# Rock Mechanics I

Course CEE9577

# Properties of Rocks

# Rock as an Engineering Material

## *Rock as an Engineering Material*

- It differs from other engineering materials in that it contains discontinuities such as joints, bedding planes, folds, shear zones and faults which render its structure discontinuous
- It could be broadly classified into two categories according to the scale and its influence on the overall behaviour of the rock mass

## *Intact Rock*

- Continuum of polycrystalline solid between continuities consisting of an aggregate of minerals or grains. Its properties are governed by the physical properties of the materials of which it is composed of and the manner in which they are bonded to each other

## *Rock Mass*

- The in-situ medium which comprises intact rock blocks separated by discontinuities. Rock masses are generally discontinuous and often have heterogeneous and anisotropic properties.

# Simplified Representation of Transition from Intact Rock to Heavily Jointed Rock Mass

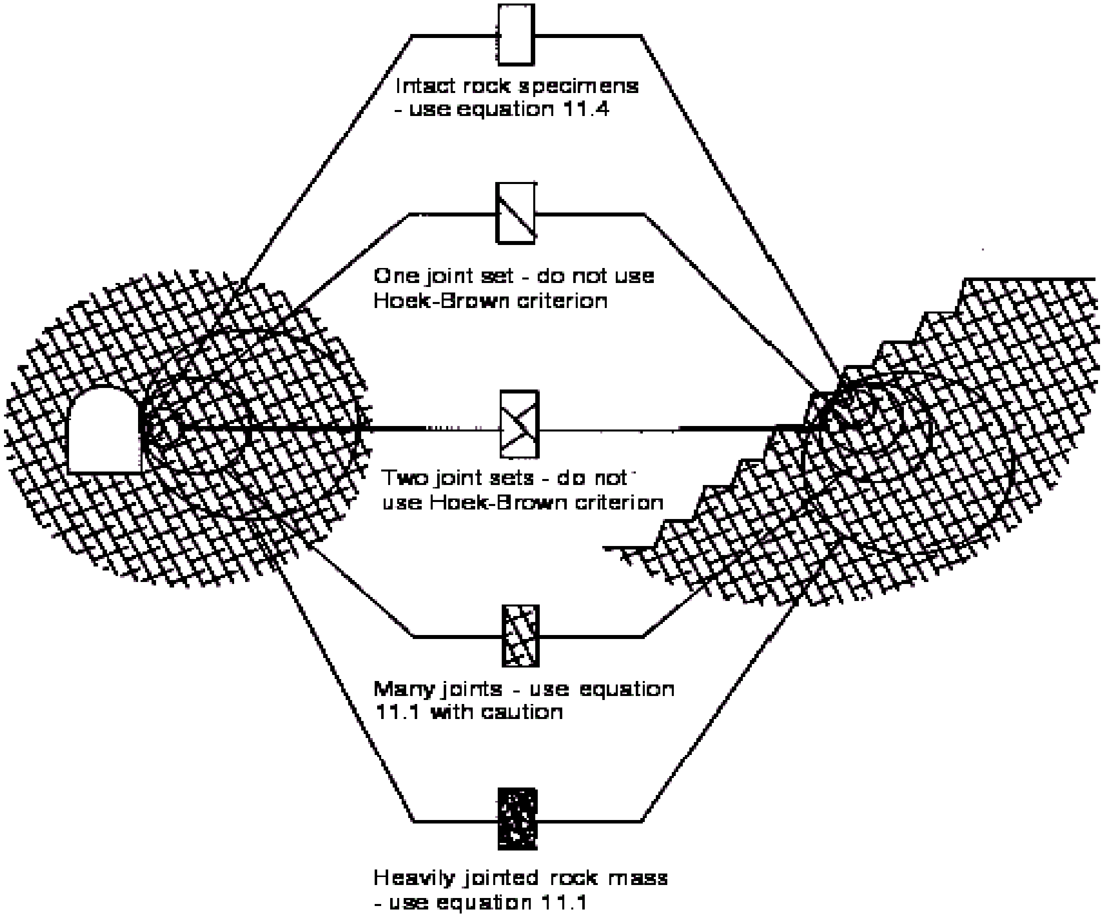

Figure 11.5: Idealised diagram showing the transition from intact to a heavily jointed rock mass with increasing sample size.

***Simplified representation of transition from intact rock to heavily jointed rock mass due to scale effect (after Hoek, 1995)***

# Geological Classification of Intact Rock

## Geological Classification of Intact Rock

### *(a) Intact Rock - Rock-forming minerals*

Rock are composed of minerals. The common rock forming minerals are:

- Orthoclase felspar
- Plagioclase felspar
- Quartz
- Muscovite
- Biotite
- Hornblende
- Augite
- Olivine
- Calcite
- Dolomite
- Kaolinite
- Hematite

# Common Rock Forming Minerals

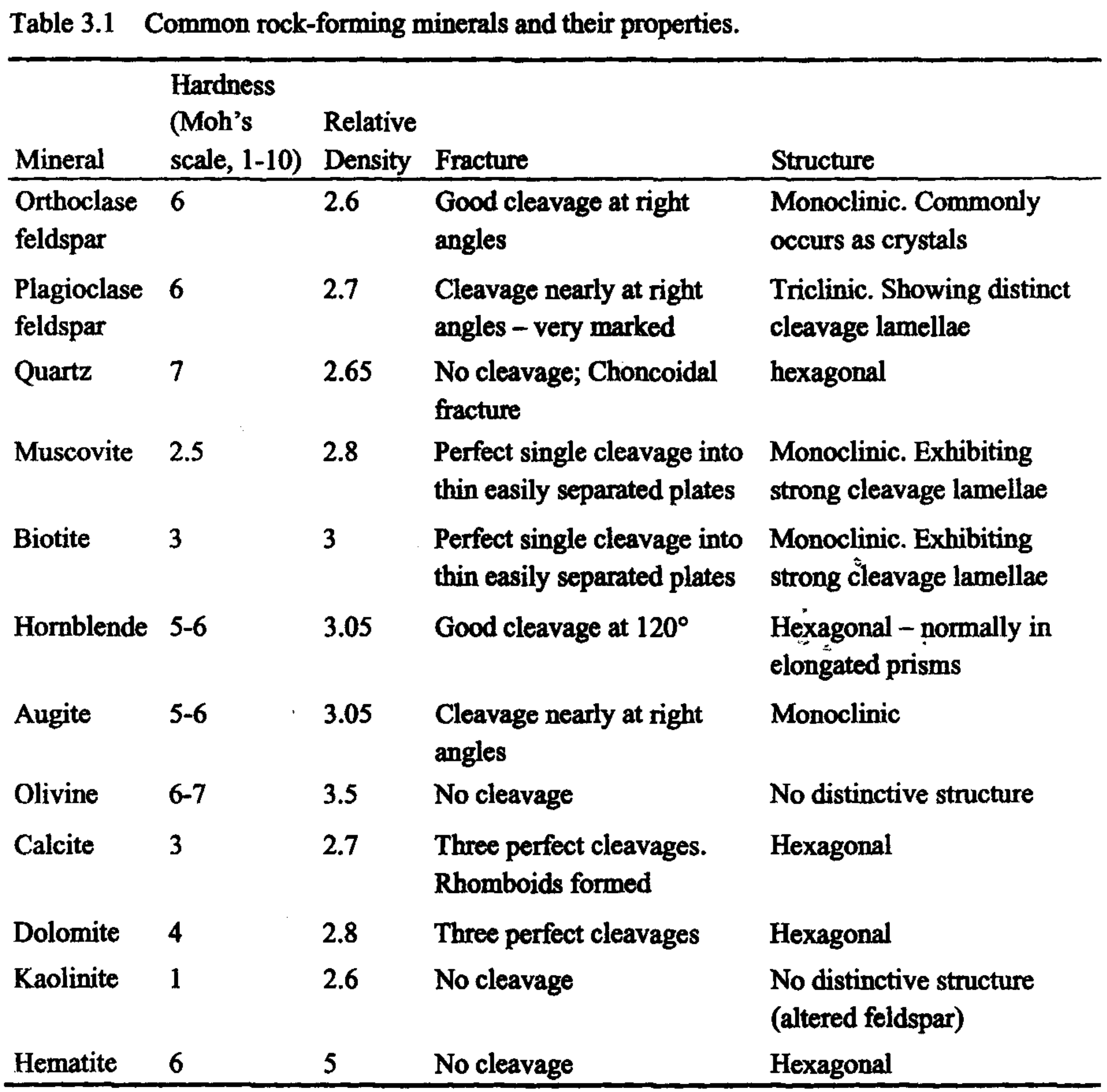

Table 3.1 Common rock-forming minerals and their properties.

| Mineral | Hardness (Moh's scale, 1-10) | Relative Density | Fracture | Structure |
|---|---|---|---|---|
| Orthoclase feldspar | 6 | 2.6 | Good cleavage at right angles | Monoclinic. Commonly occurs as crystals |
| Plagioclase feldspar | 6 | 2.7 | Cleavage nearly at right angles – very marked | Triclinic. Showing distinct cleavage lamellae |
| Quartz | 7 | 2.65 | No cleavage; Choncoidal fracture | hexagonal |
| Muscovite | 2.5 | 2.8 | Perfect single cleavage into thin easily separated plates | Monoclinic. Exhibiting strong cleavage lamellae |
| Biotite | 3 | 3 | Perfect single cleavage into thin easily separated plates | Monoclinic. Exhibiting strong cleavage lamellae |
| Hornblende | 5-6 | 3.05 | Good cleavage at 120° | Hexagonal – normally in elongated prisms |
| Augite | 5-6 | 3.05 | Cleavage nearly at right angles | Monoclinic |
| Olivine | 6-7 | 3.5 | No cleavage | No distinctive structure |
| Calcite | 3 | 2.7 | Three perfect cleavages. Rhomboids formed | Hexagonal |
| Dolomite | 4 | 2.8 | Three perfect cleavages | Hexagonal |
| Kaolinite | 1 | 2.6 | No cleavage | No distinctive structure (altered feldspar) |
| Hematite | 6 | 5 | No cleavage | Hexagonal |

# Intact Rock – Elementary Rock Classification

## *(b) Intact Rock – Elementary Rock Classification*

Intact rocks are classified into three (3) main groups according to processes by which they are formed:

- ***Igneous Rocks*** – formed by crystallization of molten magma. Mode of crystallization at depth or by extrusion (rising from depth) and the rate of cooling affect the rock structure and crystal size
- ***Metamorphic Rocks*** – formed as a result of metamorphism which is the solid state conversion of pre-existing rocks by temperature, pressure or chemical changes
- ***Sedimentary Rocks*** – sedimentary rocks are formed from the consolidation of sediments. As a result of this process, sedimentary rocks almost invariably possess a distinct stratified, or bedded structure

# Geological Classification of Igneous Rocks

## *Geological Classification of Igneous Rocks*

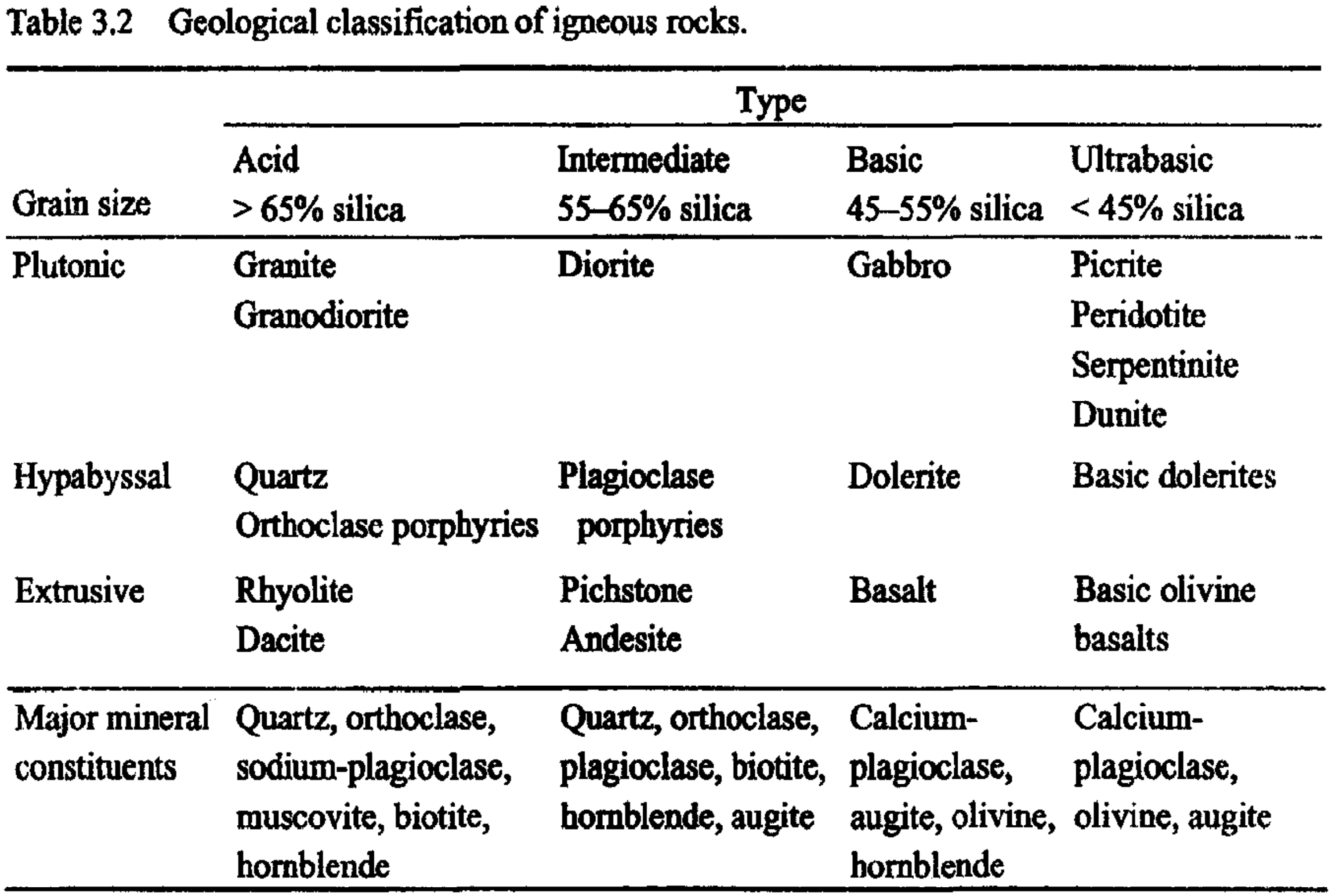

Table 3.2 Geological classification of igneous rocks.

| | Type | | | |
|---|---|---|---|---|
| Grain size | Acid<br>> 65% silica | Intermediate<br>55–65% silica | Basic<br>45–55% silica | Ultrabasic<br>< 45% silica |
| Plutonic | Granite<br>Granodiorite | Diorite | Gabbro | Picrite<br>Peridotite<br>Serpentinite<br>Dunite |
| Hypabyssal | Quartz<br>Orthoclase porphyries | Plagioclase porphyries | Dolerite | Basic dolerites |
| Extrusive | Rhyolite<br>Dacite | Pichstone<br>Andesite | Basalt | Basic olivine basalts |
| Major mineral constituents | Quartz, orthoclase, sodium-plagioclase, muscovite, biotite, hornblende | Quartz, orthoclase, plagioclase, biotite, hornblende, augite | Calcium-plagioclase, augite, olivine, hornblende | Calcium-plagioclase, olivine, augite |

# Igneous Rocks in Thin Sections

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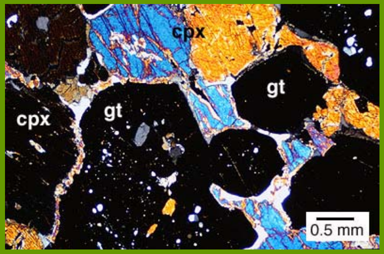
- Granite

- Diorite

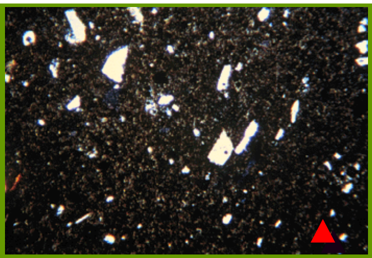
**Igneous Rocks**

- Gabbro

- Diabase

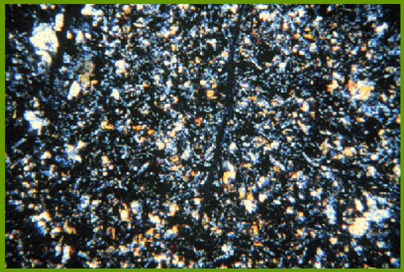


- Serpentinite



- Rhyolite

- Andesite



- Basalt

cross-sections under polarized light

# Mafic Igneous Rocks

## Mafic Igneous Rocks

*Mafic minerals are usually dark in colour with high s..g (>3)*

- gabbro
- diabase
- basalt

# Felsic Igneous Rocks

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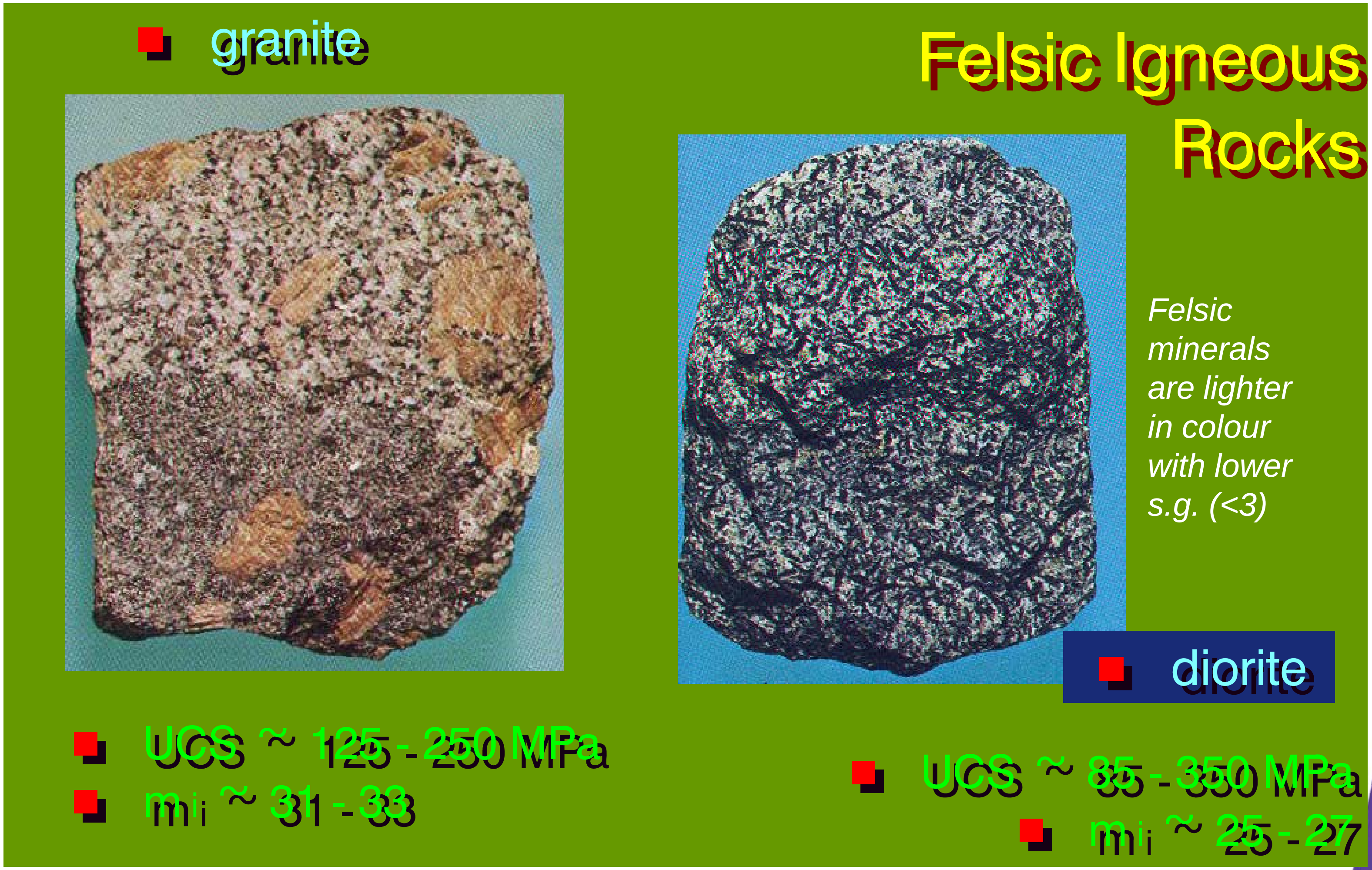


## Felsic Igneous Rocks

- granite
- UCS ~ 125 - 250 MPa
- $m_i$ ~ 31 - 33

*Felsic minerals are lighter in colour with lower s.g. (<3)*

- diorite
- UCS ~ 85 - 350 MPa
- $m_i$ ~ 25 - 27

# Geological Classification of Metamorphic Rocks

- **Geological Classification of Metamorphic Rocks**

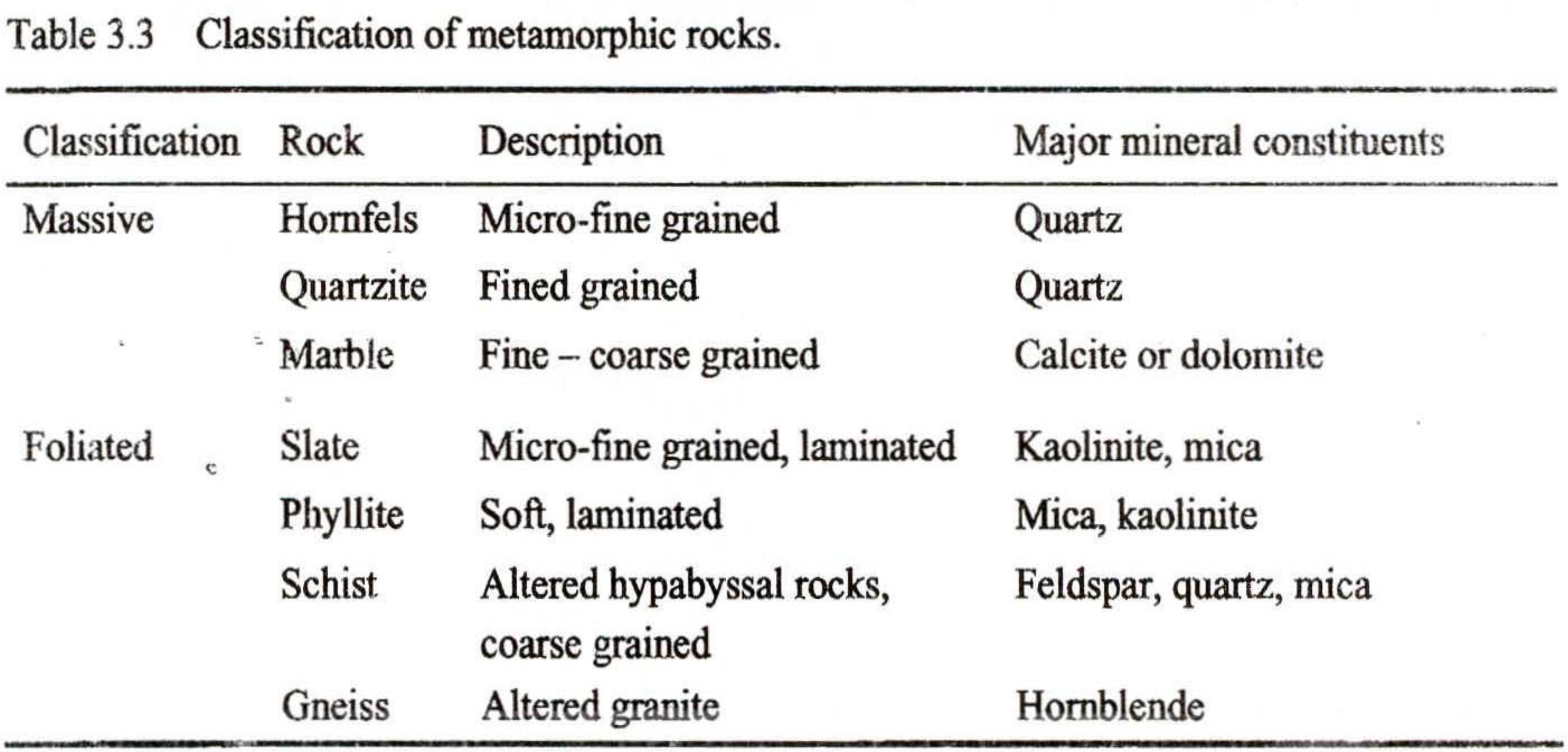
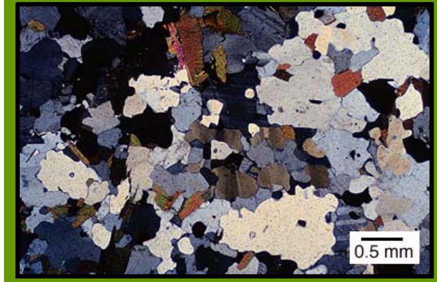


Table 3.3 Classification of metamorphic rocks.

| Classification | Rock | Description | Major mineral constituents |
|---|---|---|---|
| Massive | Hornfels | Micro-fine grained | Quartz |
| | Quartzite | Fined grained | Quartz |
| | Marble | Fine – coarse grained | Calcite or dolomite |
| Foliated | Slate | Micro-fine grained, laminated | Kaolinite, mica |
| | Phyllite | Soft, laminated | Mica, kaolinite |
| | Schist | Altered hypabyssal rocks, coarse grained | Feldspar, quartz, mica |
| | Gneiss | Altered granite | Hornblende |

# Metamorphic Rocks in Thin Sections

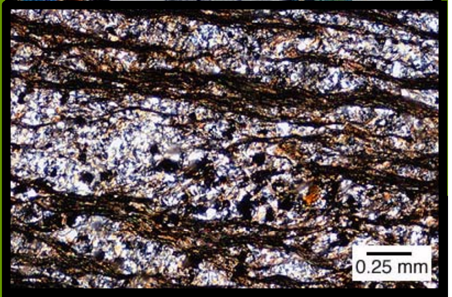
## Metamorphic Rocks



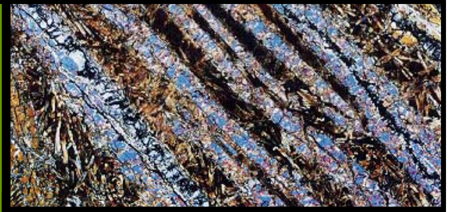
- Granulite

- Gneiss

- Amphibolite

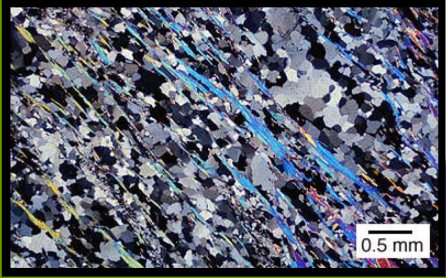


- Slate



- Phyllite

- Hornfels



- Schist

cross-sections under polarized light

# Geological Classification of Sedimentary Rocks

## Geological Classification of Sedimentary Rocks

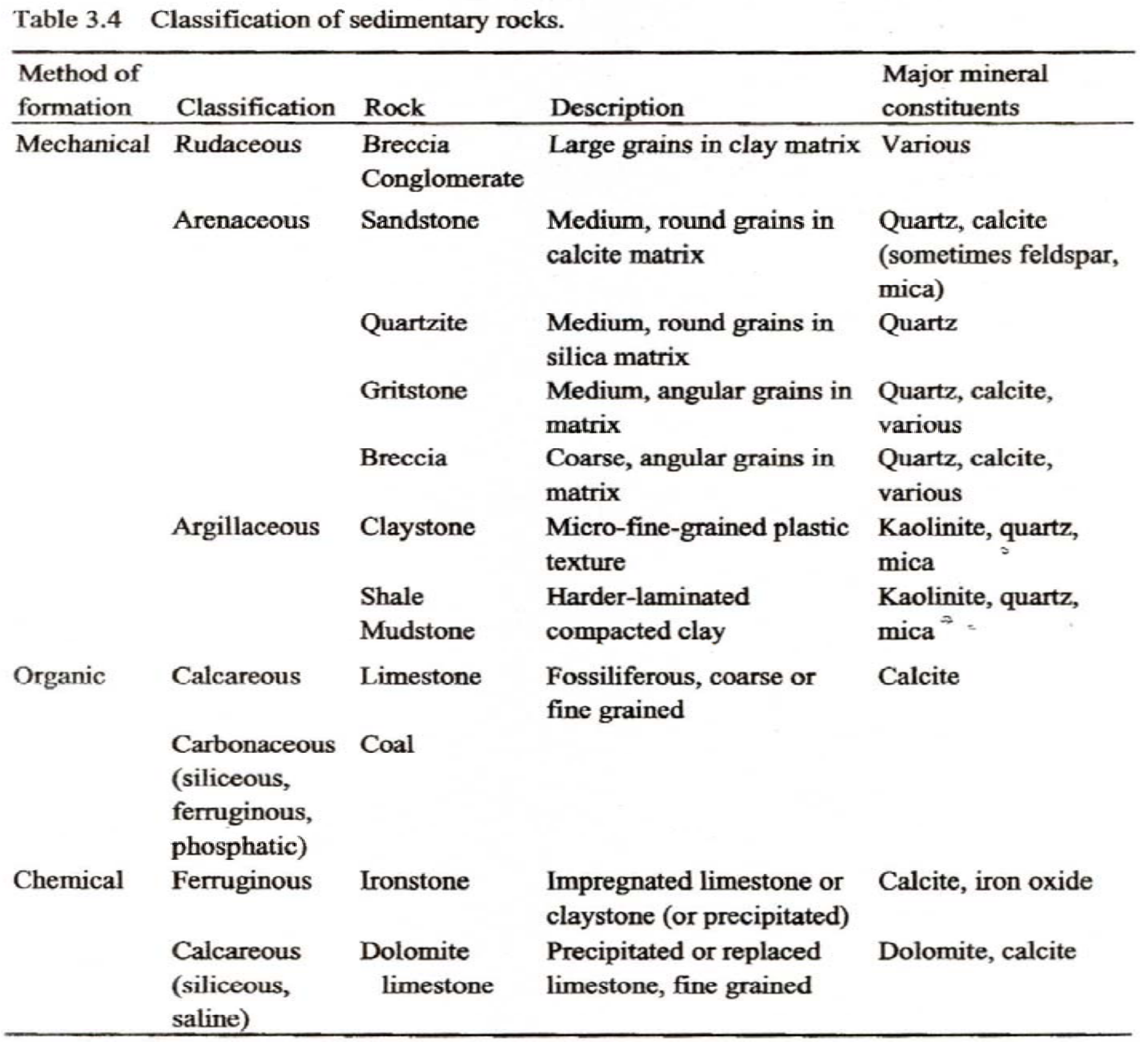
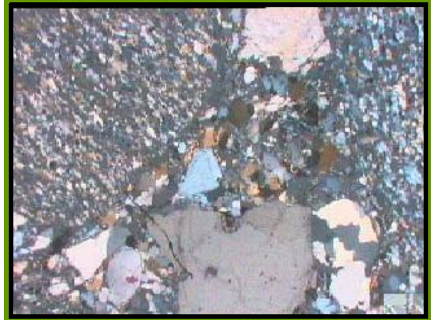


Table 3.4 Classification of sedimentary rocks.

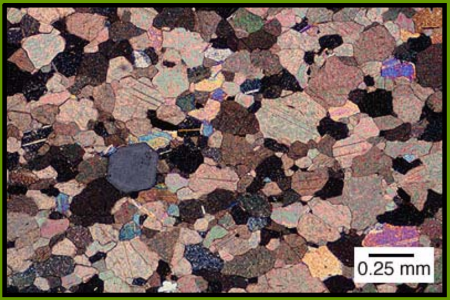
| Method of formation | Classification | Rock | Description | Major mineral constituents |
|---|---|---|---|---|
| Mechanical | Rudaceous | Breccia<br>Conglomerate | Large grains in clay matrix | Various |
| | Arenaceous | Sandstone | Medium, round grains in calcite matrix | Quartz, calcite (sometimes feldspar, mica) |
| | | Quartzite | Medium, round grains in silica matrix | Quartz |
| | | Gritstone | Medium, angular grains in matrix | Quartz, calcite, various |
| | | Breccia | Coarse, angular grains in matrix | Quartz, calcite, various |
| | Argillaceous | Claystone | Micro-fine-grained plastic texture | Kaolinite, quartz, mica |
| | | Shale<br>Mudstone | Harder-laminated compacted clay | Kaolinite, quartz, mica |
| Organic | Calcareous | Limestone | Fossiliferous, coarse or fine grained | Calcite |
| | Carbonaceous (siliceous, ferruginous, phosphatic) | Coal | | |
| Chemical | Ferruginous | Ironstone | Impregnated limestone or claystone (or precipitated) | Calcite, iron oxide |
| | Calcareous (siliceous, saline) | Dolomite limestone | Precipitated or replaced limestone, fine grained | Dolomite, calcite |

# Sedimentary Rocks in Thin Sections

## Sedimentary Rocks



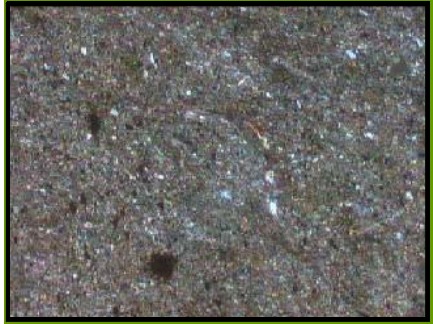
- Conglomerate



  - Microcrystalline Limestone

- Sandstone

  - Argillaceous Limestone



- Mudstone

cross-sections under polarized light

# Engineering Classification of Intact Rocks

***Engineering Classification of Intact Rocks***

- The engineering classification of intact rocks is based of strength and/or deformation properties of the rock.
- According to the classification system recommended by the International Society of Rock Mechanics (ISRM 1978c), rock may range from extremely weak to extremely strong depending on the unconfined compressive strength (or Point Load Strength Index) or approximate field identification.

# Engineering Classification of Rocks by Strength

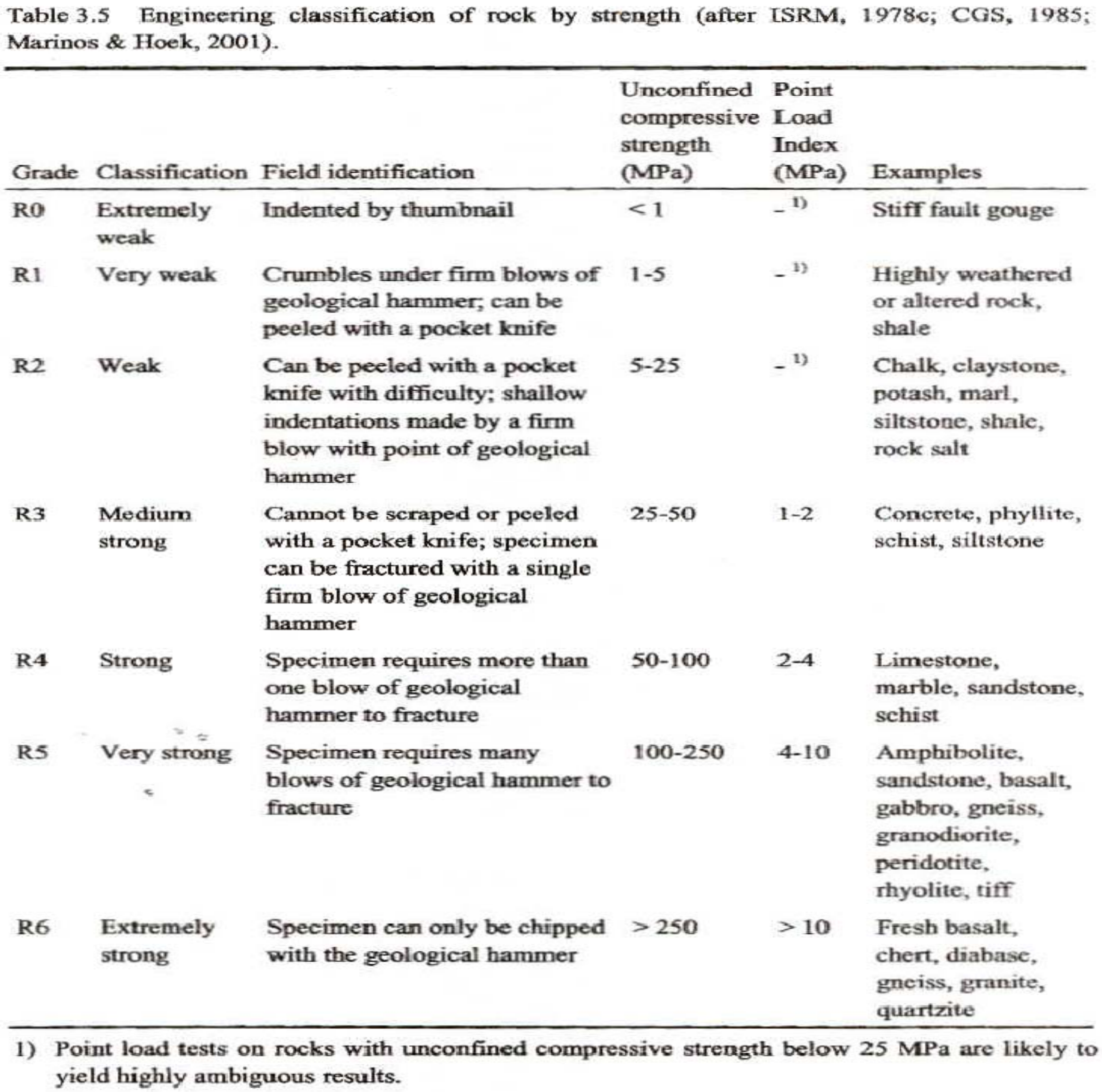


Table 3.5 Engineering classification of rock by strength (after ISRM, 1978c; CGS, 1985; Marinos & Hoek, 2001).

| Grade | Classification | Field identification | Unconfined compressive strength (MPa) | Point Load Index (MPa) | Examples |
|---|---|---|---|---|---|
| R0 | Extremely weak | Indented by thumbnail | < 1 | - 1) | Stiff fault gouge |
| R1 | Very weak | Crumbles under firm blows of geological hammer; can be peeled with a pocket knife | 1-5 | - 1) | Highly weathered or altered rock, shale |
| R2 | Weak | Can be peeled with a pocket knife with difficulty; shallow indentations made by a firm blow with point of geological hammer | 5-25 | - 1) | Chalk, claystone, potash, marl, siltstone, shale, rock salt |
| R3 | Medium strong | Cannot be scraped or peeled with a pocket knife; specimen can be fractured with a single firm blow of geological hammer | 25-50 | 1-2 | Concrete, phyllite, schist, siltstone |
| R4 | Strong | Specimen requires more than one blow of geological hammer to fracture | 50-100 | 2-4 | Limestone, marble, sandstone, schist |
| R5 | Very strong | Specimen requires many blows of geological hammer to fracture | 100-250 | 4-10 | Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, peridotite, rhyolite, tiff |
| R6 | Extremely strong | Specimen can only be chipped with the geological hammer | > 250 | > 10 | Fresh basalt, chert, diabase, gneiss, granite, quartzite |

1) Point load tests on rocks with unconfined compressive strength below 25 MPa are likely to yield highly ambiguous results.

# Engineering Classification of Intact Rocks by Strength and Deformation Properties

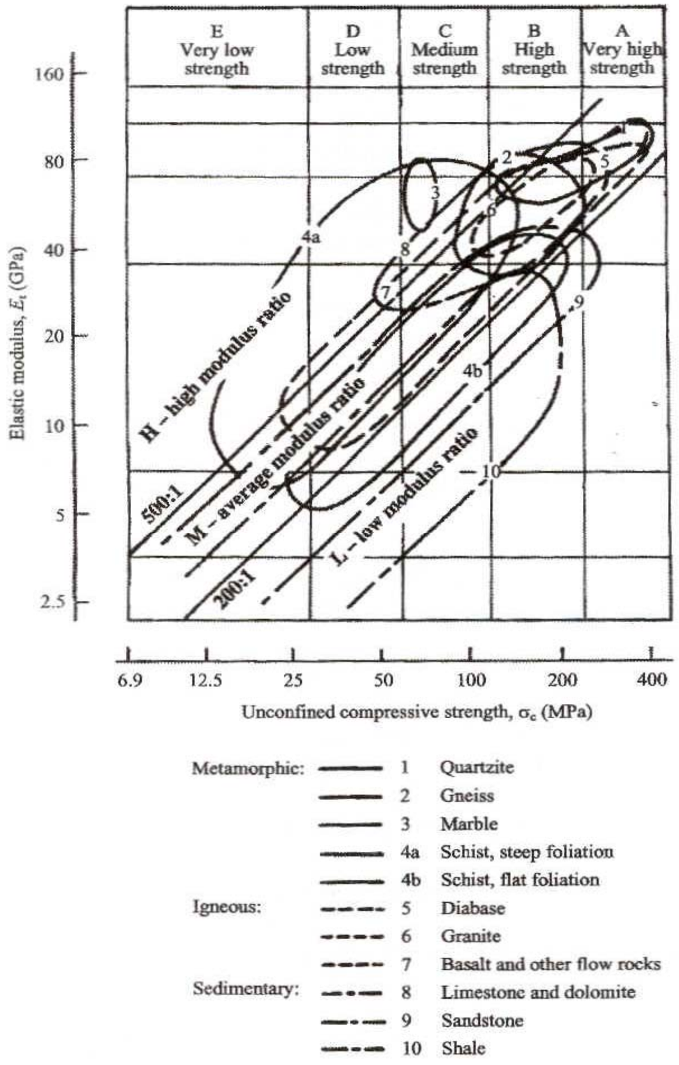


Fig. 3.1 Engineering classification of intact rocks ($E_t$ is the tangent modulus at 50% ultimate strength) (after Deere & Miller, 1966).

***Engineering Classification of Intact Rocks by Strength and Deformation Properties (After Deere and Miller, 1966)***

# Index Properties of Intact Rocks

Index properties of rocks are generally determined in the laboratory or in the field to provide an initial quantitative description of the rocks. They can be used to estimate the mechanical and hydraulic properties of the rocks. However, determination of the index properties could not replace detailed characterization of the rocks.

# Common Laboratory Index Tests for Rock

| | |
|---|---|
| *Unconfined (uniaxial) compression* | Primary index test for strength and deformability of intact rock; required input to rock mass classification systems. |
| *Point load test* | Indirect method to determine unconfined compressive (UC) strength; can be performed in the field on core pieces unsuitable for UC tests |
| *Water content* | Indirect indication of porosity of intact rock or clay content of sedimentary rock. |
| *Unit weight and total porosity* | Indirect indication of weathering and soundness. |
| *Splitting strength of rock (Brazilian tensile strength method)* | Indirect method to determine the tensile strength of intact rock. |
| *Durability (Slake durability)* | Index of weatherability of rock exposed in excavations. |
| *Specific gravity of solids* | Indirect indication of soundness of rock intended for use as riprap. |
| *Rebound number* | Index of relative hardness of intact rock cores. |
| *Permeability* | Intact rock (no joints or major defects). |
| *Petrographic examination* | Performed on representative cores of each significant lithologic unit. |
| *Specific gravity and absorption* | Indirect indication of soundness and deformability |

# Typical Porosity Values of Intact Rocks

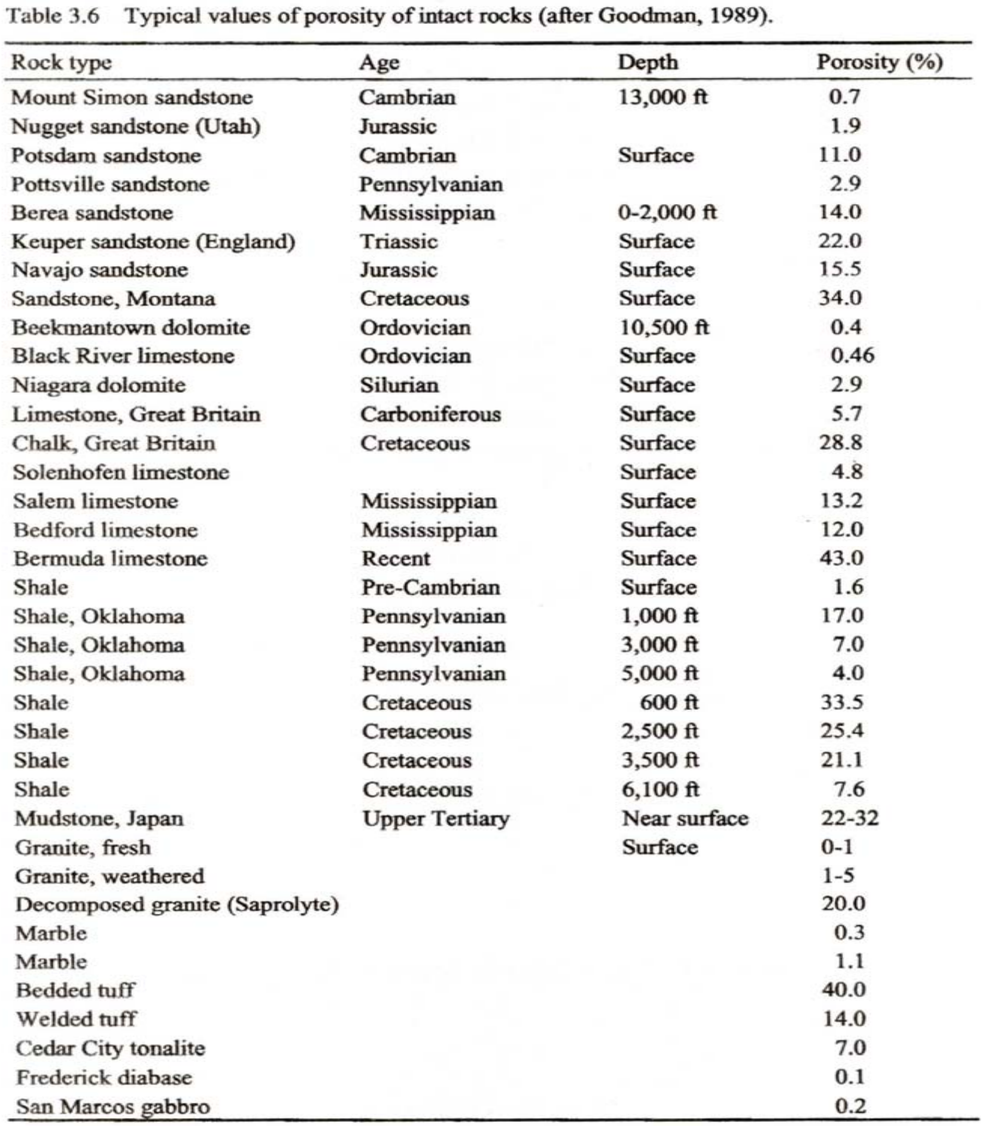


Table 3.6 Typical values of porosity of intact rocks (after Goodman, 1989).

| Rock type | Age | Depth | Porosity (%) |
|---|---|---|---|
| Mount Simon sandstone | Cambrian | 13,000 ft | 0.7 |
| Nugget sandstone (Utah) | Jurassic | | 1.9 |
| Potsdam sandstone | Cambrian | Surface | 11.0 |
| Pottsville sandstone | Pennsylvanian | | 2.9 |
| Berea sandstone | Mississippian | 0-2,000 ft | 14.0 |
| Keuper sandstone (England) | Triassic | Surface | 22.0 |
| Navajo sandstone | Jurassic | Surface | 15.5 |
| Sandstone, Montana | Cretaceous | Surface | 34.0 |
| Beekmantown dolomite | Ordovician | 10,500 ft | 0.4 |
| Black River limestone | Ordovician | Surface | 0.46 |
| Niagara dolomite | Silurian | Surface | 2.9 |
| Limestone, Great Britain | Carboniferous | Surface | 5.7 |
| Chalk, Great Britain | Cretaceous | Surface | 28.8 |
| Solenhofen limestone | | Surface | 4.8 |
| Salem limestone | Mississippian | Surface | 13.2 |
| Bedford limestone | Mississippian | Surface | 12.0 |
| Bermuda limestone | Recent | Surface | 43.0 |
| Shale | Pre-Cambrian | Surface | 1.6 |
| Shale, Oklahoma | Pennsylvanian | 1,000 ft | 17.0 |
| Shale, Oklahoma | Pennsylvanian | 3,000 ft | 7.0 |
| Shale, Oklahoma | Pennsylvanian | 5,000 ft | 4.0 |
| Shale | Cretaceous | 600 ft | 33.5 |
| Shale | Cretaceous | 2,500 ft | 25.4 |
| Shale | Cretaceous | 3,500 ft | 21.1 |
| Shale | Cretaceous | 6,100 ft | 7.6 |
| Mudstone, Japan | Upper Tertiary | Near surface | 22-32 |
| Granite, fresh | | Surface | 0-1 |
| Granite, weathered | | | 1-5 |
| Decomposed granite (Saprolyte) | | | 20.0 |
| Marble | | | 0.3 |
| Marble | | | 1.1 |
| Bedded tuff | | | 40.0 |
| Welded tuff | | | 14.0 |
| Cedar City tonalite | | | 7.0 |
| Frederick diabase | | | 0.1 |
| San Marcos gabbro | | | 0.2 |

***Porosity (n)*** *– ratio of void or pore volume , Vv to the total volume, V of the rock. It is dimensionless and varies significantly for different rock types or even for the same rock type due to different factors such as grain size distribution, grain shape, depth and pressure*

$n = Vv/V$

# Point Load Strength Index

The Point Load Strength Index is often used to provide a quick assessment of the uniaxial tensile and compressive strength of the rock and can easily be determined in the field or laboratory on rock lumps or cored samples.

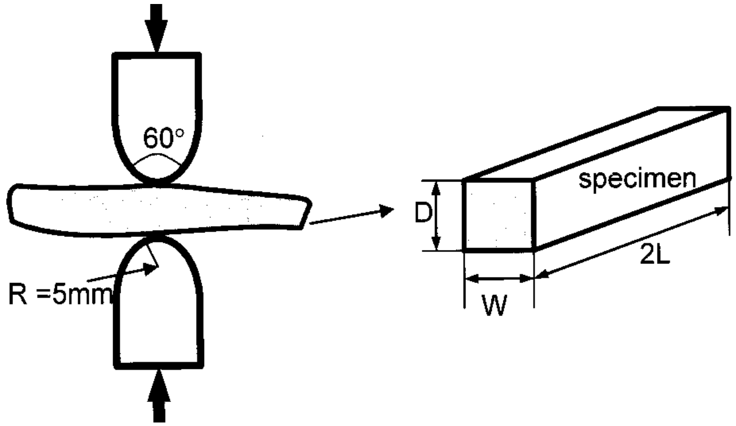


**Fig. 4.1**

. Schematic figure showing point load test apparatus and the specimen.

# Determination of Point Load Strength Index

**Step 1**: calculate initial index, $I_s$:

$$I_s = \frac{P}{D_e^2} \tag{4.1}$$

where $D_e$ is the specimen equivalent diameter in mm. According to the sample geometry and loading direction, $D_e$ is calculated as:

For diametral test, $D_e = D$

For axial, block and lump test, $D_e = \sqrt{WD/\pi}$

where $D$, $W$ are the parameters related to sample size in mm, as shown in Fig. 4.1.

**Step 2**: calculate standard index, $I_{s(50)}$ for size effect:

$$I_{s(50)} = \left(\frac{D_e}{50}\right)^{0.45} I_s \tag{4.2}$$

**Note: N-size core is 50mm dia.**

# Determination of Uniaxial Tensile Strength from Point Load Strength Index

**Step 3**: calculate uniaxial tensile strength, $T_0$:

$$T_0 = \frac{S_a P}{\left(L - \frac{1.7P}{22 I_{s(50)}}\right)^2} \tag{4.3}$$

where $L$ is the sample size in mm, as defined in Fig. 4.1; $S_a$ is the shape factor determined by:

For diametral test $S_a = 0.79$

For other test $S_a = 0.79\,D/L$

# Correlation Between Point Load Strength Index and Uniaxial Compressive Strength

The point load test also can be used for determining rock uniaxial compressive strength (UCS). A linear regression between the mean $I_{s(50)}$ and mean UCS values determined for 908 samples in US coal measure rocks yields the following equation (Rusnak and Mark 2000):

$$UCS = 1970 + 17.6 I_{s(50)} \tag{4.4}$$

where UCS and $I_{s(50)}$ are in psi, and 1 MPa is approximately equal to 145 psi.

The zero-intercept regression equation obtained from the entire data set is as follows:

$$UCS = 21 I_{s(50)} \tag{4.5}$$

Early studies (Bieniawski 1975) were conducted on hard, strong rocks, and found that relationship between UCS and the point load strength could be expressed as:

$$UCS = 24 I_{s(50)} \tag{4.6}$$

# Typical Values of Schmidt Hammer Rebound Numbers and Variation of Point Load Index

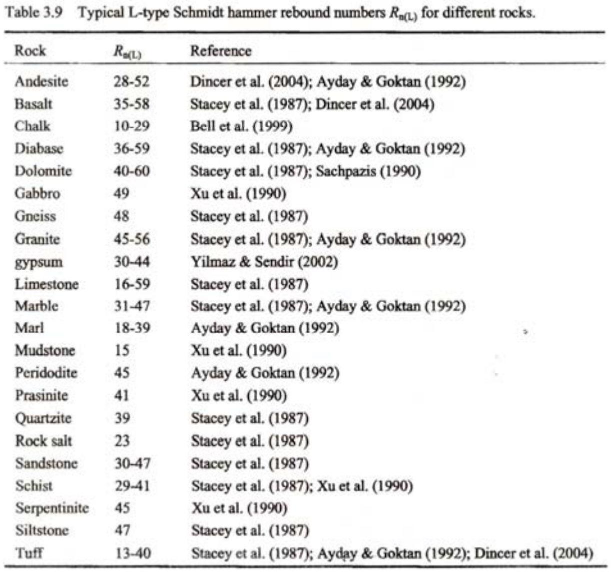


Table 3.9 Typical L-type Schmidt hammer rebound numbers $R_{n(L)}$ for different rocks.

| Rock | $R_{n(L)}$ | Reference |
|---|---|---|
| Andesite | 28-52 | Dincer et al. (2004); Ayday & Goktan (1992) |
| Basalt | 35-58 | Stacey et al. (1987); Dincer et al. (2004) |
| Chalk | 10-29 | Bell et al. (1999) |
| Diabase | 36-59 | Stacey et al. (1987); Ayday & Goktan (1992) |
| Dolomite | 40-60 | Stacey et al. (1987); Sachpazis (1990) |
| Gabbro | 49 | Xu et al. (1990) |
| Gneiss | 48 | Stacey et al. (1987) |
| Granite | 45-56 | Stacey et al. (1987); Ayday & Goktan (1992) |
| gypsum | 30-44 | Yilmaz & Sendir (2002) |
| Limestone | 16-59 | Stacey et al. (1987) |
| Marble | 31-47 | Stacey et al. (1987); Ayday & Goktan (1992) |
| Marl | 18-39 | Ayday & Goktan (1992) |
| Mudstone | 15 | Xu et al. (1990) |
| Peridodite | 45 | Ayday & Goktan (1992) |
| Prasinite | 41 | Xu et al. (1990) |
| Quartzite | 39 | Stacey et al. (1987) |
| Rock salt | 23 | Stacey et al. (1987) |
| Sandstone | 30-47 | Stacey et al. (1987) |
| Schist | 29-41 | Stacey et al. (1987); Xu et al. (1990) |
| Serpentinite | 45 | Xu et al. (1990) |
| Siltstone | 47 | Stacey et al. (1987) |
| Tuff | 13-40 | Stacey et al. (1987); Ayday & Goktan (1992); Dincer et al. (2004) |

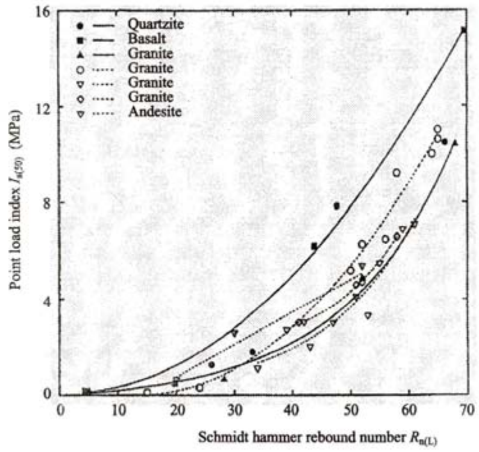


Fig. 3.9 Variation of point load index with Schmidt hammer rebound number for fresh and weathered crystalline rock (from Gupta & Rao, 1998).

**Typical Values of L-type Schmidt Hammer Rebound Numbers and Variation of Point Load Index with Schmidt Hammer Rebound Number**

# Dynamic Elastic Constants

- The dynamic elastic constants of a solid material can be determined by measuring the propagation velocities of the material.

- For an isotropic solid, there are two types of body or free-medium waves:
  - a longitudinal or compression wave which travels with velocity *V**p***
  - a shear or trasverse wave which travels with velocity ***Vs***

- These velocities are related to the elastic constants by

$$V_p = \left[\frac{Eg(1-\nu)}{\gamma(1+\nu)(1-2\nu)}\right]^{1/2}$$

$$V_s = \left[\frac{Gg}{\gamma}\right]^{1/2}$$

E = Modulus of elasticity, G = Modulus of rigidity (or Shear modulus)
**ν**= Poisson's ratio , g = gravitational acceleration, **γ**= Unit weight of the material

# Dynamic Elastic Constants

G can be determined from the shear wave velocity, Vs ,without the knowledge of the Poisson's ratio, ν. However the determination of the Elastic modulus E requires the value of ν.

Based on the relationship:

$$G = \frac{E}{2(1+\nu)}$$

Both the E and **ν**can be determined by the following equation:

$$E = \frac{V_s{}^2\gamma}{g}\left[\frac{3(V_p/V_s)^2 - 4}{(V_p/V_s)^2 - 1}\right]$$

$$\nu = \frac{1}{2}\left[\frac{(V_p/V_s)^2 - 2}{(V_p/V_s)^2 - 1}\right]$$

Also from the relationship

$$K = \frac{E}{3(1-2\nu)}$$

The bulk modulus K can be determined

$$K = \frac{\gamma}{g}V_s{}^2\left[\left(\frac{V_p}{V_s}\right)^2 - \frac{4}{3}\right]$$

# Range of P wave velocity and S Wave Velocity of Intact Rocks

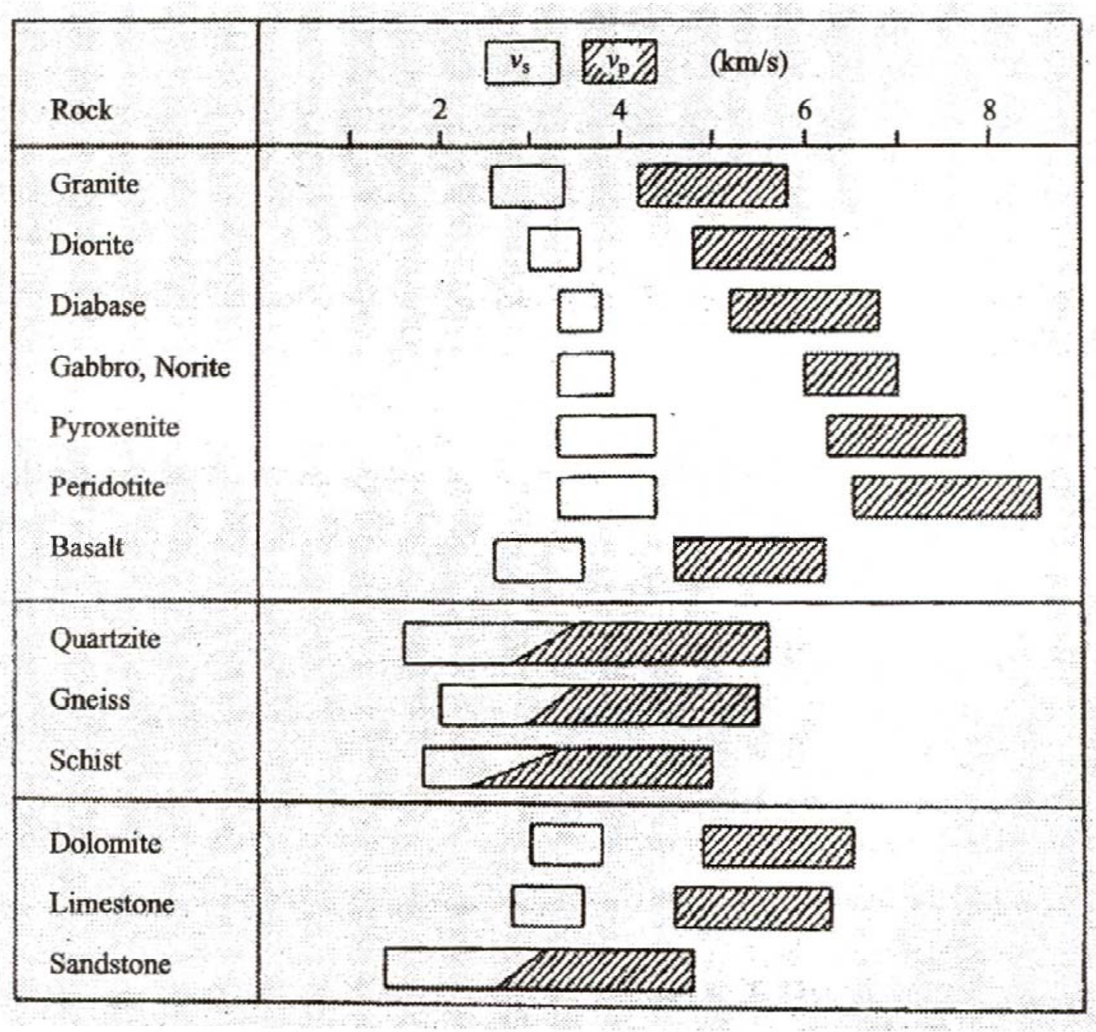


Fig. 3.4 Range of P-wave velocity $v_p$ and S-wave velocity $v_s$ of different rocks (from Schön, 1996).

**Range of P wave velocity and S Wave velocity of Intact Rocks**

# Variation of P Wave Velocity with Porosity and Density

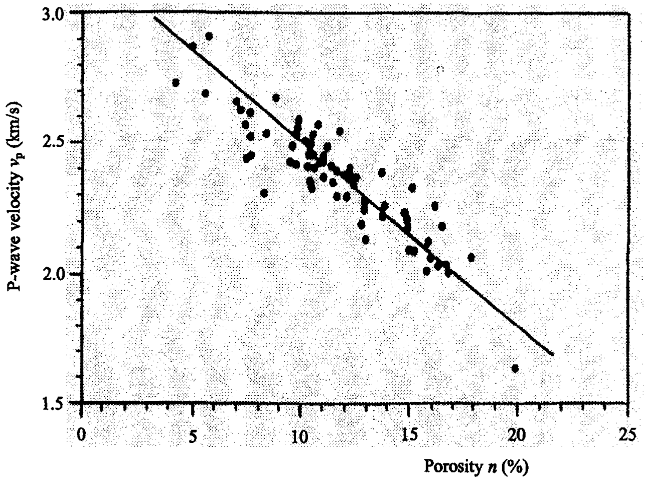


Fig. 3.5 Variation of P-wave velocity with porosity for water saturated sandstone from Rotliegenes, Northern Germany (from Schön, 1996).

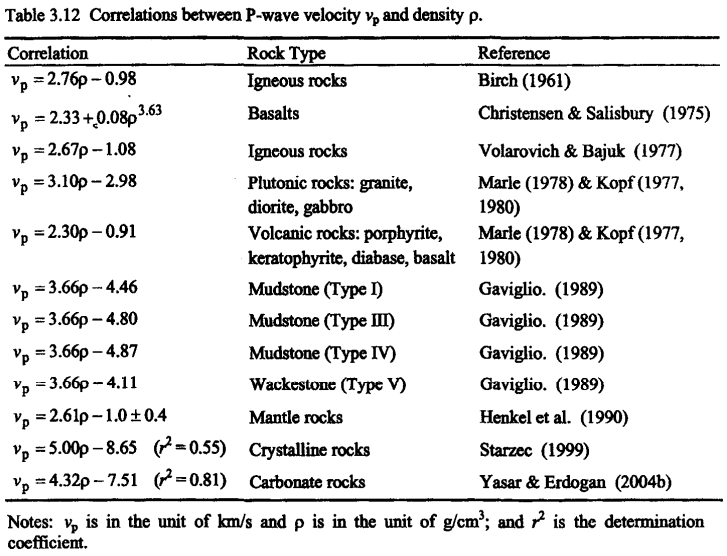


Table 3.12 Correlations between P-wave velocity $v_p$ and density ρ.

| Correlation | Rock Type | Reference |
|---|---|---|
| $v_p = 2.76\rho - 0.98$ | Igneous rocks | Birch (1961) |
| $v_p = 2.33 + 0.08\rho^{3.63}$ | Basalts | Christensen & Salisbury (1975) |
| $v_p = 2.67\rho - 1.08$ | Igneous rocks | Volarovich & Bajuk (1977) |
| $v_p = 3.10\rho - 2.98$ | Plutonic rocks: granite, diorite, gabbro | Marle (1978) & Kopf (1977, 1980) |
| $v_p = 2.30\rho - 0.91$ | Volcanic rocks: porphyrite, keratophyrite, diabase, basalt | Marle (1978) & Kopf (1977, 1980) |
| $v_p = 3.66\rho - 4.46$ | Mudstone (Type I) | Gaviglio. (1989) |
| $v_p = 3.66\rho - 4.80$ | Mudstone (Type III) | Gaviglio. (1989) |
| $v_p = 3.66\rho - 4.87$ | Mudstone (Type IV) | Gaviglio. (1989) |
| $v_p = 3.66\rho - 4.11$ | Wackestone (Type V) | Gaviglio. (1989) |
| $v_p = 2.61\rho - 1.0 \pm 0.4$ | Mantle rocks | Henkel et al. (1990) |
| $v_p = 5.00\rho - 8.65 \quad (r^2 = 0.55)$ | Crystalline rocks | Starzec (1999) |
| $v_p = 4.32\rho - 7.51 \quad (r^2 = 0.81)$ | Carbonate rocks | Yasar & Erdogan (2004b) |

Notes: $v_p$ is in the unit of km/s and ρ is in the unit of g/cm$^3$; and $r^2$ is the determination coefficient.

**Variation of P Wave Velocity with Porosity and Density**

# Variation of Point Loand Index with P Wave Velocity and Porosity

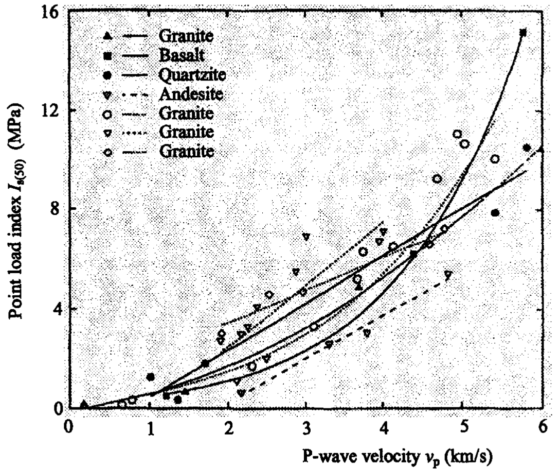


Fig. 3.7 Variation of point load index with P-wave velocity for fresh and weathered crystalline rock (from Gupta & Rao, 1998).

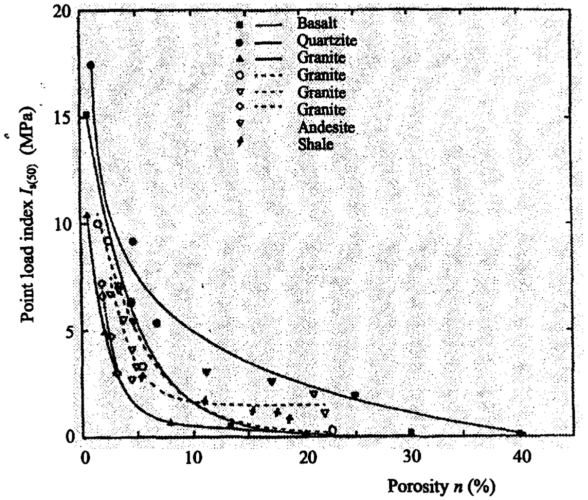


Fig. 3.8 Variation of point load index with porosity for fresh and weathered crystalline rock (from Gupta & Rao, 1998).

**Variation of Point Load Index with P Wave Velocity and Porosity**

# Weathering Grade of Rock Mass

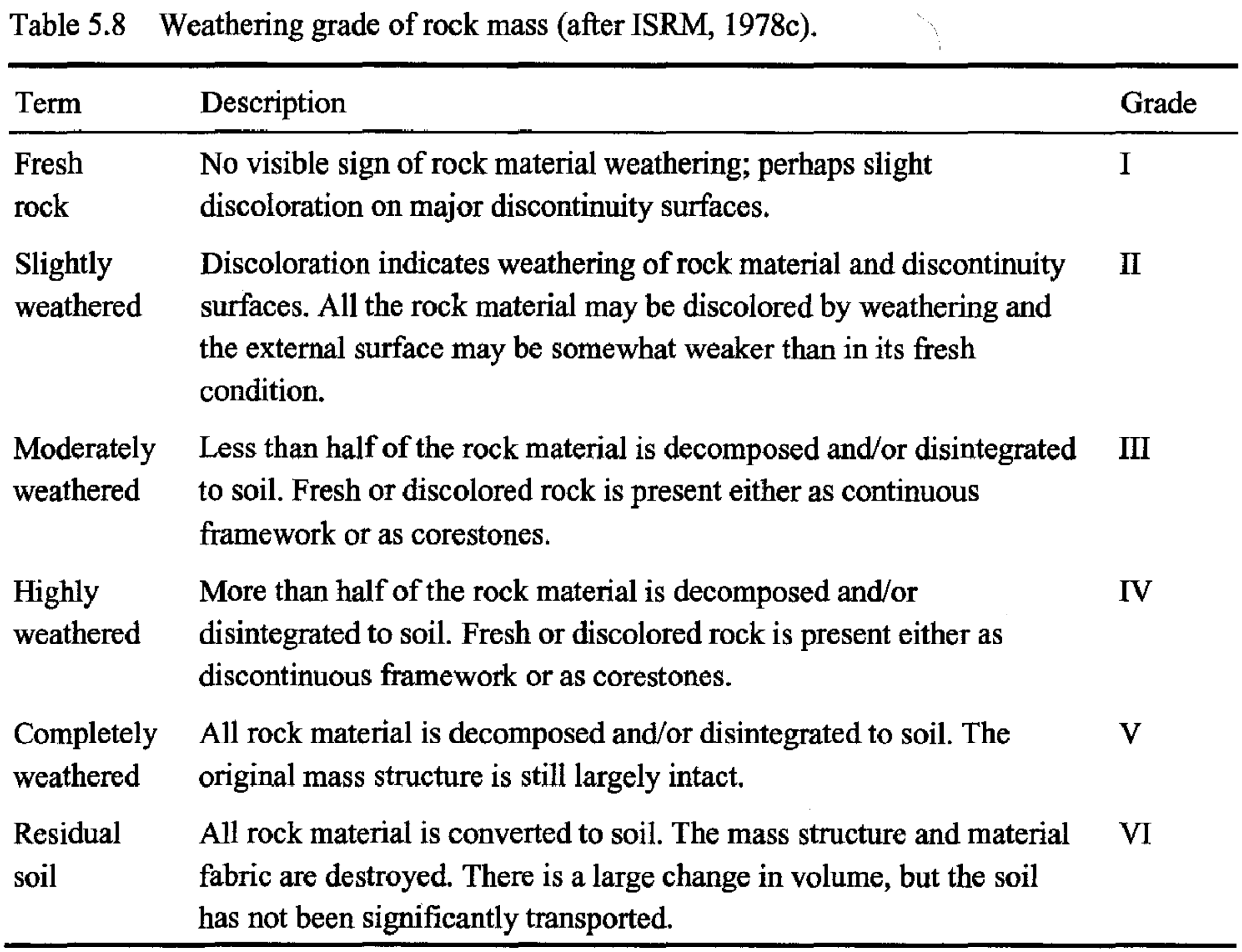


Table 5.8 Weathering grade of rock mass (after ISRM, 1978c).

| Term | Description | Grade |
|---|---|---|
| Fresh rock | No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surfaces. | I |
| Slightly weathered | Discoloration indicates weathering of rock material and discontinuity surfaces. All the rock material may be discolored by weathering and the external surface may be somewhat weaker than in its fresh condition. | II |
| Moderately weathered | Less than half of the rock material is decomposed and/or disintegrated to soil. Fresh or discolored rock is present either as continuous framework or as corestones. | III |
| Highly weathered | More than half of the rock material is decomposed and/or disintegrated to soil. Fresh or discolored rock is present either as discontinuous framework or as corestones. | IV |
| Completely weathered | All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact. | V |
| Residual soil | All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported. | VI |

# Weathering State of Rock Shown in Rock Cores

| Photo | Run No. | Depth (m) | TCR/ RQD | Rmk |
|---|---|---|---|---|
| | | 0.0~2.5 | | TS |
| | | 2.5~9.0 | | WS |
| | 1 | 9.0~10.3 | 75/0 | GR |
| | 2 | 10.3~12.4 | 85/0 | " |
| | 3 | 12.4~13.2 | 100/0 | BD |
| | 4 | 13.2~14.5 | 80/0 | GR |
| | 4 | 14.5~14.9 | 80/0 | GR |
| | 5 | 14.9~16.2 | 100/0 | " |
| | 6 | 16.2~17.4 | 100/0 | " |
| | 7 | 17.4~19.3 | 100/0 | BD |
| | 8 | 19.3~20.4 | 100/0 | " |
| | 8 | 20.4~20.6 | 100/0 | BD |
| | 9 | 20.6~22.6 | 100/5 | " |
| | 10 | 22.6~24.3 | 100/5 | " |
| | 11 | 24.3~25.8 | 100/0 | " |
| | 12 | 25.8~26.1 | 100/0 | BD |
| | 12 | 26.1~27.5 | 100/0 | GR |
| | 13 | 27.5~29.1 | 100/15 | " |
| | 14 | 29.1~31.1 | 100/45 | " |
| | 15 | 31.1~31.9 | 100/80 | " |

*Completely weathered*

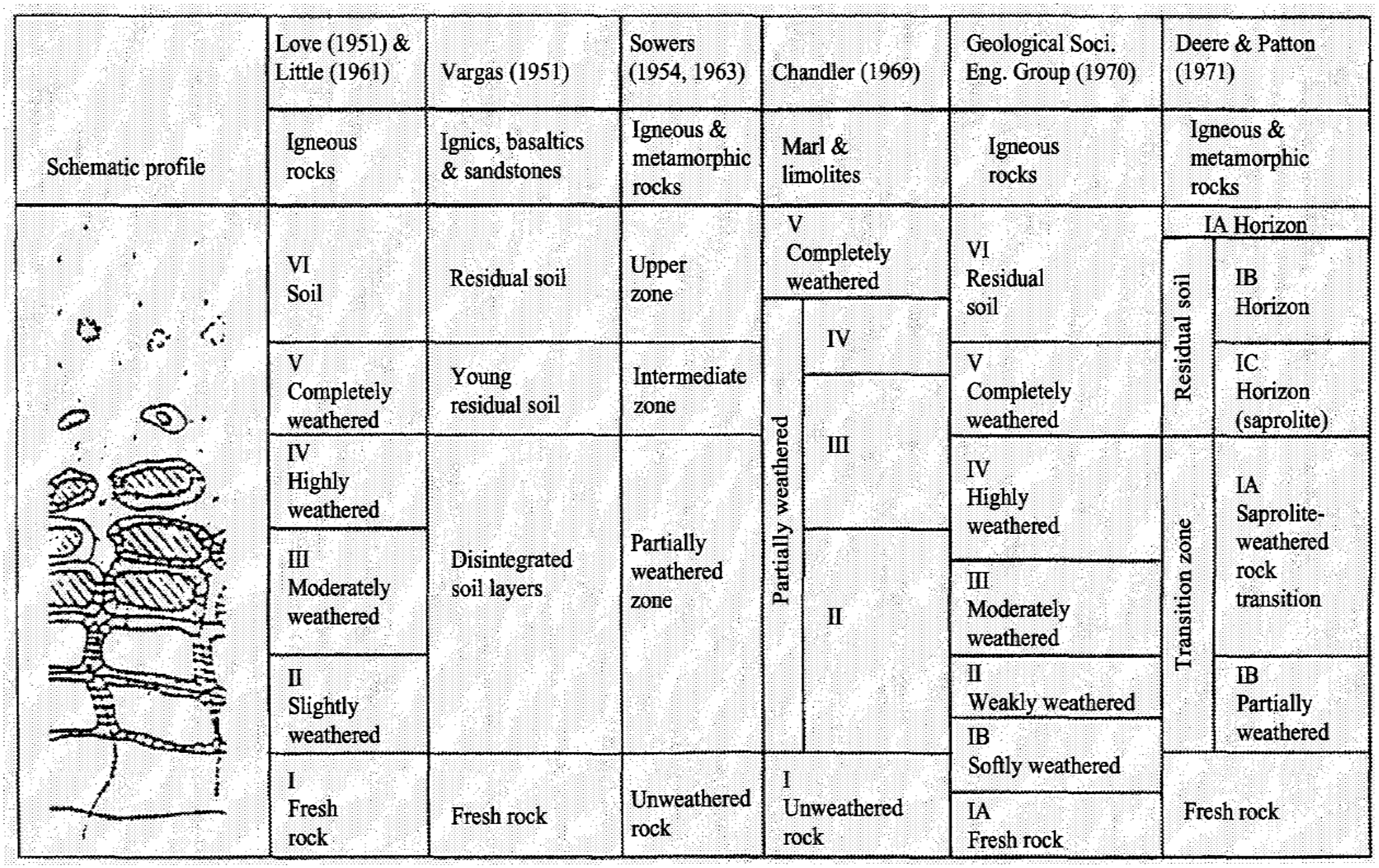
*Highly weathered*

*Moderately weathered*

*Slightly weathered*

*Fresh*

# Schematic Profile and Descriptions of Weathering in Rock



| Schematic profile | Love (1951) & Little (1961) | Vargas (1951) | Sowers (1954, 1963) | Chandler (1969) | Geological Soci. Eng. Group (1970) | Deere & Patton (1971) |
|---|---|---|---|---|---|---|
| | Igneous rocks | Ignics, basaltics & sandstones | Igneous & metamorphic rocks | Marl & limolites | Igneous rocks | Igneous & metamorphic rocks |
| | VI Soil | Residual soil | Upper zone | V Completely weathered | VI Residual soil | IA Horizon<br>Residual soil: IB Horizon |
| | V Completely weathered | Young residual soil | Intermediate zone | Partially weathered: IV | V Completely weathered | Residual soil: IC Horizon (saprolite) |
| | IV Highly weathered | Disintegrated soil layers | Partially weathered zone | Partially weathered: III | IV Highly weathered | Transition zone: IA Saprolite-weathered rock transition |
| | III Moderately weathered | | | Partially weathered: II | III Moderately weathered | |
| | II Slightly weathered | | | | II Weakly weathered | Transition zone: IB Partially weathered |
| | | | | | IB Softly weathered | |
| | I Fresh rock | Fresh rock | Unweathered rock | I Unweathered rock | IA Fresh rock | Fresh rock |

# Weathering Indices for Granite and Relationship between Weathering and RQD

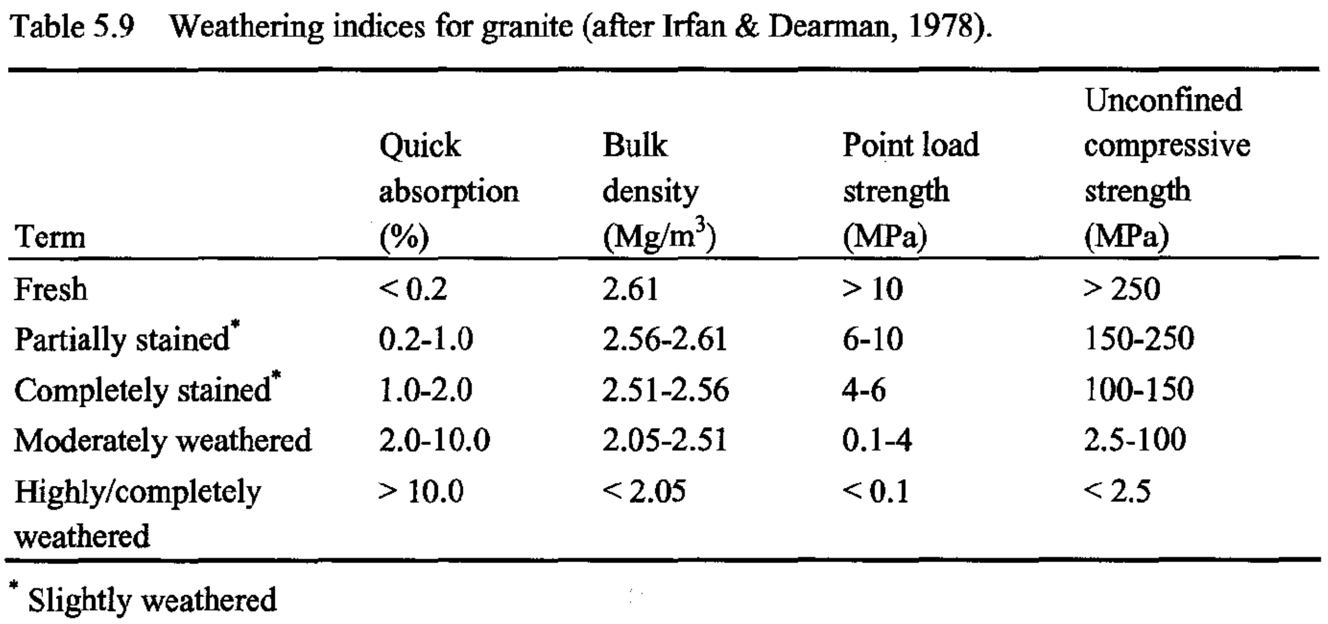


Table 5.9 Weathering indices for granite (after Irfan & Dearman, 1978).

| Term | Quick absorption (%) | Bulk density (Mg/m$^3$) | Point load strength (MPa) | Unconfined compressive strength (MPa) |
|---|---|---|---|---|
| Fresh | < 0.2 | 2.61 | > 10 | > 250 |
| Partially stained* | 0.2-1.0 | 2.56-2.61 | 6-10 | 150-250 |
| Completely stained* | 1.0-2.0 | 2.51-2.56 | 4-6 | 100-150 |
| Moderately weathered | 2.0-10.0 | 2.05-2.51 | 0.1-4 | 2.5-100 |
| Highly/completely weathered | > 10.0 | < 2.05 | < 0.1 | < 2.5 |

* Slightly weathered

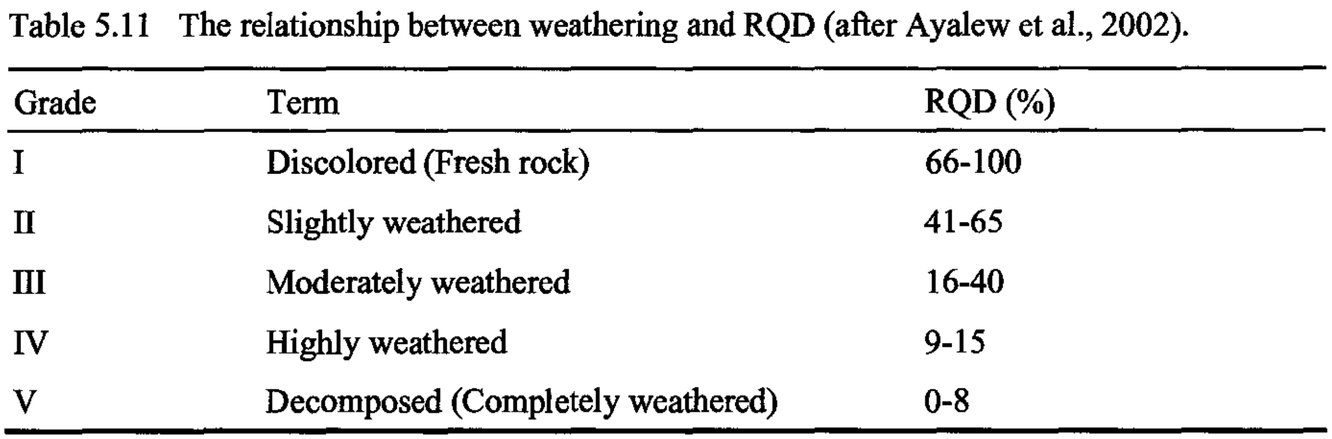


Table 5.11 The relationship between weathering and RQD (after Ayalew et al., 2002).

| Grade | Term | RQD (%) |
|---|---|---|
| I | Discolored (Fresh rock) | 66-100 |
| II | Slightly weathered | 41-65 |
| III | Moderately weathered | 16-40 |
| IV | Highly weathered | 9-15 |
| V | Decomposed (Completely weathered) | 0-8 |

# Total Porosity and Dry Density of Granitic Rocks at Different Weathering Stages

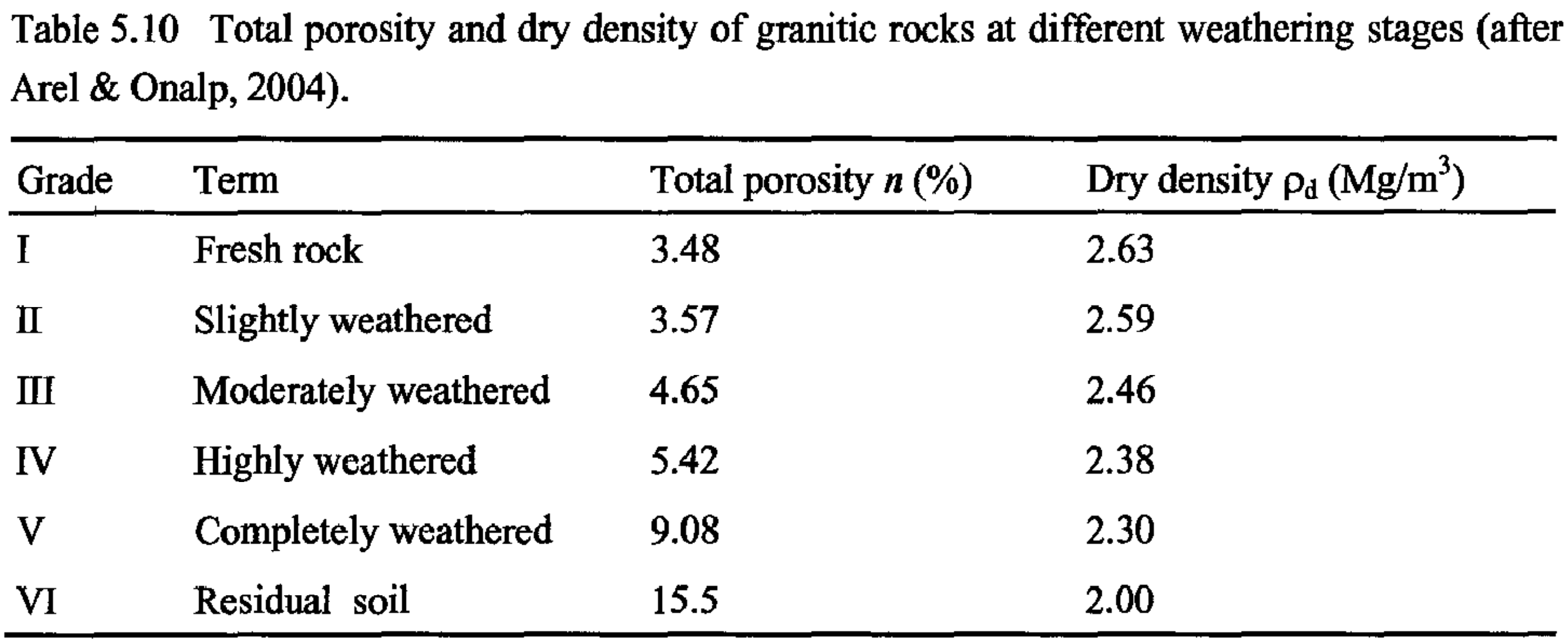


Table 5.10 Total porosity and dry density of granitic rocks at different weathering stages (after Arel & Onalp, 2004).

| Grade | Term | Total porosity *n* (%) | Dry density $\rho_d$ (Mg/m$^3$) |
|---|---|---|---|
| I | Fresh rock | 3.48 | 2.63 |
| II | Slightly weathered | 3.57 | 2.59 |
| III | Moderately weathered | 4.65 | 2.46 |
| IV | Highly weathered | 5.42 | 2.38 |
| V | Completely weathered | 9.08 | 2.30 |
| VI | Residual soil | 15.5 | 2.00 |

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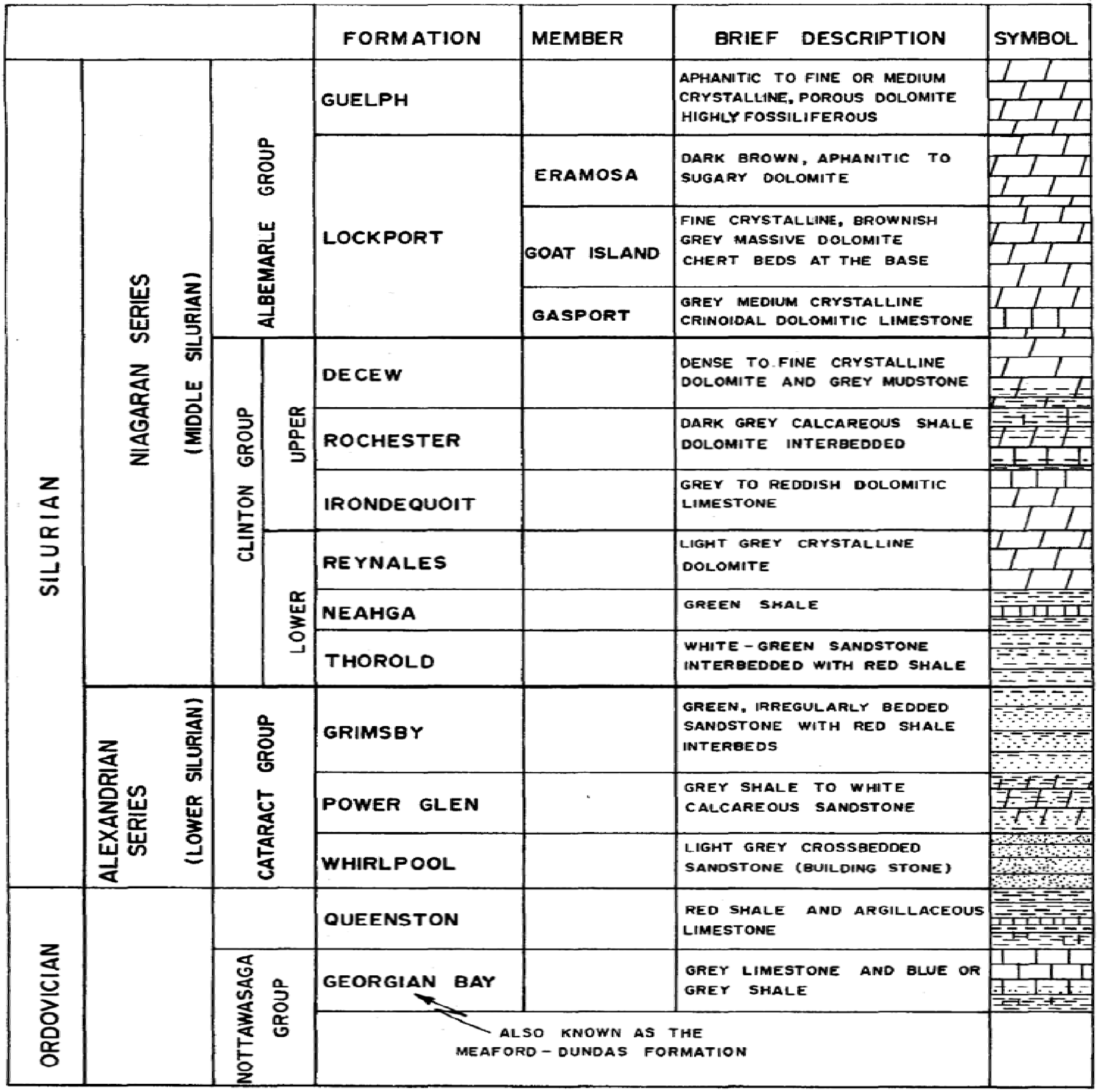

| | | | | FORMATION | MEMBER | BRIEF DESCRIPTION | SYMBOL |
|---|---|---|---|---|---|---|---|
| SILURIAN | NIAGARAN SERIES (MIDDLE SILURIAN) | ALBEMARLE GROUP | | GUELPH | | APHANITIC TO FINE OR MEDIUM CRYSTALLINE, POROUS DOLOMITE HIGHLY FOSSILIFEROUS | |
| | | | | LOCKPORT | ERAMOSA | DARK BROWN, APHANITIC TO SUGARY DOLOMITE | |
| | | | | | GOAT ISLAND | FINE CRYSTALLINE, BROWNISH GREY MASSIVE DOLOMITE CHERT BEDS AT THE BASE | |
| | | | | | GASPORT | GREY MEDIUM CRYSTALLINE CRINOIDAL DOLOMITIC LIMESTONE | |
| | | CLINTON GROUP | UPPER | DECEW | | DENSE TO FINE CRYSTALLINE DOLOMITE AND GREY MUDSTONE | |
| | | | | ROCHESTER | | DARK GREY CALCAREOUS SHALE DOLOMITE INTERBEDDED | |
| | | | | IRONDEQUOIT | | GREY TO REDDISH DOLOMITIC LIMESTONE | |
| | | | LOWER | REYNALES | | LIGHT GREY CRYSTALLINE DOLOMITE | |
| | | | | NEAHGA | | GREEN SHALE | |
| | | | | THOROLD | | WHITE – GREEN SANDSTONE INTERBEDDED WITH RED SHALE | |
| | ALEXANDRIAN SERIES (LOWER SILURIAN) | CATARACT GROUP | | GRIMSBY | | GREEN, IRREGULARLY BEDDED SANDSTONE WITH RED SHALE INTERBEDS | |
| | | | | POWER GLEN | | GREY SHALE TO WHITE CALCAREOUS SANDSTONE | |
| | | | | WHIRLPOOL | | LIGHT GREY CROSSBEDDED SANDSTONE (BUILDING STONE) | |
| ORDOVICIAN | | | | QUEENSTON | | RED SHALE AND ARGILLACEOUS LIMESTONE | |
| | | NOTTAWASAGA GROUP | | GEORGIAN BAY | | GREY LIMESTONE AND BLUE OR GREY SHALE | |

ALSO KNOWN AS THE MEAFORD – DUNDAS FORMATION

FIGURE 2-4 STRATIGRAPHY OF THE NIAGARA ESCARPMENT, NIAGARA–HAMILTON AREA (ADAPTED FROM HEWITT, 1971 AND BOLTON, 1957)

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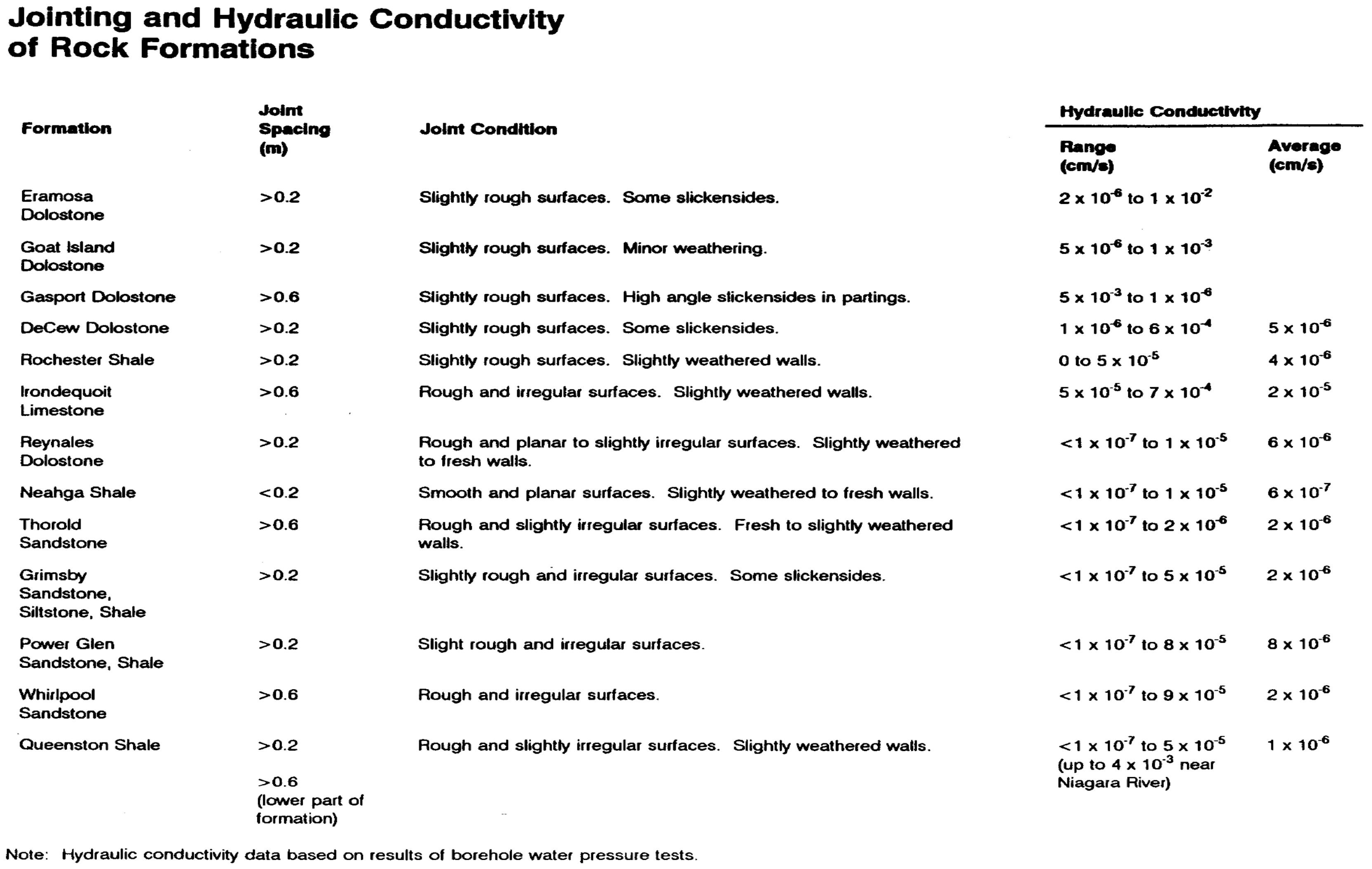
Western

# Jointing and Hydraulic Conductivity of Rock Formations in the Niagara Escarpment – Niagara Area

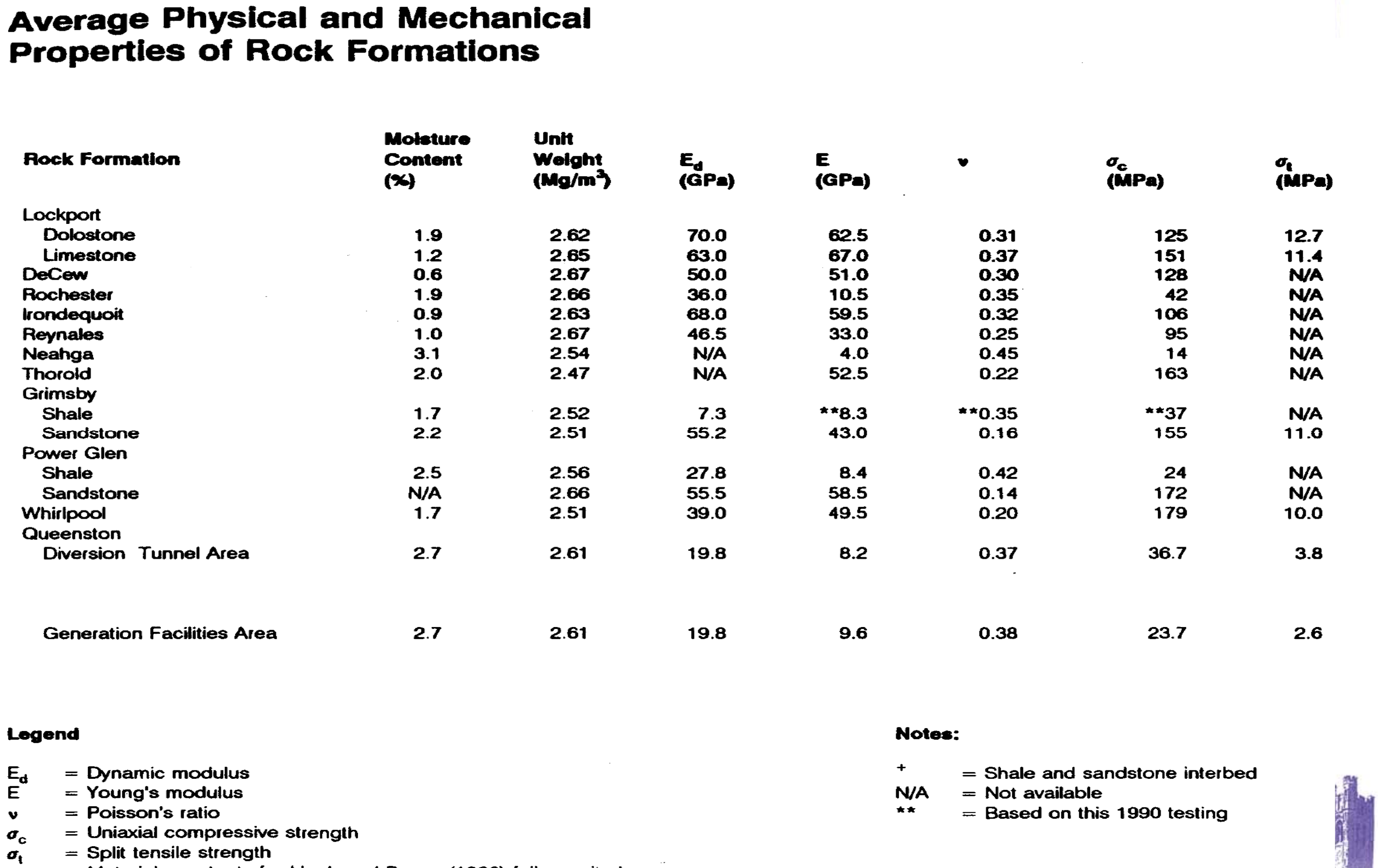


## Jointing and Hydraulic Conductivity of Rock Formations

| Formation | Joint Spacing (m) | Joint Condition | Hydraulic Conductivity | |
|---|---|---|---|---|
| | | | Range (cm/s) | Average (cm/s) |
| Eramosa Dolostone | >0.2 | Slightly rough surfaces. Some slickensides. | $2 \times 10^{-6}$ to $1 \times 10^{-2}$ | |
| Goat Island Dolostone | >0.2 | Slightly rough surfaces. Minor weathering. | $5 \times 10^{-6}$ to $1 \times 10^{-3}$ | |
| Gasport Dolostone | >0.6 | Slightly rough surfaces. High angle slickensides in partings. | $5 \times 10^{-3}$ to $1 \times 10^{-6}$ | |
| DeCew Dolostone | >0.2 | Slightly rough surfaces. Some slickensides. | $1 \times 10^{-6}$ to $6 \times 10^{-4}$ | $5 \times 10^{-6}$ |
| Rochester Shale | >0.2 | Slightly rough surfaces. Slightly weathered walls. | 0 to $5 \times 10^{-5}$ | $4 \times 10^{-6}$ |
| Irondequoit Limestone | >0.6 | Rough and irregular surfaces. Slightly weathered walls. | $5 \times 10^{-5}$ to $7 \times 10^{-4}$ | $2 \times 10^{-5}$ |
| Reynales Dolostone | >0.2 | Rough and planar to slightly irregular surfaces. Slightly weathered to fresh walls. | $<1 \times 10^{-7}$ to $1 \times 10^{-5}$ | $6 \times 10^{-6}$ |
| Neahga Shale | <0.2 | Smooth and planar surfaces. Slightly weathered to fresh walls. | $<1 \times 10^{-7}$ to $1 \times 10^{-5}$ | $6 \times 10^{-7}$ |
| Thorold Sandstone | >0.6 | Rough and slightly irregular surfaces. Fresh to slightly weathered walls. | $<1 \times 10^{-7}$ to $2 \times 10^{-6}$ | $2 \times 10^{-6}$ |
| Grimsby Sandstone, Siltstone, Shale | >0.2 | Slightly rough and irregular surfaces. Some slickensides. | $<1 \times 10^{-7}$ to $5 \times 10^{-5}$ | $2 \times 10^{-6}$ |
| Power Glen Sandstone, Shale | >0.2 | Slight rough and irregular surfaces. | $<1 \times 10^{-7}$ to $8 \times 10^{-5}$ | $8 \times 10^{-6}$ |
| Whirlpool Sandstone | >0.6 | Rough and irregular surfaces. | $<1 \times 10^{-7}$ to $9 \times 10^{-5}$ | $2 \times 10^{-6}$ |
| Queenston Shale | >0.2<br>>0.6 (lower part of formation) | Rough and slightly irregular surfaces. Slightly weathered walls. | $<1 \times 10^{-7}$ to $5 \times 10^{-5}$ (up to $4 \times 10^{-3}$ near Niagara River) | $1 \times 10^{-6}$ |

Note: Hydraulic conductivity data based on results of borehole water pressure tests.

# Average Physical and Mechanical Properties of Rock Formations in the Niagara Escarpment – Niagara Area



## Average Physical and Mechanical Properties of Rock Formations

| **Rock Formation** | **Moisture Content (%)** | **Unit Weight (Mg/m$^3$)** | **$E_d$ (GPa)** | **E (GPa)** | **$\nu$** | **$\sigma_c$ (MPa)** | **$\sigma_t$ (MPa)** |
|---|---|---|---|---|---|---|---|
| Lockport | | | | | | | |
| Dolostone | 1.9 | 2.62 | 70.0 | 62.5 | 0.31 | 125 | 12.7 |
| Limestone | 1.2 | 2.65 | 63.0 | 67.0 | 0.37 | 151 | 11.4 |
| DeCew | 0.6 | 2.67 | 50.0 | 51.0 | 0.30 | 128 | N/A |
| Rochester | 1.9 | 2.66 | 36.0 | 10.5 | 0.35 | 42 | N/A |
| Irondequoit | 0.9 | 2.63 | 68.0 | 59.5 | 0.32 | 106 | N/A |
| Reynales | 1.0 | 2.67 | 46.5 | 33.0 | 0.25 | 95 | N/A |
| Neahga | 3.1 | 2.54 | N/A | 4.0 | 0.45 | 14 | N/A |
| Thorold | 2.0 | 2.47 | N/A | 52.5 | 0.22 | 163 | N/A |
| Grimsby | | | | | | | |
| Shale | 1.7 | 2.52 | 7.3 | **8.3 | **0.35 | **37 | N/A |
| Sandstone | 2.2 | 2.51 | 55.2 | 43.0 | 0.16 | 155 | 11.0 |
| Power Glen | | | | | | | |
| Shale | 2.5 | 2.56 | 27.8 | 8.4 | 0.42 | 24 | N/A |
| Sandstone | N/A | 2.66 | 55.5 | 58.5 | 0.14 | 172 | N/A |
| Whirlpool | 1.7 | 2.51 | 39.0 | 49.5 | 0.20 | 179 | 10.0 |
| Queenston | | | | | | | |
| Diversion Tunnel Area | 2.7 | 2.61 | 19.8 | 8.2 | 0.37 | 36.7 | 3.8 |
| Generation Facilities Area | 2.7 | 2.61 | 19.8 | 9.6 | 0.38 | 23.7 | 2.6 |

**Legend**

$E_d$ = Dynamic modulus
E = Young's modulus
$\nu$ = Poisson's ratio
$\sigma_c$ = Uniaxial compressive strength
$\sigma_t$ = Split tensile strength

**Notes:**

+ = Shale and sandstone interbed
N/A = Not available
** = Based on this 1990 testing