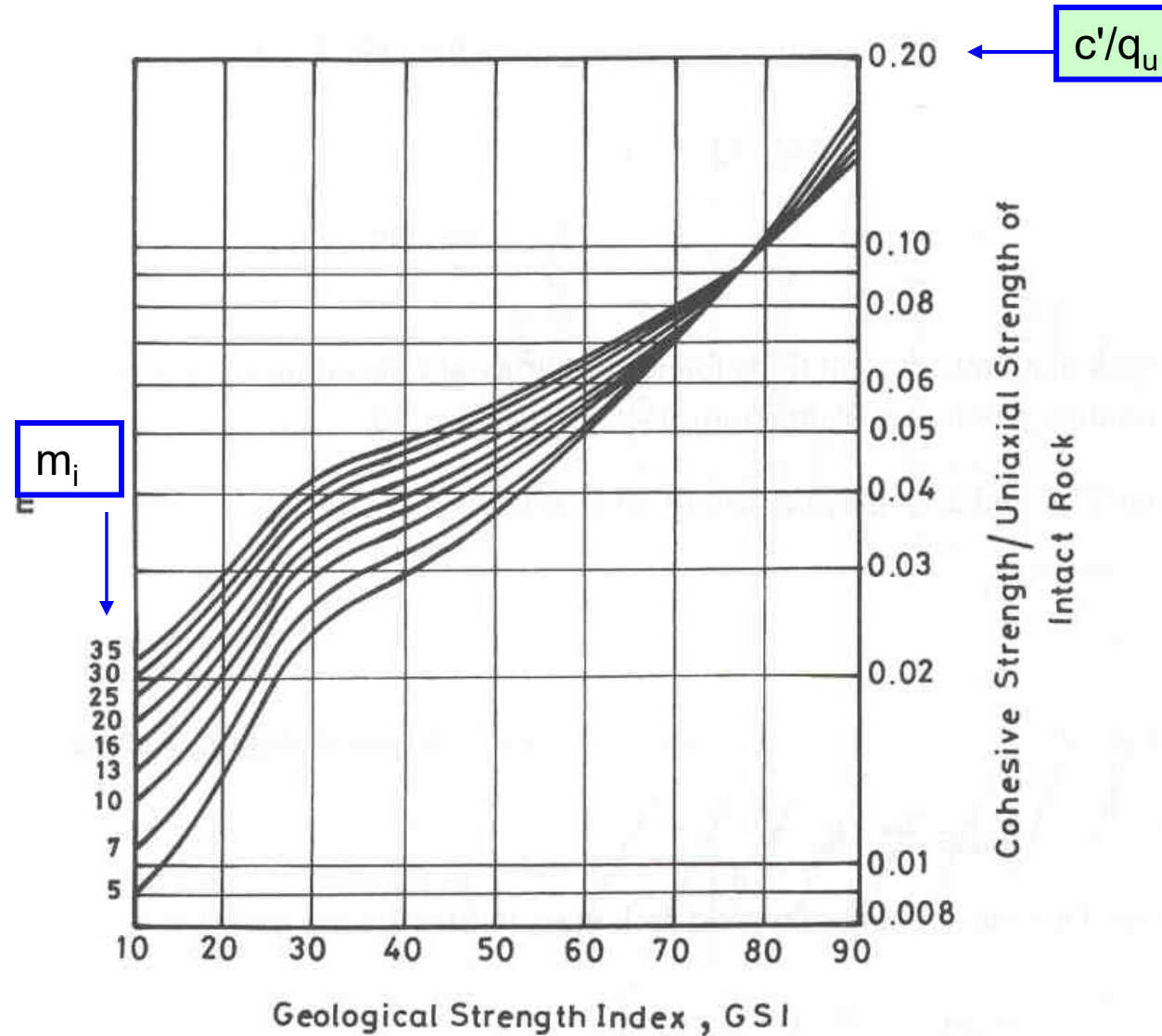
- Parameter: $m_b = m_i \exp [(GSI-100)/28]$
- For $GSI > 25$:
 - $s = \exp [(GSI-100)/9]$
 - exponent $a = 0.5$
- For $GSI < 25$:
 - $s = 0$
 - exponent $a = 0.65 - (GSI/200)$

$$\sigma_1' = \sigma_3' + \sigma_u \left[m_b \left(\frac{\sigma_3'}{\sigma_u} \right) + s \right]^a$$

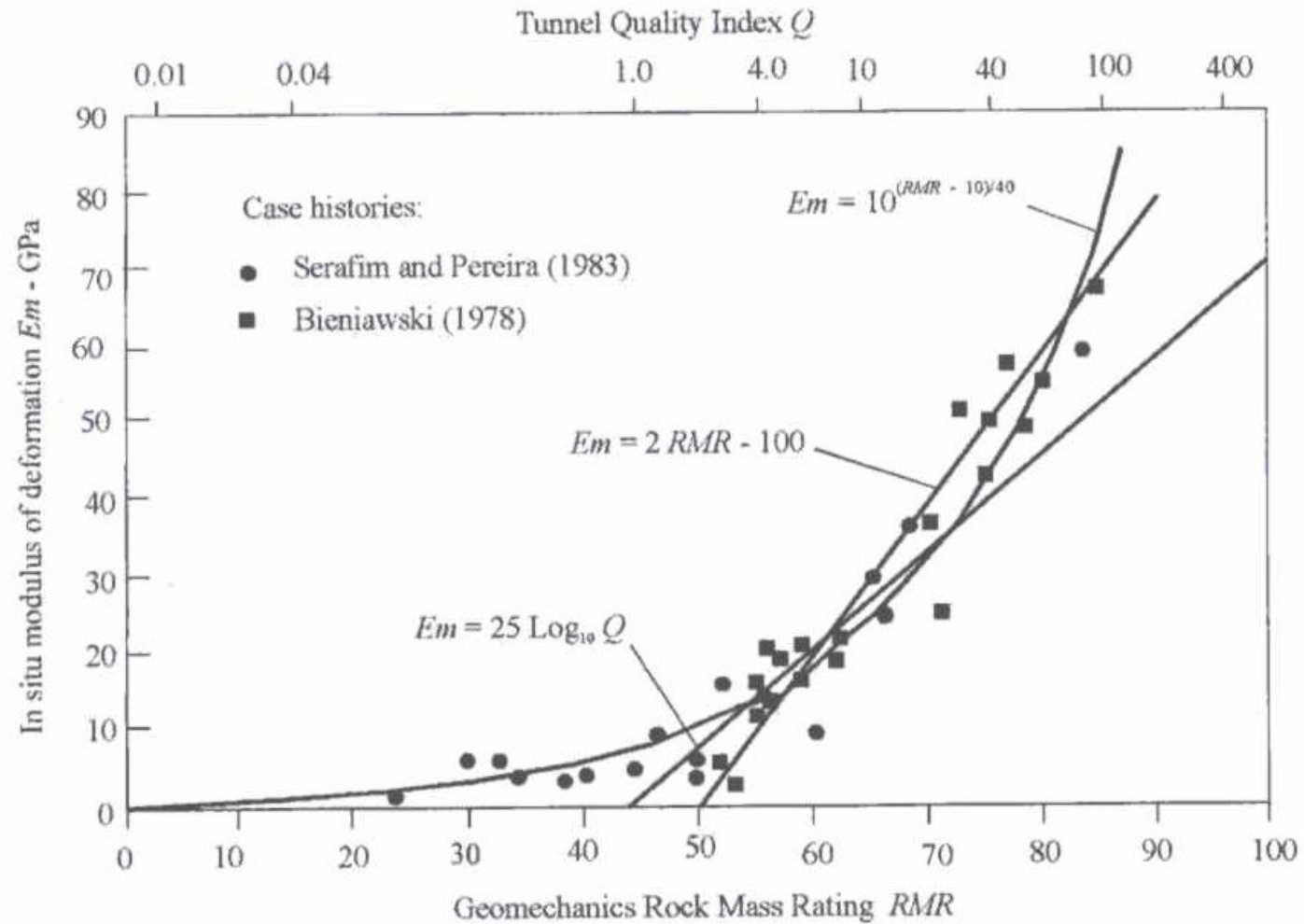
Strength of Rock Masses



Strength of Rock Masses

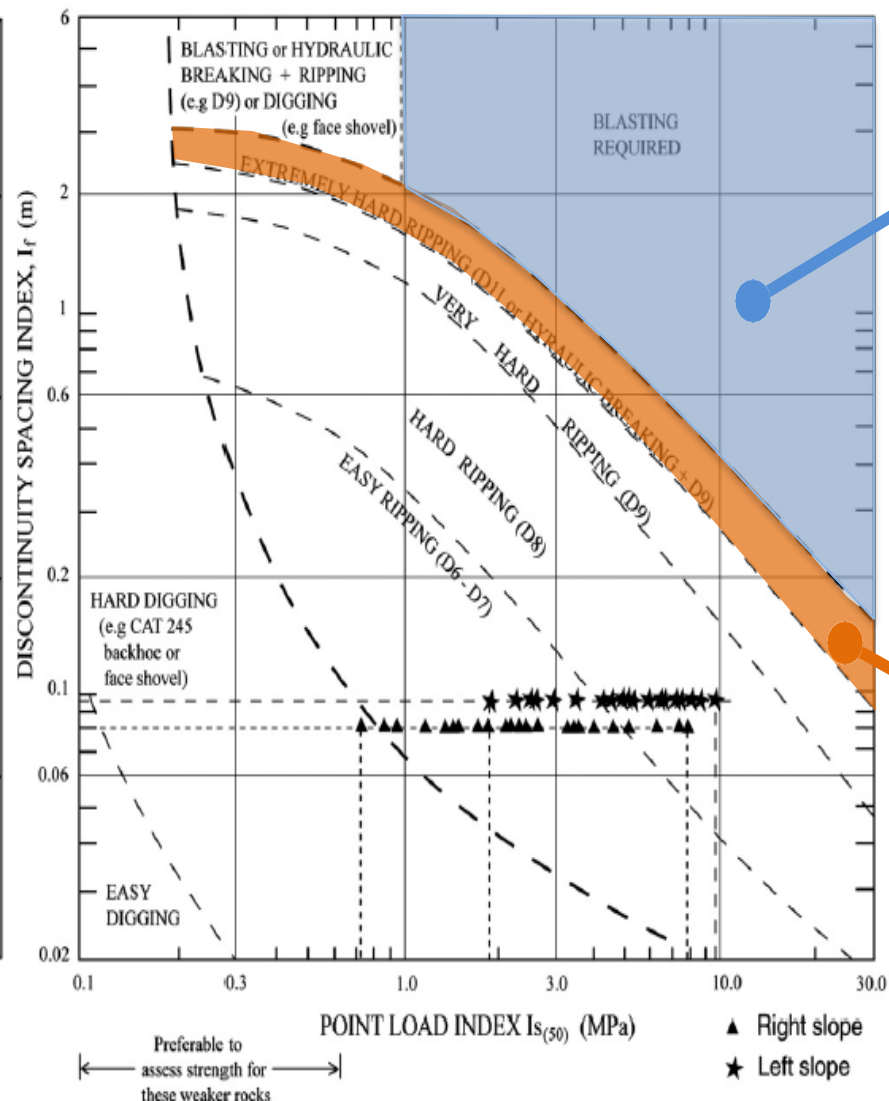


Equivalent Modulus of Rock Masses



VERY SMALL	SMALL	MEDIUM	LARGE	VERY LARGE
------------	-------	--------	-------	------------

Weak-broken by leaning on sample with hammer, scratched with thumbnail	Moderate weak-broken in hand by hitting with hammer; scratched with knife	Moderate strong	Strong	Very strong	Extremely strong
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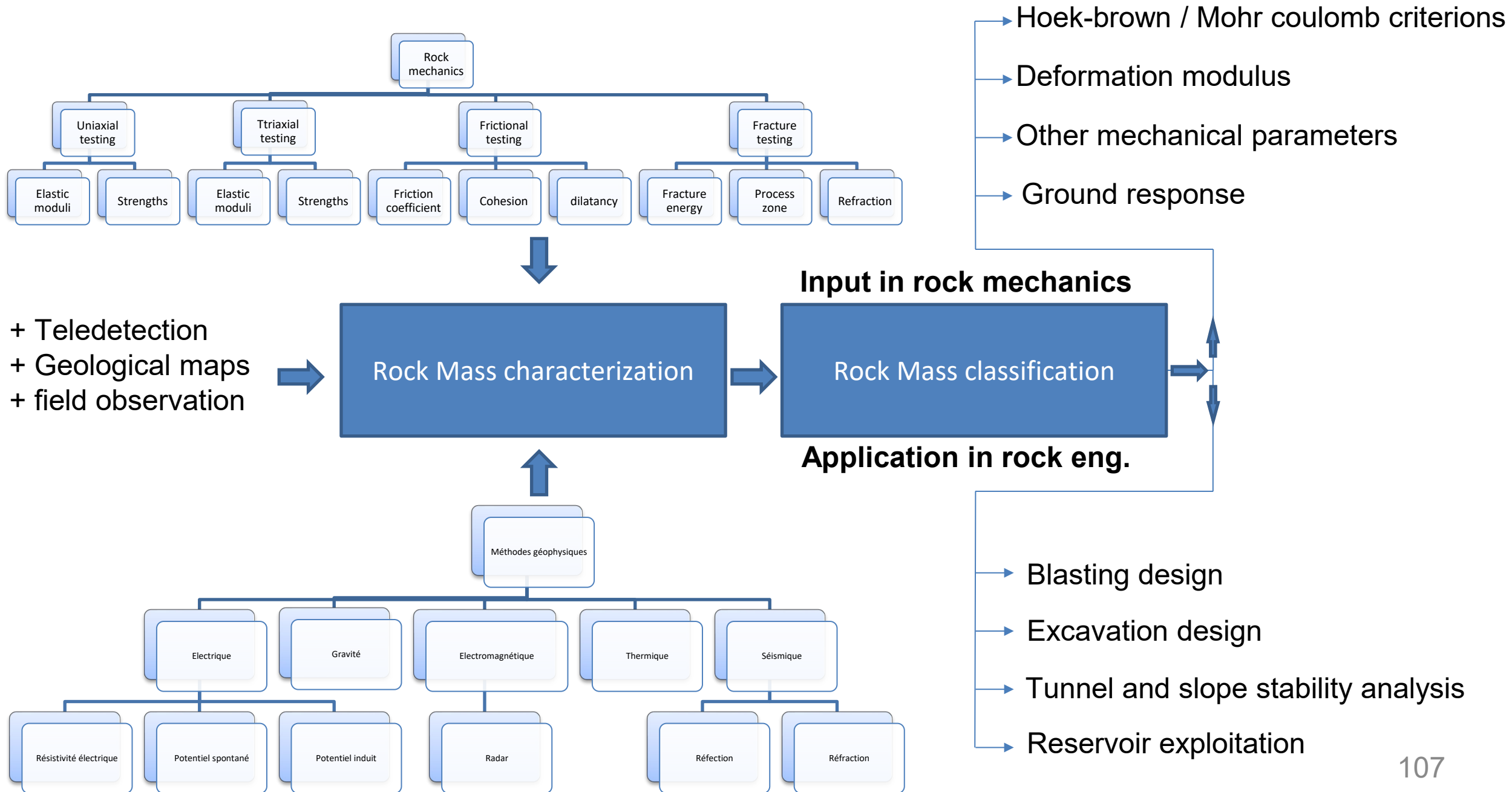


This course

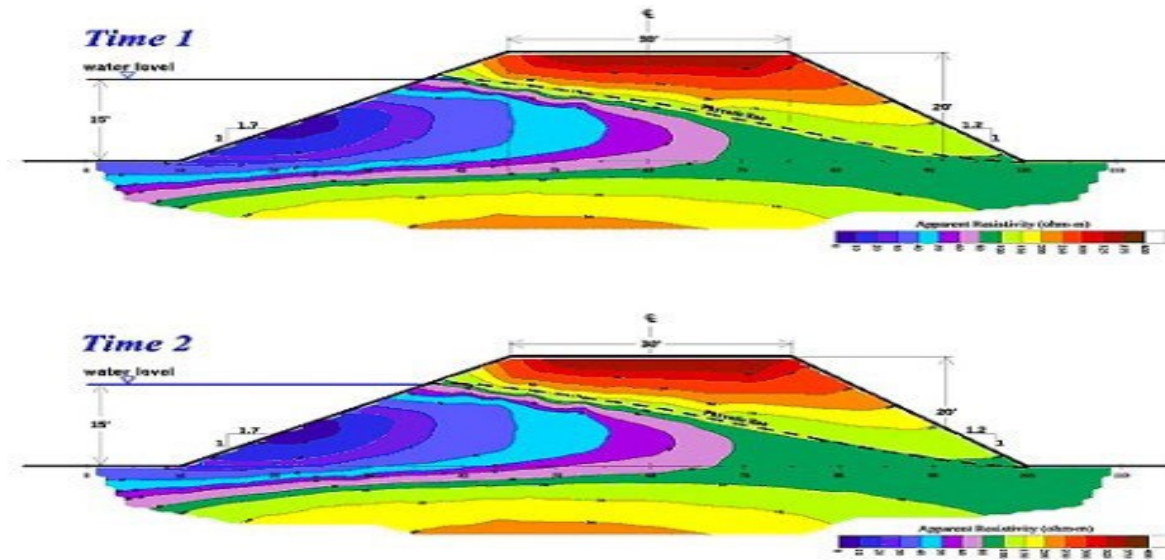
- **Indirect surface surveys** (surface geophysics)
- **Direct surveys** (excavation, drilling, gallery)
- **Indirect borehole surveys** (geophysical logging and other associated tests)



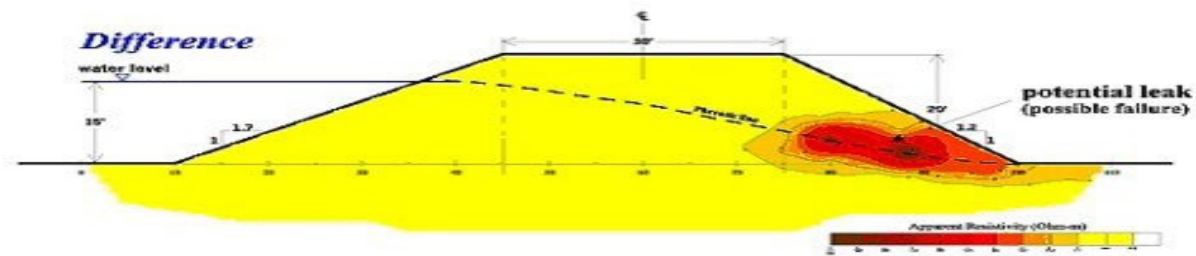
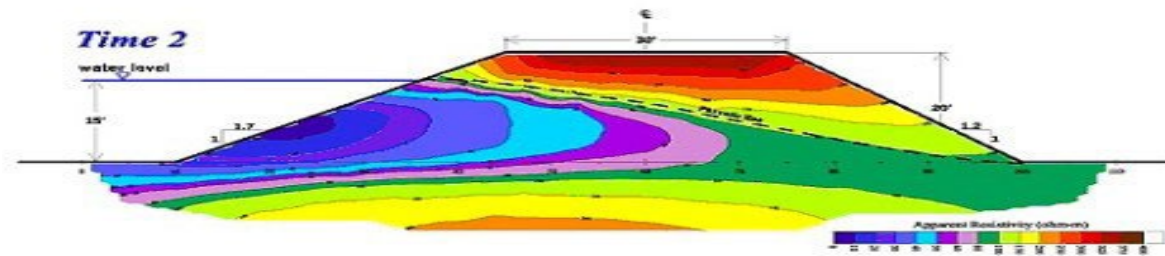
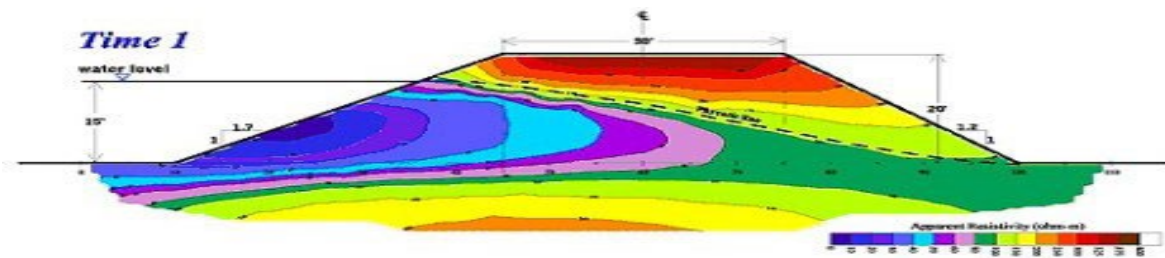
1. Introduction



Example of dam integrity assessment using resistivity

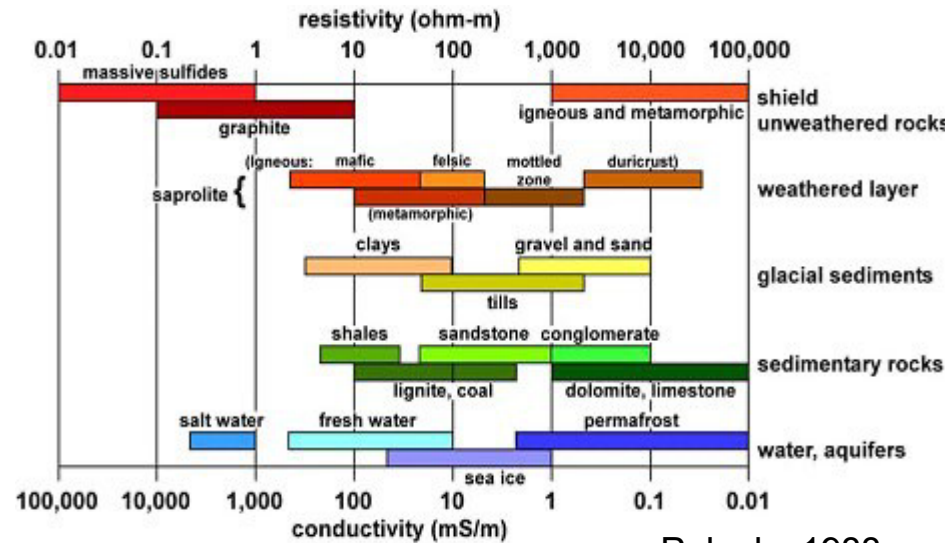


Example of dam integrity assessment using resistivity



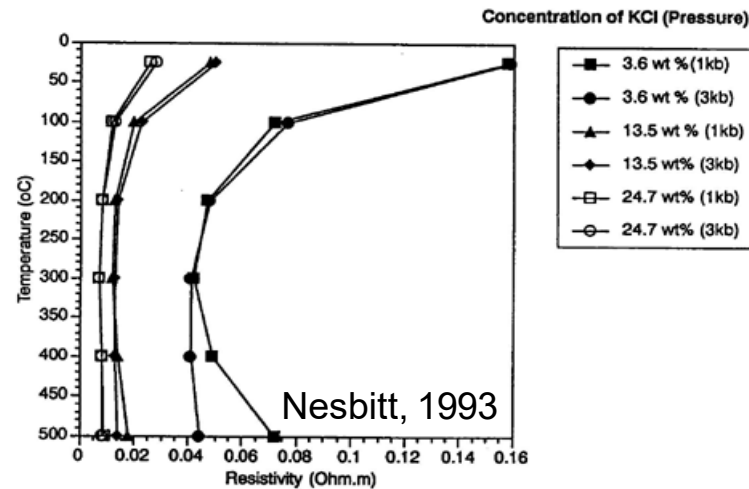
What controls the amplitude of electrical resistivity?

What we measure



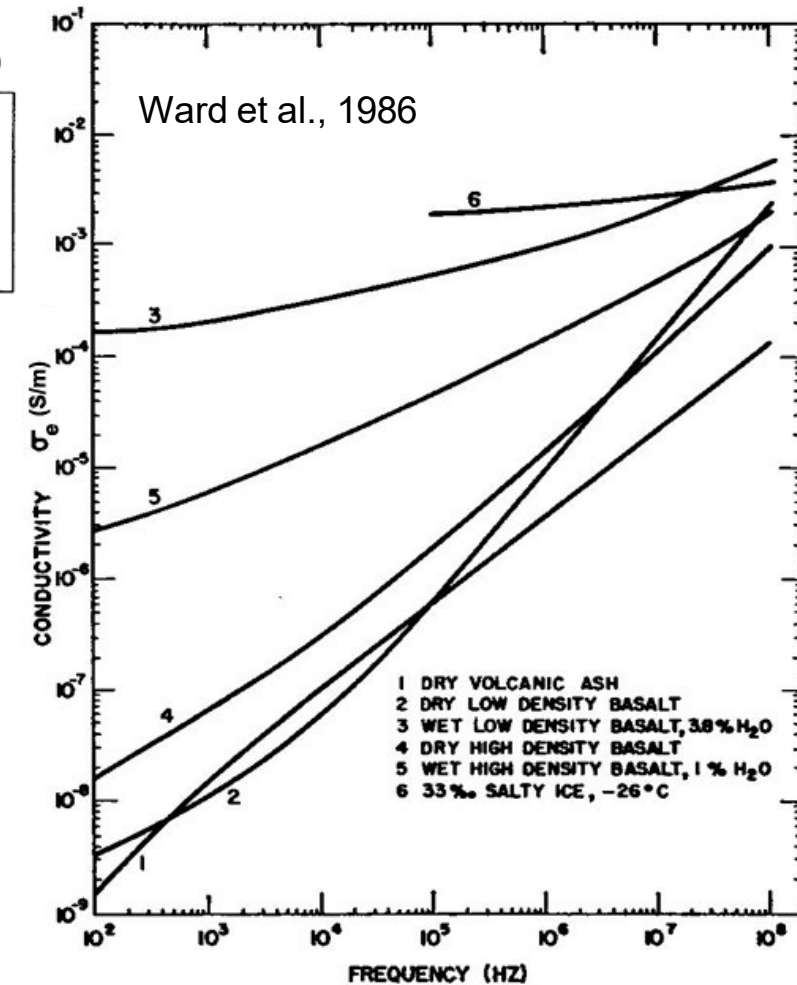
Palacky 1988

Where we measure it



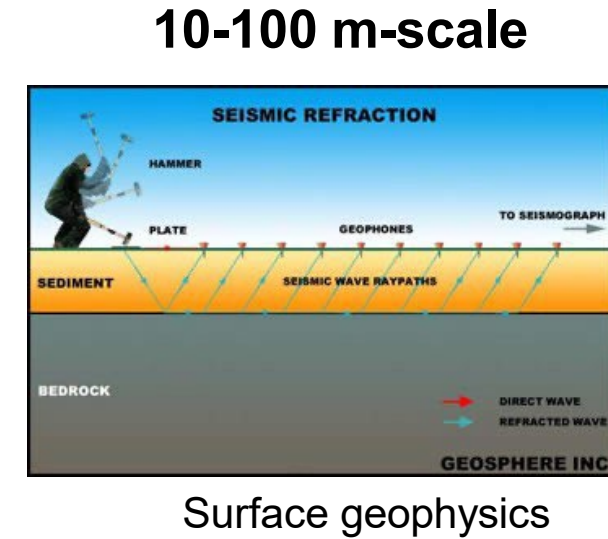
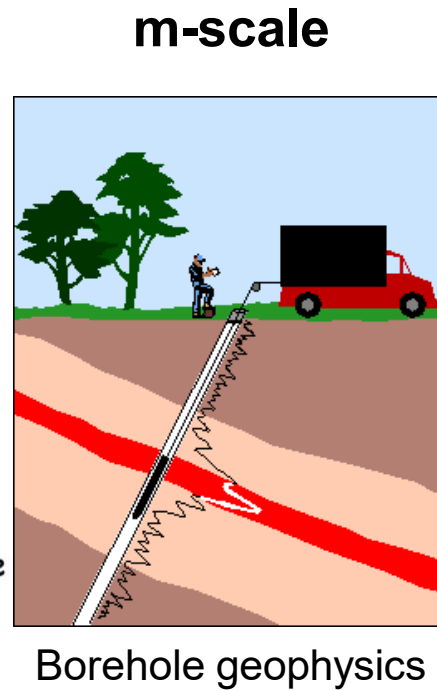
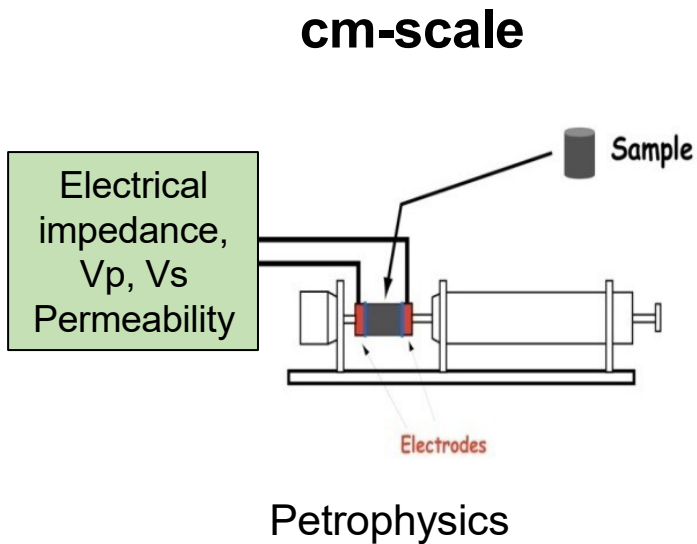
Nesbitt, 1993

How we measure it



Can we understand this quantitatively?

Scale of investigation



Course schedule

monday17 feb	Introduction to rock mass	Marie
Tuesday 18 feb	microstructures and texture	Ghassan
Lundi 24 feb	Porosity and perm lecture	Alex
Mardi 25 feb	Porosity and perm exercices	Alex +TA Andrea
Lundi 3 mars	rock phys acoustics lecture	2H Marie 1H Lucas
Mardi 4 mars	rock phys acoustics exercices Info	Marie + TA Francesco
lundi 10 mars	rock phys elect lecture	Marie
Mardi 11 mars	rock phys elect exercices Info	Marie + TA Franco
lundi 17mars	TP - Session 1	TA
Mardi 18 mars	TP - Session 2	TA
lundi 24 mars	Borehole geophy intro- radioactivity lecture	Marie
Mardi 25 mars	Borehole geophy intro- radioactivity exo	Marie +TA Karin
Lundi 31 mars	TP - Session 3	TA
Mardi 1 avril	TP - Session 4	TA
lundi 7 avril	Borehole geophy sonic electric lecture	Marie
mardi 8 avril	Borehole geophy sonic electric exo	Marie +TA Franco
lundi 14 avril	TP - Session 5	TA
mardi 15 avril	TP - Session 6	TA
lundi 21 avril	Vacances	
mardi 22 avril	Vacances	
lundi 28 avril	in situ stress lecture	Marie
mardi 29 avril	in situ stress exercices	Marie +TA Antoine
lundi 5 mai	TP - Session 7	TA
mardi 6 mai	TP - Session 8	TA
lundi 12 mai	seismic refraction reflexion lecture	Marie
mardi 13 mai	seismic refraction reflexion exercice	Marie +TA Francesco
lundi 19 mai	electric radar lecture	Marie
mardi 20mai	electric radar exercice	Marie +TA Karin
lundi 26 mai	EXAM	Marie, Alex, TAs
mardi 27 mai	EXAM	Marie, Alex, TAs

Course schedule

TP1	Porosity / xray analysis	Ghassan
TP2	Permeability	Andrea
TP3	Electrical impedance	Franco
TP4	seismic velocity	Simon/Lucas
TP5	Uniaxial	Francesco
TP6	triaxial	Laurent
TP7	direct shear	Karin
TP8	Microscopy	Cindy