From Palmström A.: RMi – a rock mass characterization system for rock engineering purposes.
PhD thesis, Oslo University, Norway, 1995, 400 p.

APPENDIX 1

ON JOINTS AND JOINTING

> *"From an engineering point of view, a knowledge of the type and intensity of the rock defects may be much more important than of the types of rock which will be encountered."*
> Karl Terzaghi, 1946

Joints and related features are certain types of discontinuities in the rocks. Discontinuity is the general term used in rock mechanics for any mechanical discontinuity in a rock mass having zero or low tensile strength. It is the collective term for most types of joints, weak bedding planes, weak schistocity planes and faults or weakness zones.

As there are not any distinct and generally accepted rules or nomenclature for a terminology of discontinuities for engineering purposes Brekke and Howard (1972) suggest to make use of

- scale, based on aperture, persistence and occurrence, and
- character, based on occurrence of filling material.

Based on this it has in this work been chosen to divide discontinuities into 3 main groups:

micro-fissures	length < 10 mm
joints	length 0.1 - 100 m
weakness zones	length > 30 m

Micro-fissure is usually considered as a defect or flaw in the rock material (Brekke and Howard, 1972). Being a rock material parameter rather than genuine discontinuity, it is generally included in the properties of rock; therefore it is not further dealt with here.

Weakness zones including faults, are described in Appendix 2.

Joints. There is a difficulty in giving a hard and fast definition of what constitutes a joint. Many geologists will reserve the term 'joint' for typical extension discontinuities, without any perceptible movement along it. During the years there has been several discussions if 'joint', 'fracture' or other terms should be preferred in rock mechanics, engineering geology and rock engineering for those features forming the network of discontinuities in the rock masses. ISRM (1975) has chosen 'joint' as this term defined as: *"Joint is a discontinuity plane of natural origin along where it has been no visible displacement."* This is the same definition as used by many geologists.

In this work, the term 'joint' is used for a group of discontinuities in the range of approximately 0.1 - 100 m, as indicated in Table 2-1. This is the same definition as suggested by Brekke and Howard (1972). A similar definition is used by the Norwegian Rock Mechanics Group (1985).

Joints may be the result of failure under natural forces (Fig. A1-1), including small seams (filled joints) and some fractures such as minor and moderate shear ruptures. They also include weakness planes caused by rock texture or anisotropy. Thus, the main types of joint are:

– *Tectonic joints;* [1] i.e. breaks formed from the tensile stresses accompanying uplift or lateral stretching, or from the effects of regional tectonic compression (ISRM, 1975). They commonly occur as planar, rough-surfaced sets of intersecting joints, with one or two of the sets usually dominating in persistence.
– *Sheeting joints;* a set of joints developed more or less parallel to the surface of the ground, especially in plutonic igneous intrusions such as granite; probably as a result of the unloading of the rock mass when the cover is eroded away.
– *Exfoliation joints;* breaks developed as a product of exfoliation; the breaking or
– splitting off from bare rock surfaces by the action of chemical or physical forces, such as differential expansion and contracting during heating and cooling over the daily temperature range.
– *Cooling joints,* breaks formed as a result from cooling of igneous rocks.
– *Foliation joints and partings,* discontinuities developed along the foliation planes in metamorphic rocks.
– *Bedding joints and partings,* discontinuities developed along the bedding planes in sedimentary rocks.

Table A1-1 THE VARIOUS TYPES OF JOINTS USED IN THIS WORK

NATURAL JOINTS			**MAN MADE JOINTS**	
term	**length**	**aperture**	**term**	**length**
JOINT (small, medium, large size)	0.1 - 100 m	< 100 mm	rupture	< 10 m
- parting	< 1 m	< 1 mm	crack	< 0.1 m
- seam (minor and moderate)*)	> 3 m	10 - 100 mm		

*) Large seams or shears are included in the term weakness zone

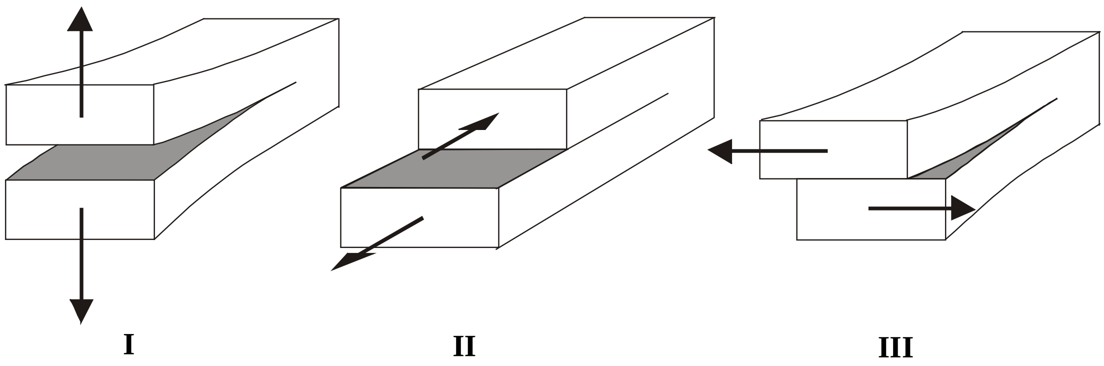

Fig. A1-1 The three main modes for development of tectonic joints (from Scholz, 1990)

The terms for the various types of joints in Table A1-1 are generally chosen from their size and composition. Some supplementary definitions of these are given as follows:

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[1] ISRM (1975) advises against the use of the terms *tension joint* and *shear joint*, since there are many possible ways that they can be developed. For example, tension joints can be developed from cooling of igneous rock, from shrinkage of sediments, from folding, or from ice retreat.

Crack a small, partial or incomplete discontinuity. (ISRM, 1975)

Parting a plane or surface along which a rock is readily separated or is naturally divided into layers, e.g. bedding-plane parting. (Glossary of geology, 1980).[2]

Seam 1) A minor, often clay-filled zone with a thickness of some centimetres. When occurring as weak clay zone in a sedimentary sequence, a seam can be considerably thicker. Otherwise, seams may represent very minor faults or altered zones along joints, dikes, beds or foliation. (Brekke and Howard, 1972).

2) A plane in a coal bed at which the different layers of coal are easily separated. (Dictionary of geological terms, 1962)

Rupture a fracture or break, in this work limited to have been caused by excavation works or by other activities of man.

Fracture a break in rock due to intense folding or faulting. (Dictionary of geological terms, 1962)

Fracture is a general term used in *geology* for all kinds of discontinuities caused by mechanical stresses in the bedrock. Fractures include joints and cracks and faults.

Shear a seam of sheared and crushed rock usually spaced more widely than joints and is marked by several millimetres to as much as a metre thickness of soft or friable rock or soil.

Singularity is used in this work as a general term for seams, filled joints or other persistent discontinuities which often in engineering are not considered as belonging to the detailed jointing.

1 JOINT CHARACTERISTICS

A joint is a three-dimensional discontinuity composed of two matching surfaces called joint walls. The main joint *characteristics* are condition of joint walls, possible joint infilling material together with joint size and continuity or termination. Also joint aperture or thickness may have great impact on the rock mass behaviour.

Joints commonly *terminate* at another joint. Joints that terminate in massive rock, are in this work called discontinuous joints. Such joints can be foliation partings, en echelon joints in addition to many of the smaller joints (less than 1 metre long). One joint set will often be more persistent than the other sets. The joints of the other sets will therefore tend to terminate against the main joints. Joint terminations are also described in Section 2.3 in this appendix, see also Fig. A1-3.

Pollard and Aydin (1988) mention that the *shape and size* of joints are largely related to the rocks they penetrate and to the size and geometry of the rock mass. For example, joint dimensions perpendicular to layering is controlled by the thickness of the jointed unit.

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[2] Partings, which often occur as bedding plane and foliation partings, are separations parallel to a mineralogically defined structural weakness in the rock. They are most often tight and rough except where flaky minerals (mica, chlorite) occur. In agreement with Burton (1965) they have been included in the term joints : *"I think it would be advantageous to regard bedding planes in sedimentary rocks and foliation planes in metamorphic rocks as planes of weakness (discontinuity planes) which do not differ in any significant way from joints."*

These joints are roughly rectangular in shape. Their size is rarely more than some tens of metres, while the dimension of joints parallel to layering can be more than a hundred metres.

Joints formed by cooling of a lava flow or by desiccation of a sediment layer are also rectangular in shape and are usually perpendicular to the flow surface or layer (Pollard and Aydin, 1988). The long (vertical) dimension of the rectangle, which is limited by the thickness of the flow layer or unit, seldom exceeds several tens of meters. The short (horizontal) dimension controlled by the fracture process, is generally less than the thickness of the flow.
Analyses of dip lengths and strike lengths performed by Robertson (1970) indicate that joints tend to be of approximately isotropic dimensions. When terminating in solid rock they may therefore tend to be circular, and presumably rectilinear when terminating against other discontinuities.
The size of a joint plane may vary within the same joint set. This is specially the case for foliation joints where small joints or partings occur between long, persistent joints. Pollard and Aydin (1988) further note that joints rarely exceed several hundred metres.

Persistence implies the size or areal extent within a joint plane. It can be crudely quantified by observing the joint trace lengths on the surface exposures (ISRM, 1978). Frequently rock exposures are small compared to the area or length of persistent joints, and the real persistence can only be guessed.
Persistence is an important rock mass parameter, but one of the most difficult to quantify in anything but crude terms. Less frequently, it may be possible to record dip length and the strike length of exposed joints and thereby estimate their persistence. Joint continuity or persistence can be distinguished by the terms *persistent, sub-persistent* and *non-persistent* (ISRM, 1978), or more simply as *continuous* and *discontinuous*.

Aperture or thickness of joints, i.e. maximum distance between joint walls is generally small; mainly less than a millimetre, except for filled joints, seams or shears. Nieto (1983) and Barton (1990b) have observed that persistence generally is proportional to the thickness of the discontinuity, especially for the larger types in igneous and metamorphic terrains. Also Kikuchi et al. (1985) have arrived at similar results from studies in andesite, as shown in Fig. A1-2.

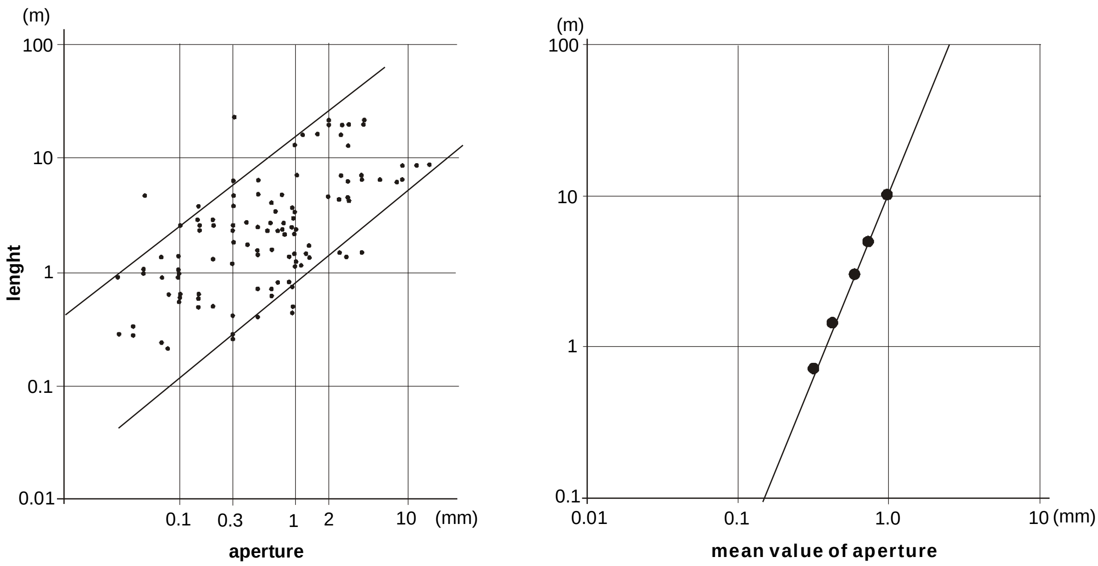


Fig. A1-2 Relation between joint length and aperture in andesite (from Kikuchi et al., 1985).

Large aperture can be a result from shear displacement of discontinuities having appreciable roughness and waviness, from tensile opening, from outwash, or from solution activity (ISRM, 1978). Steep or vertical discontinuities that have opened in tension as a result of unloading due to valley erosion or glacial retreat may have very large apertures.

The *character* of the joint surface may be fresh, weathered, coated, stained, etc. and may strongly influence on the strength and roughness of the surface and hence the frictional properties of the joint. Weathering and alteration generally affect the walls of the discontinuities more than the interior of the rock (Piteau, 1970). These processes may completely change the joint after it has been formed. The properties of the rock may be important in determining this feature (Piteau, 1970) as described later in this appendix.

Surprisingly, little has been published on the course or the *planarity* of joints. A general trend is that homogeneous rocks often exhibit relatively planar joint walls. Bedding and foliation joints show often waviness or undulation, especially where the rocks are folded.

Filling includes materials derived from breakage of the country rock due to movements (i.e. fault zone materials such as breccia), in situ weathered materials (i.e. alteration products), foreign infilling materials deposited between the structural planes (such as calcite), and also intruded igneous materials, which are different from the host rock. The filling can therefore consist of several different minerals and materials. The main groups of these are:

- Hard and resistant minerals (quartz, epidote and serpentine).
- Soft minerals (clay, chlorite, talc and graphite).
- Soluble minerals (calcite, gypsum).
- Swelling minerals (swelling clays (smectites), anhydrite).
- Loose materials (silt, sand and gravel).

These materials are further described in Appendix 2 and 3.

Joints, seams and sometimes even minor faults may be healed through precipitation from hydrothermal solutions of quartz, epidote or calcite. This may be the case for layered igneous and metamorphic rocks in which the layers are strongly *welded* together (Burton, 1965); therefore such planes are not planes of weakness in the way bedding planes in sedimentary rocks are, but can be regarded more appropriately as planes of reduced strength. The influence of joint characteristics has been discussed in several papers, among others Goodman (1970, 1989), Brekke and Howard (1972), Barton et al. (1974), Barton (1973, 1976), Nieto (1983), ISRM (1978).

2 JOINTING CHARACTERISTICS

Jointing is the occurrence of joint sets forming the system or pattern of joints as well as the amount or intensity of joints. The network of joints in the massifs between the weakness zones can according to Selmer-Olsen (1964) be characterized as 'the detailed jointing'.

2.1 Joint sets

Field studies of several workers have shown that rocks are invariably jointed in preferential directions and occur in *joint sets*. Two or three prominent sets and one or more minor sets often occur; in addition random joints may be present. Pollard and Aydin (1988) propose that each continuous joint set have been formed during a single deformation episode.

The conditions of the joints in the various sets can vary greatly depending on their mode of origin and the type of rocks in which they occur. Not only can the size and average spacing of joints vary, but also the other characteristics mentioned above. Variations in these properties cause that one joint set can have very different effect on the shear strength characteristics than another.

Although some characteristics are common for joints of different sets in a structural region, it does not, however, seem to be any general connection between all joint conditions in the different types of rock. Thus, for each of the joint sets, within a structural region with similar jointing characteristics, the various properties of each set must be considered individually.

In many cases one joints set is dominant, being both larger and/or more frequent than joints of other sets in the same locality. This set is often referred to as the *main joint set* (or by geologists as primary joints). Often, only one more joint set is developed (Price, 1969).

2.2 Joint spacing

Joint spacings varying from some millimetres to many metres may often seem arbitrary. There are, however, sometimes certain trends in the density of joints caused by spacings.

Nieto (1983) has observed variations in average spacing between joints from centimetres in highly tectonized rocks (folded, faulted, and intruded) of all types to more than 10 metres in massive, horizontally layered rocks. The regularity of joint spacing decreases with the amount of tectonic activity of the area.

Similarly, Pollard and Aydin (1988) mention that spacing of joints in some sets in intrusive igneous rocks is not uniform and that distances between joints range from less than 20 cm to more than 25 m, and that clusters of joints crop out sporadically.

Pollard and Aydin (1988) have further observed regular distribution of joints in sedimentary rocks and that the spacing of joints can scale with the thickness of the layer. Nieto (1983) mentions a general trend to a marked increase in the spacing or even the virtual disappearance of joints in flat-lying sedimentary sequences at depths of as little as 100 m.

Pollard and Aydin (1988) suggest from field data that the following other factors also influence joint spacing:

- Two joint sets in the same lithologic unit often have different spacings.
- Spacing of joints in different lithologic units of comparable thickness can be different.
- Spacing can change as a joint set evolves. For example, columnar jointing - initiated at a flow base show an increase in spacing towards the interior - and the number of joints in a sedimentary unit decreases with distance from the initiation surface. The spacing of cooling joints that grow from the top of a lava flow is smaller than the spacing of those that grow up from the base. This has been attributed to a faster cooling rate at the flow top.

In addition two other trends should be mentioned:

- Rock masses that have undergone tectonic disturbance often present clusters of joints (joint zones). Often the joint spacing decreases near faults and shear zones.

– Spacing is also influenced by weathering, as there often is an increase in jointing density within the zone of weathering, especially where mechanical disintegration has taken place.

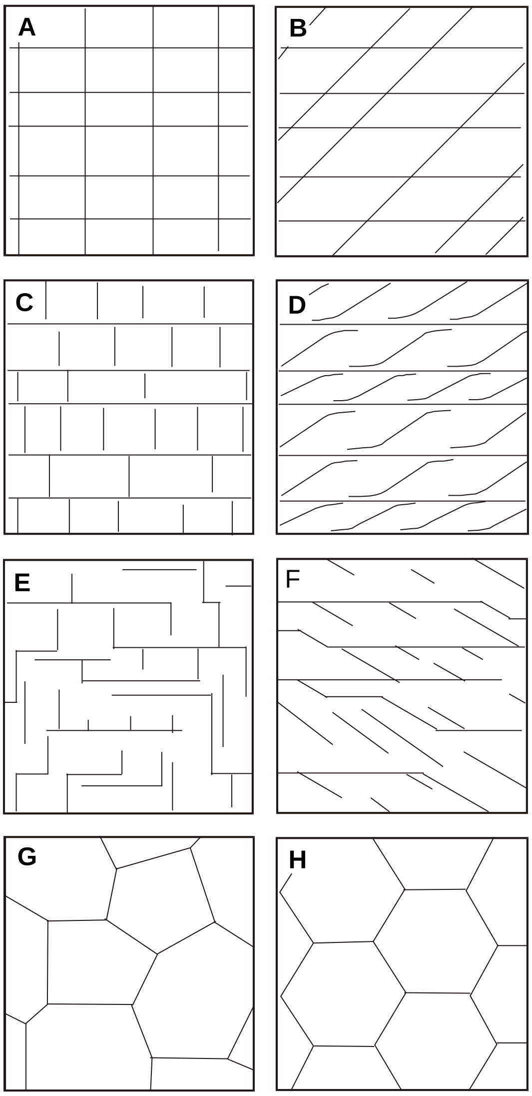
2.3 Jointing pattern and block types

Joint *patterns* comprising of more than one set are common in nature. Piteau (1970) has observed that in instances where jointing is considered to have *random* distribution, it is usually the case that several joint sets occur simultaneously or are superimposed on earlier sets and the resulting complexity gives the appearance of randomness.

Although there are many varieties of joint patterns in nature, there are few types of joint intersection geometries, which can be classified as *orthogonal* (+ intersections) and *non-orthogonal* (X intersections), see Fig. A1-3. Both types can be divided into three groups according to the persistence of the joints at intersections:

1. All joints are persistent (crossing other joints)
2. Some persistent, some non-persistent
3. All joints are non-persistent

This is schematically illustrated in Fig. A1-3.



A. Orthogonal pattern, with persistent sets (+ intersection)

B. Non-orthogonal pattern, with persistent sets (X intersections)

C. Orthogonal pattern, one set is persistent (T intersections)

D. Non-orthogonal pattern, one set with persistent joints

E. Orthogonal pattern, both sets have mainly discontinuous joints

F. Non-orthogonal pattern, both sets have mainly discontinuous joints

G. Triple intersections with all joints

H. Tripple intersections with 120^{o} angles

Fig. A1-3 Schematic illustration of main joint patterns (from Pollard and Aydin, 1988).

Pollard and Aydin (1988) have observed that orthogonal joints often terminate against persistent joints. They mention, however, that there are many examples of joints that apparently cut across bedding interfaces and other joints. The + or X types of such intersections seem to contradict the notion that older discontinuities act as barriers to joint propagation, as implied by T intersections.

The results from analyses carried out by Kikuchi et al. (1985) of joint connections in granitic rocks showed that most of the joints belonged to the X type, but also the T type and the + type were frequently observed. The joint termination type mainly belonged to the T type. Dershowitz and Einstein (1988) mention that 60% of joints in Stripa, Sweden terminate at T-type intersections; in other places 42% of this type has been recorded.

According to Price (1969) joints frequently occur in relatively narrow zones, in which one joint is replaced *en echelon* by another joint, which is slightly off-set, see Fig. A1-4.

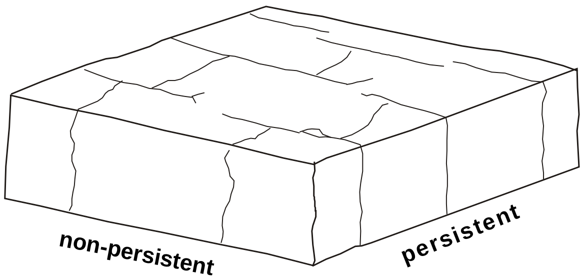
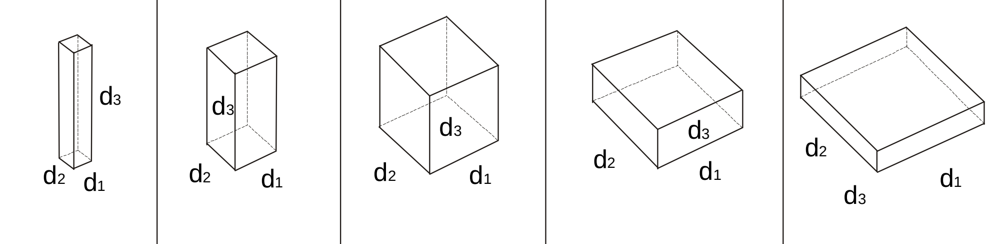


Fig. A1-4 Joints are sometimes arranged in zones with reduced spacing and replacing each other *en echelon* (modified from Price, 1969).

2.3.1 Block types and sizes

The joint sets and possible random joints divide the rock volumes into characteristic blocks. The jointing pattern and the difference in spacing between the joints within each joint set determine the shape of the resulting blocks, which can take the form of cubes, rhombohedrons, tetrahedrons, sheets etc. The unit block can be described by its volume, type and shape as described in Appendix 3.

Müller et al. (1970) have made the division of block shapes as shown below in Fig. A1-5.



Shape of rock block Joint spacing d (cm)					
Ratio $d_1 / d_3 : d_2 / d_3$	< 1 : 5	1 : 2 to 1 : 5	~ 1 : 1	2 : 1 to 5 : 1	> 5 : 1
$d_{max} > 100$	column	big block paralleliped	metric cube	slab	plate
$100 > d_{max} > 10$	small column	medium block parallelepiped	decimetric cube	medium slab	medium plate
$d_{max} < 10$	pencil	small block parallelepiped	centimetric cube	small slab	small plate

Fig. A1-5 The classification of block types applied by Müller et al. (1970).

Another characterization into *block types* has been presented by Dearman (1991), based on a description by Matula and Holzer (1978) as shown in Table A1-2 and Fig. A1-6.

TABLE A1-2 BLOCK TYPES AND JOINTING CHARACTERISTICS (after Dearman, 1991).

Type of block	**Jointing characteristics**
Polyhedral blocks	Irregular jointing without arrangement into distinct sets, and of small joints.
Tabular blocks	One dominant set of parallel joints, for example bedding planes, with other non-persistent joints; thickness of blocks much less than length or width.
Prismatic blocks	Two dominant sets of joints, approximately orthogonal and parallel, with a third irregular set; thickness of blocks much less than length or width.
Equidimensional blocks	Three dominant sets of joints, approximately orthogonal, with occasional irregular joints, giving equidimensional blocks.
Rhomboidal blocks	Three (or more) dominant mutually oblique sets of joints, giving oblique-shaped, equidimensional blocks.
Columnar blocks	Several, - usually more than three, - sets of continuous, parallel joints; length much greater than other dimensions.

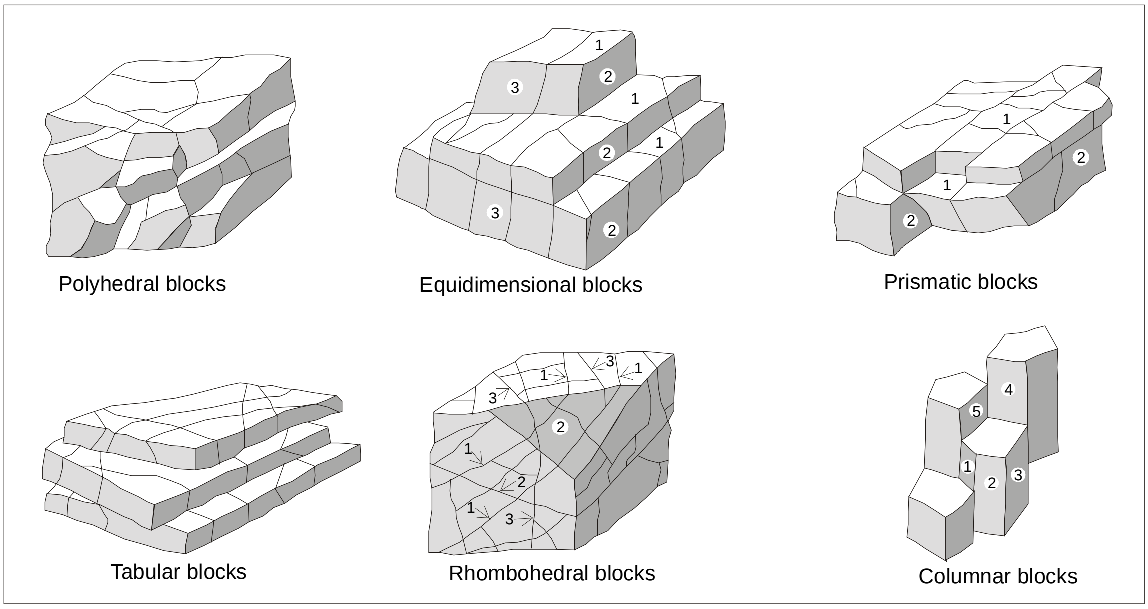


Fig. A1-6 Various types of jointing pattern expressed as block shape. The numbers refer to various joint sets (from Dearman, 1991, based on data from Matula and Holzer, 1978)

Sen and Eissa (1991) has given the following, simpler characterization of block types:

Prismatic blocks: The three dimensions of these blocks are individually significant in their definitions.

Platy blocks: These are similar to slabs where two of the three dimensions are relatively larger than the third dimension.

Bar blocks: Only one dimension is significant.

This division has earlier also been applied by Burton (1965).

However, regular geometric shapes as given above are the exception rather than the rule since the joints in any one set are seldom consistently parallel (ISRM, 1978). Jointing in sedimentary and plutonic rocks usually produces the most regular block shapes.

Block size delineated by the joint planes is a volumetric expression for jointing density. Block size is determined by the joint spacings and the number of joint sets - partly also by the joint length. Individual or random discontinuities may further influence the block size. The connection between soil diameter (d) and block volume (Vb) is shown in Table A1-3. Here, a transition $Vb = 0.58\ d^3$ has been applied.

Table A1-3 PARTICLE OR BLOCK DIAMETER ACCORDING TO THE MODIFIED WENTWORTH SCALE RELATED TO VOLUME

Term	Diameter (d)	Volume (Vb)
Boulders	200 - 600 mm	4.6 dm^3 - 0.125 m^3
Cobbles	60 - 200 mm	0.13 dm^3 - 4.6 dm^3
Coarse gravel	20 - 60 mm	4.6 cm^3 - 0.13 dm^3
Medium gravel	6 - 20 mm	0.13 cm^3 - 4.6 cm^3
Fine gravel	2 - 6 mm	4.6 mm^3 - 0.13 cm^3
Coarse sand	0.6 - 2 mm	0.13 mm^3 - 4.6 mm^3
Medium sand	0.2 - 0.6 mm	0.0046 mm^3 - 0.13 mm^3
Fine sand	0.06 - 0.2 mm	
Silt, clay	< 0.06 mm	

The features influencing on the block size are further outlined in Section 3 in Appendix 3.

3 ATTITUDE OF JOINTS

Nieto (1983) has observed that in the subsurface, high to very high dips (60 - 90^o) and low dips (0 - 30^o) appear to predominate over intermediate dips, in a large number of geologic settings. This seems to be particularly true in intrusive rocks (granite, diorite, and gabbro families), high-grade metamorphics (migmatites and gneisses of various types) and horizontally layered rocks. Selmer-Olsen (1964) also reports that a major part of the joints in the Palaeozoic mountain range (Caledonides) in Scandinavia are steep-dipping.

4 DEVELOPMENT OF JOINTING IN VARIOUS ROCKS

Often, the joints have certain common characteristics within the type of rock they are developed. There are also certain patterns connected to the type of rock they penetrate. The size of joint planes is largely related to the lithology and the size of the rock units being studied. Knowledge of the rock type and its properties may often help in evaluating the characteristics of the joints.

Terzaghi (1946) mentions that in many homogeneous rocks other than extrusive igneous rocks, the joints are either discontinuous or so irregular that the blocks located between them are intimately interlocked.

In some layered igneous and metamorphic rocks in which the layers are strongly *welded* together, joints, seams and sometimes even minor faults may be healed through precipitation from solutions of quartz, epidote or calcite (Burton, 1965). Such planes separating the layers are not planes of weakness in the way bedding planes in sedimentary rocks are, but can be regarded more appropriately as planes of reduced strength.

4.1 Jointing in igneous rocks

In *plutonic igneous rock* such as granite, gabbro, diorite, etc. usually three sets of joints are developed caused by tensional forces set up in a rock body as a result of cooling. Among these three sets of joints, two are often vertical and perpendicular to each other, while one will be more or less horizontal (sheet joints). They divide the rock into more ore less prismatic blocks. The set of joints, which commonly are called *sheet* joints, are more or less parallel to the surface of the ground. The existence of such joints enable the extraction of rock slabs (Terzaghi, 1946; Eshwaraiah and Upadhyaya, 1990).

The joint spacing in igneous rocks may range between some centimetres and many metres. Fresh joints are often medium sized rough and planar. In some areas the orientation and the spacing of the joints in granite is almost constant over large areas, whereas in other areas it changes from place to place in an erratic manner. Regular, large blocks developed in decorative rocks often facilitates extraction of natural stones in plutonic rocks.

In *basaltic rocks* where uniform cooling and contraction in a homogeneous magma has taken place, columnar jointing is common. It consists of hexagonal columns orientated at right angles to the surface of cooling. The columns commonly measure from one to three decimetres across. Since the joints between the columns are open, water can circulate freely through them. Terzaghi (1946) mentions that in igneous rocks which cooled rapidly the joints are generally closely spaced, and that in contrast to basalt, *rhyolite* has a tendency to develop closely spaced and irregular joints.

4.2 Jointing in sedimentary rocks

Sedimentary rocks also commonly contain three sets of joints, one of which is invariably parallel to the bedding planes. The other joints commonly intersect the planes at approximately right angles (Piteau, 1970; Terzaghi, 1946; Deere et al., 1969).

Even when strong sedimentary rocks like limestone and well cemented sandstones predominate, thin argillaceous intercalations ("shale partings") can introduce pervasive weakness planes.

In limestone and sandstone, the joint spacing of each set are commonly of metre size. In shale, they are generally closer, and they may be so close that no intact specimen can be secured with a width of more than a centimetre (Terzaghi, 1946). During excavation, such shales can disintegrate into small angular fragments along very small weakness planes. The surfaces of the fragments of some shales are shining and striated from slickensides. Nieto (1983) has observed that flat-lying sedimentary rocks display the most regular spacing.

4.3 Jointing in metamorphic rocks

In metamorphic rocks one joint set is often parallel or sub-parallel to the foliation or schistocity with two or more sets of joints oriented approximately at right angles to this direction (Deere et al., 1969; Piteau, 1970; Terzaghi, 1946). Varying amount of random joints are present in addition to the joint sets. In many cases the jointing has a character of irregular as the amount of random joints exceeds the joints connected to joint sets.

Intercalated gneisses and schists, phyllites and slates usually display well developed foliation planes which contain concentration of weak, platy or elongated minerals of mica, chlorite, amphiboles, pyroxenes. These planes are often easily splitted to form foliation joints (Nieto, 1983).

The most significant direction of weakness (cleavage) in metamorphic rocks can be independent of the primary layering after the rock has undergone regional metamorphism. Selmer-Olsen (1964) mentions that where tensile and shear stresses probably had other directions than the cleavage in the rock, cleavage partings and joints cut each other at oblique angles to form rhombohedral blocks, see Fig. A3-32 in Appendix 3. This type of pattern is often found in regions with metamorphism in connection with mountain range foldings, and in fault zones of crushed rocks developed by shear stresses.

5 STATISTICAL DISTRIBUTION OF JOINTS

The most commonly measured geometric properties of jointing are spacing (or density), trace length, and orientation. Based on results obtained by many workers, the statistical distribution of joint density can often, as shown in Table A1-4, be modeled by an exponential function.

Reported distributions of joint trace length are less consistent than those for spacing, perhaps caused in part by strong biases implicit in many common sampling plans and in part by the way data are grouped into histograms prior to analysis. Log-normal distributions are perhaps the most frequently reported, but given size biases in the way samples are collected, many different in situ distributions would produce approximately log-normal samples (Baecher and Lanney, 1978). Many workers have used exponential distributions in analysis, primarily for computational convenience, but there is little empirical verification of this assumption, see Table A1-4.

From studies made for a probabilistic slope stability analysis Herget (1982) found log-normal distribution for dip, dip direction, hardness, and strength of fillings, and negative exponential distribution for spacing, trace length, and waviness.

As noted by Hudson and Priest (1970), since the exponential density of joints is fully defined by one parameter, the following simple relation exists between rock quality designation (RQD) and average joint spacing (l) for *hard, unweathered rocks*:

$$RQD = 100 \times e^{-0.1\,l}\,(0.1\,l + 1) \qquad \text{eq. (A1-1)}$$

TABLE A1-4 STATISTICAL DISTRIBUTION OF JOINTS (based mainly on Merritt and Baecher (1981)

Source	**Spacing**	**Trace length**	**Shape**
Snow (1968)	exponential	-	-
Robertson (1970)	-	exponential	equidimensional
Louis and Perrot (1972)	exponential	-	-
McMahon (1974)	-	log-normal	-
Steffen et al. (1975)	-	exponential	-
Bridges (1976)	-	log-normal	oblong
Call, Savely, Nicholas (1976)	exponential	exponential	-
Priest and Hudson (1975)	exponential	-	-
Baecher, Lanney, Einstein (1977)	exponential	log-normal	equidimensional
Barton (1977)	-	log-normal	equidimensional
Cruden (1977)	-	censored exp.	-
Baecher and Lanney (1978)	exponential	log-normal or exp.	-
Herget (1982)	exponential	exponential	-

6 SUMMARY

Many *igneous and metamorphic* rocks without planar orientation of the minerals may have regular jointing systems with three ore more sets at right angles forming prismatic blocks. Often, they are characterized by medium-sized, rough and planar joints.

Bedded *sedimentary* rocks and *foliated or schistose metamorphic* rocks show separations as partings parallel to the bedding or foliation in the rock. This direction is often along layers or bands of mica and/or chlorite, both minerals with elastic, anisotropic mechanical properties. They mainly cause that the partings or joints have a soft and weak joint walls with smooth surfaces.

Persistence of joints seems to be greater in rocks with well developed *foliation, layering, or bedding* than in the homogeneous rocks. The other joint sets are often developed perpendicular to the weakness direction.

Joint characteristics are often similar within the same joint set, while it can be different between joint sets in the same region.

Although the jointing often is composed mainly of joint sets, additional random joints frequently disturb the pattern. Variations in spacings, number of joint sets and random joints generally result in great differences in block size and shapes within an area or a location.

Weathering occurs more frequently along the joints than in the adjacent rock block.

Joint spacing and trace length exhibit generally a logarithmic or exponential distribution.