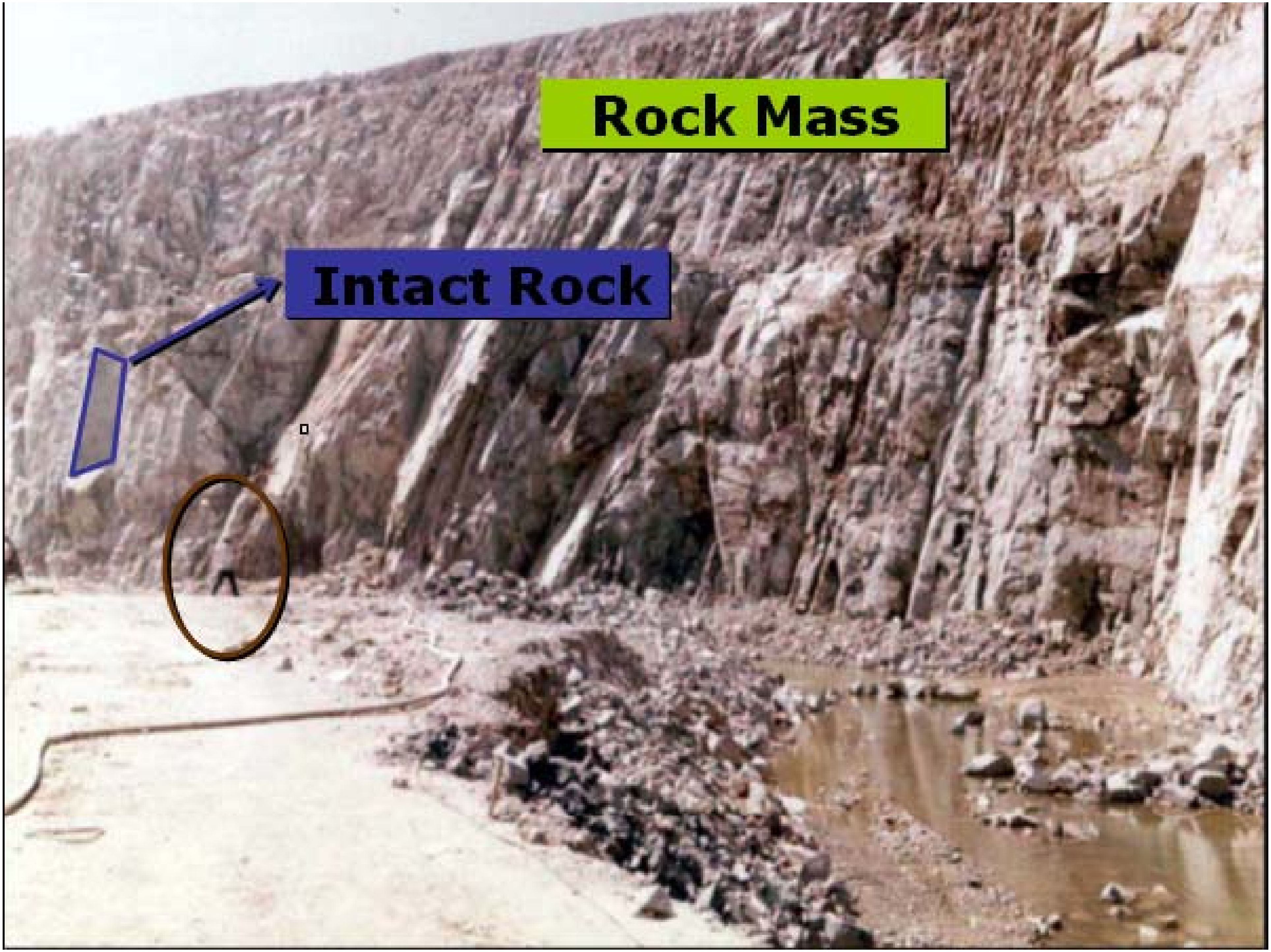
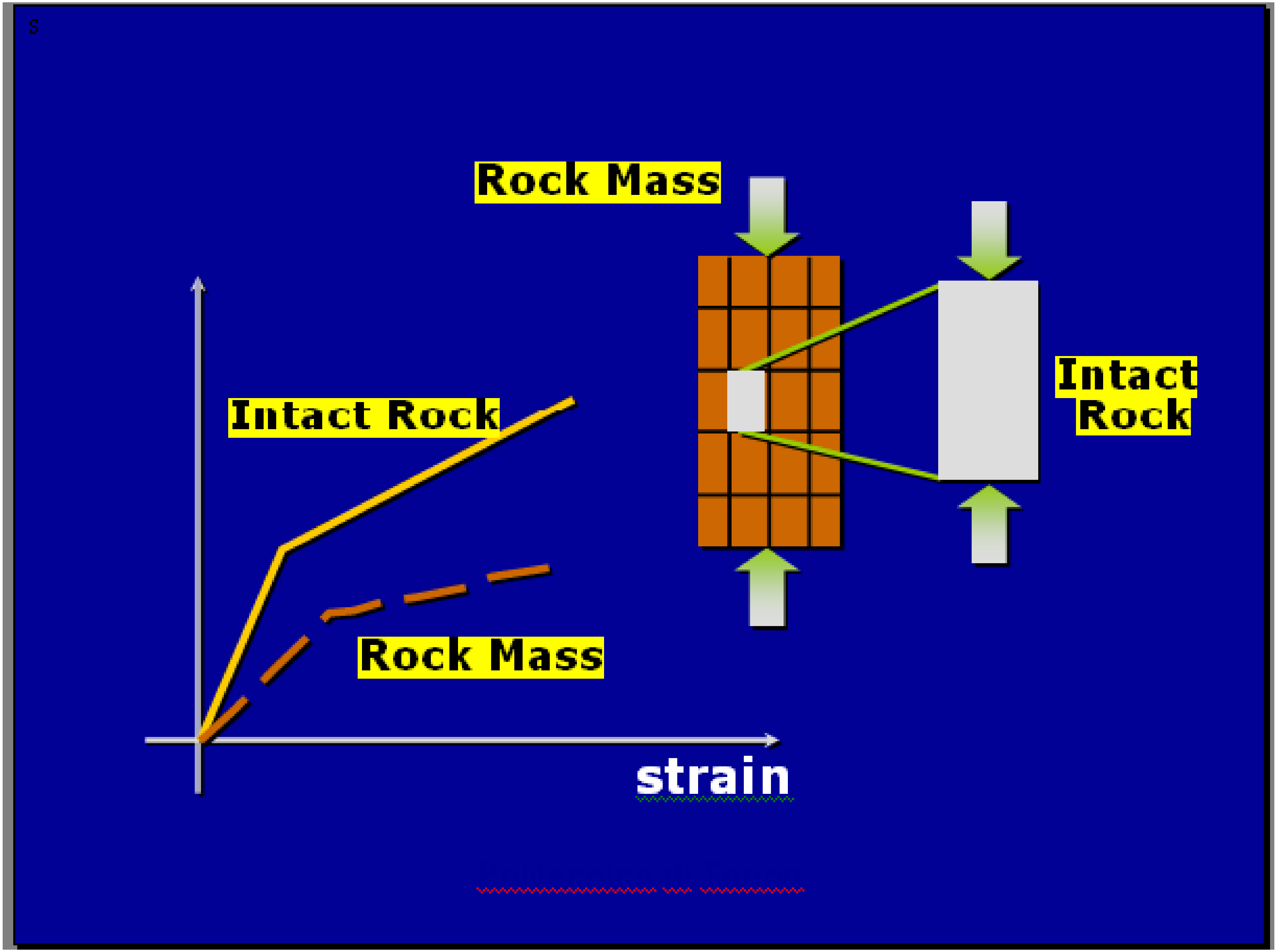

Rock Mass
Intact Rock


S
Rock Mass
Intact Rock
Rock Mass
Intact Rock
strain

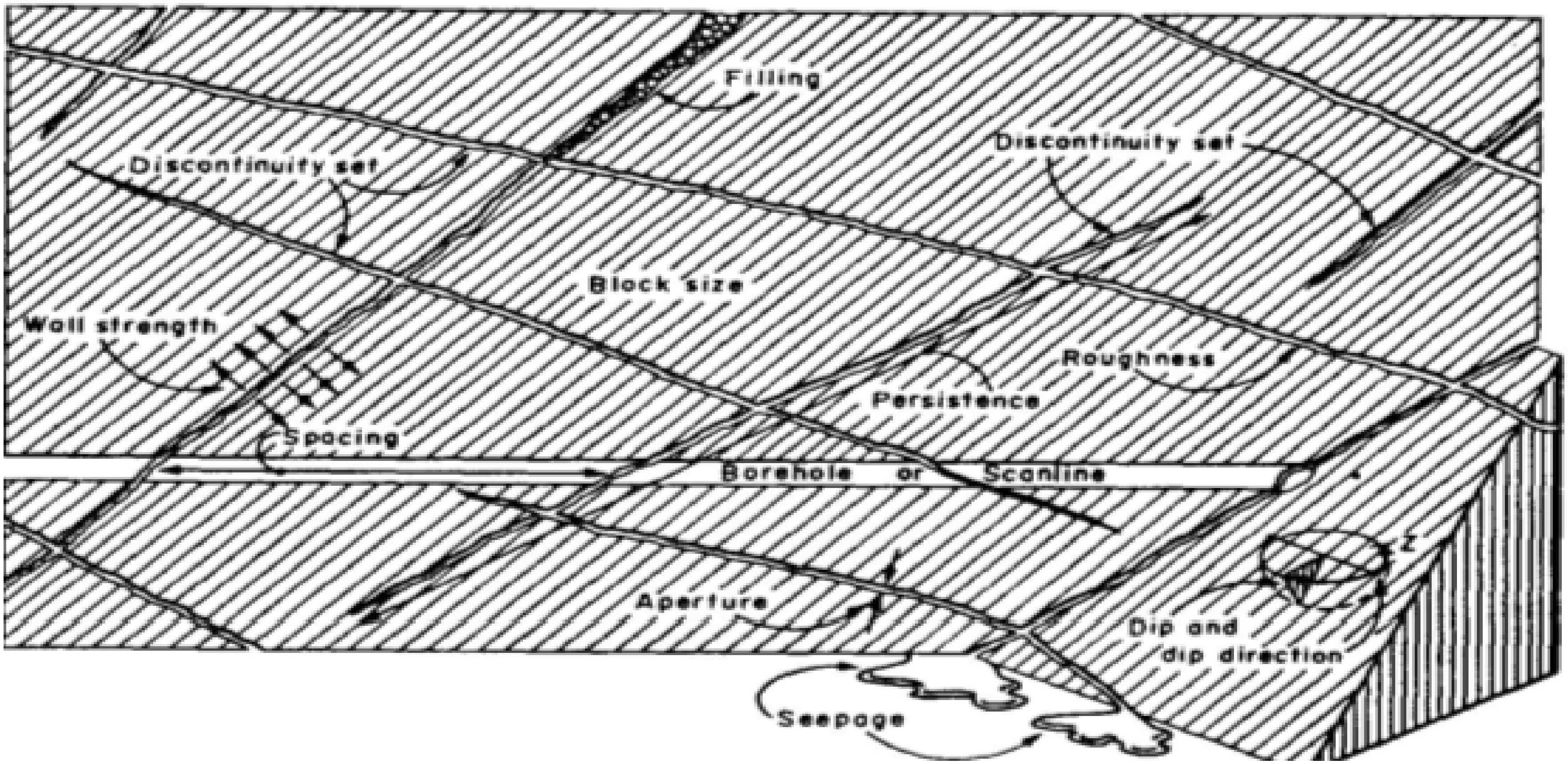
Geometrical Properties of Rock Joints

Types of Rock Discontinuities

Joints – Most common, normally in sets
Fractures – Randomly distributed
Faults – Singular and large scale
Bedding - Singular and large scale
Interfaces – Singular and large scale

Joints and fractures are often inter-used. An individual joint is often termed as a fracture.

Geometrical Properties of Rock Joints



Discontinuity Sets

Discontinuities do not occur at completely random orientations: they occur for good mechanical reasons with some degree of "clustering" around preferred orientations associated with the formation mechanisms. Hence, it is convenient to consider the concept of discontinuity set (which consists of parallel or sub-parallel discontinuities) and the number of such sets that characterize a particular rock mass geometry

Geometrical Properties of Rock Joints

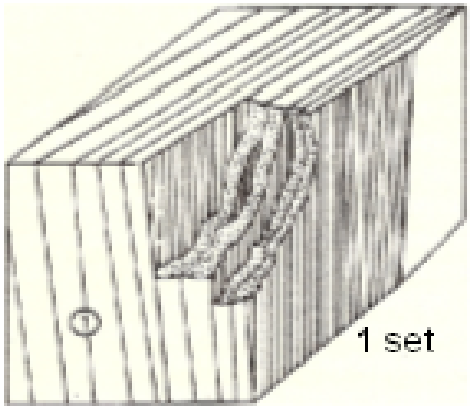
Principal Geometrical Characteristics of Rock Joints

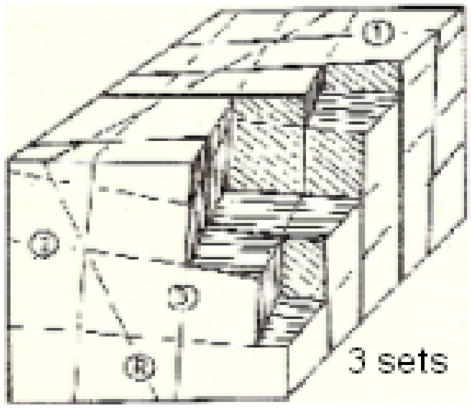
Number of joint sets
Joint persistence
Joint plane orientation
Joint spacing, joint frequency, block size, and RQD
Joint surface roughness and matching
Joint aperture and filling

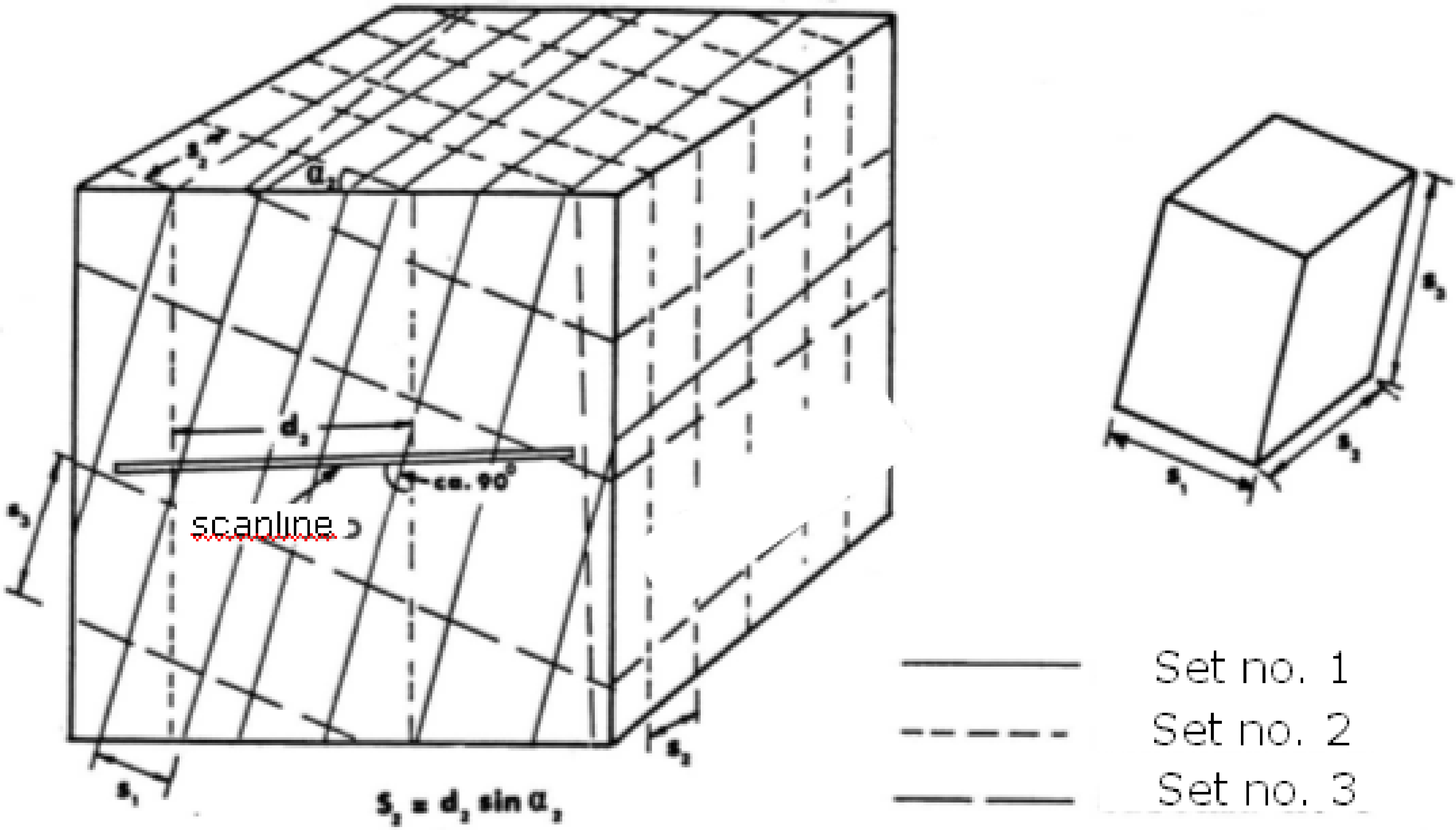
Geometrical Properties of Rock Joints

Number of Joint Sets

Joints are generally in sets, i.e., parallel joints. The number of joint sets can be up to 5. Typically one joint set cuts the rock mass into plates, two perpendicular sets cut rock into column and three into blocks, and more sets cut rocks into mixed shapes of blocks and wedges.

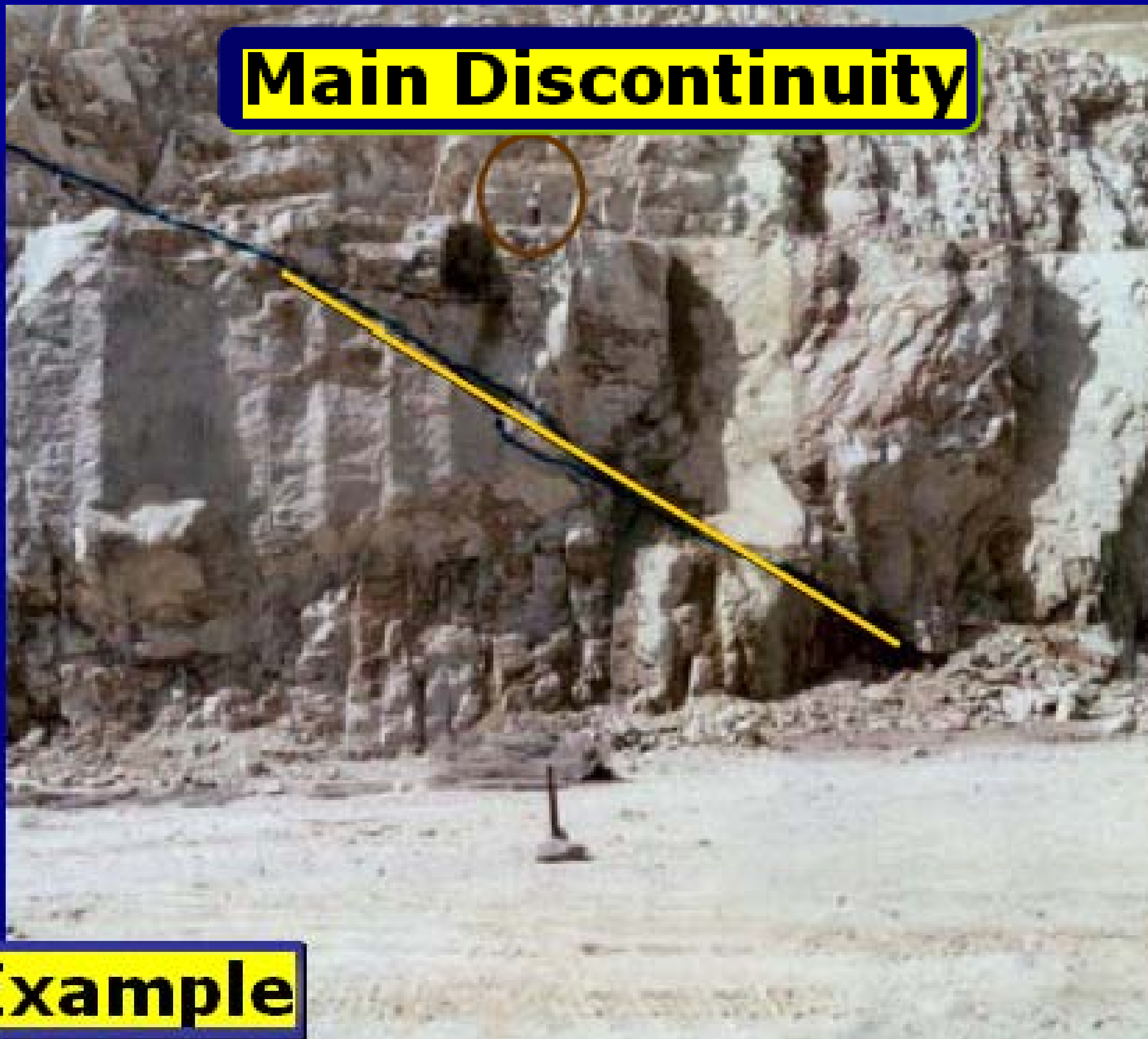






scanline
ca. 90°
S2 = d2 sin α2
Set no. 1
Set no. 2
Set no. 3

Rock Mass with 3 discontinuity sets



Example

A fault, with complex morphology

Geometrical Properties of Rock Joints

ISRM suggested description

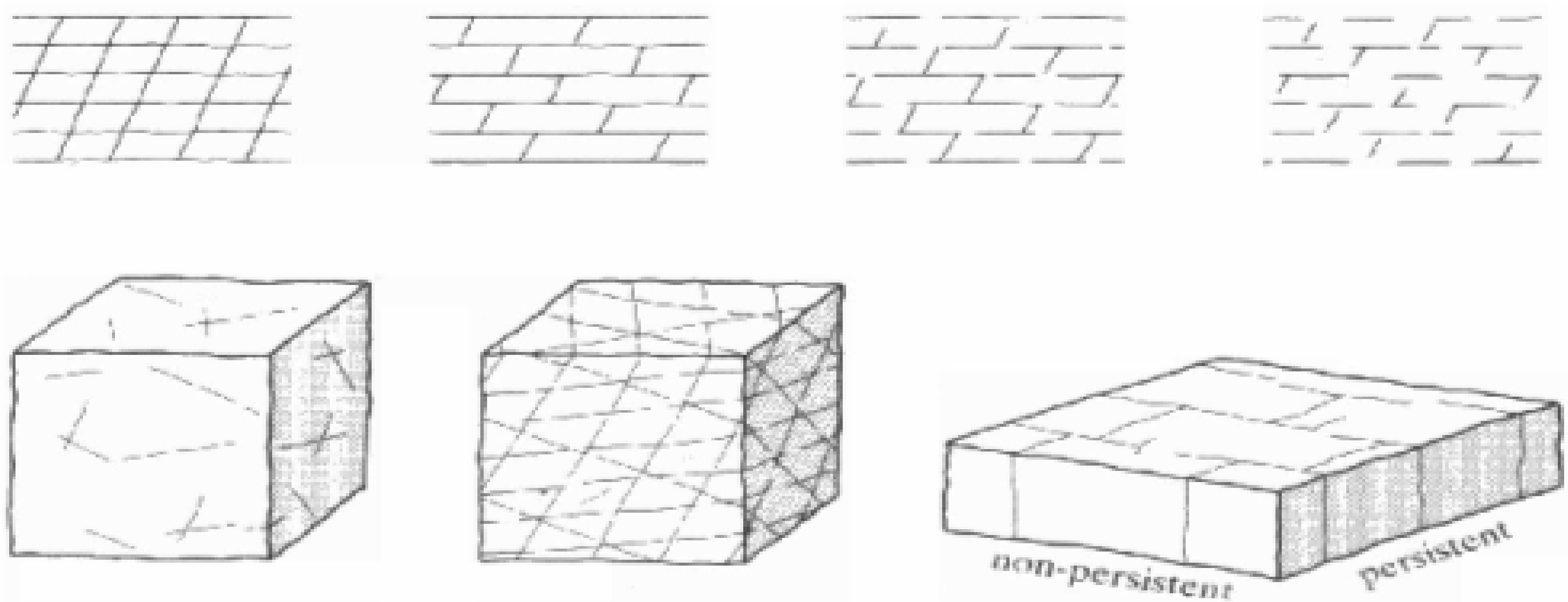
I	Massive, occasional random fractures
II	One joint set
III	One joint set plus random fractures
IV	Two joint sets
V	Two joint sets plus random fractures
VI	Three joint sets
VII	Three joint sets plus random fractures
VIII	Four or more joint sets
IX	Crushed rock, earth-like

Mechanical properties of the rock mass is influenced by joint sets. More joint sets provide more possibilities of potential slide planes .

Geometrical Properties of Rock Joints

Joint Persistence

Persistence is the areal extent or length of a discontinuity, and can be crudely quantified by observing the trace lengths of discontinuities on exposed surfaces. The persistence of joint sets controls large scale sliding or 'down-stepping' failure of slope, dam foundation and tunnel excavation.



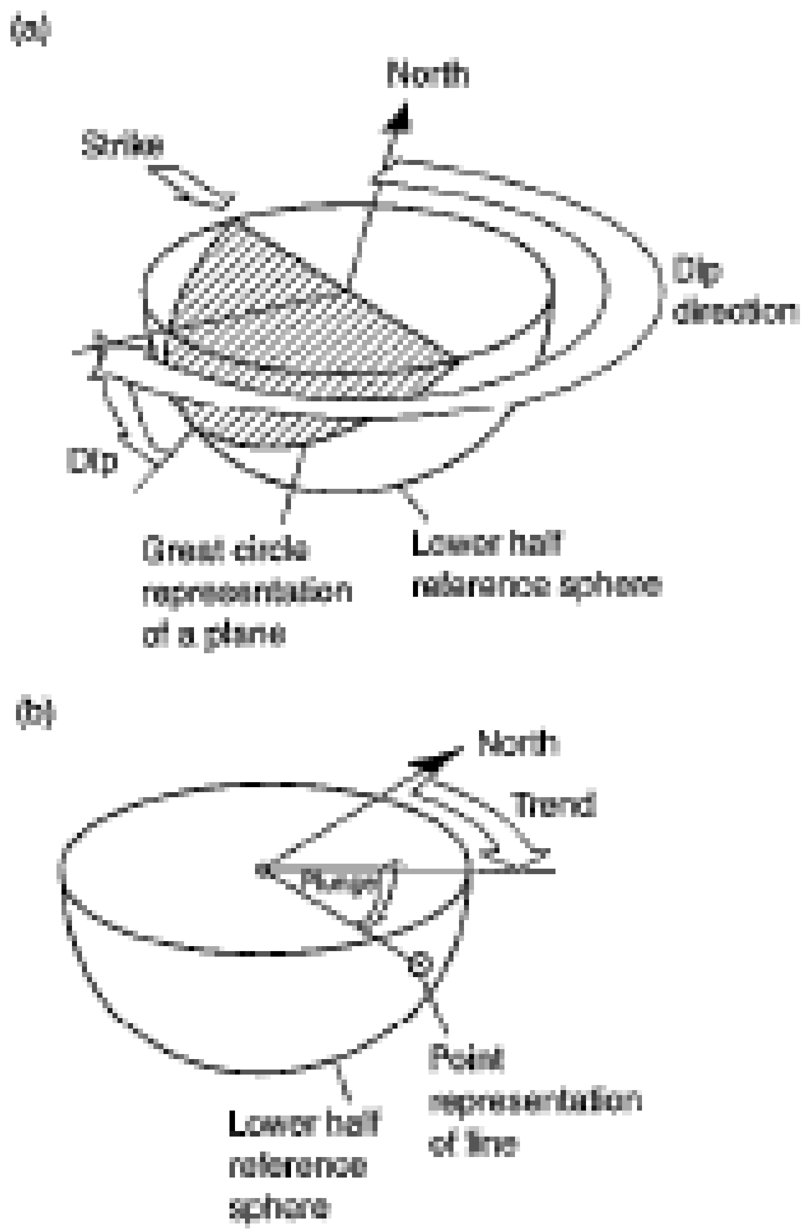
ISRM Suggested Description	Surface Trace Length (m)
Very low persistence	< 1
Low persistence	1 – 3
Medium persistence	3 – 10
High persistence	10 – 20
Very high persistence	> 20

Geometrical Properties of Rock Joints

Joint Plane Orientation

Orientation of joint sets controls the possibility of unstable conditions or excessive deformations. The mutual orientation of joints determines the shape of the rock blocks.

Orientation is defined by dip angle (inclination) and dip direction (facing) or strike (running).



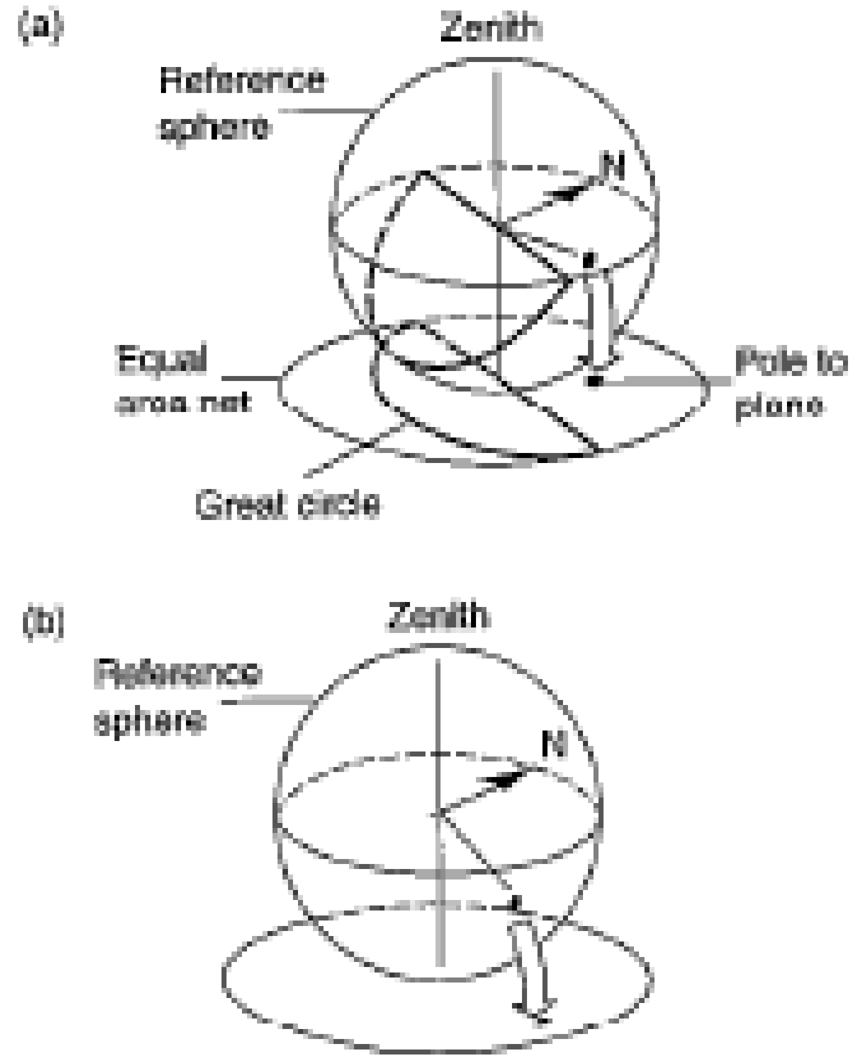
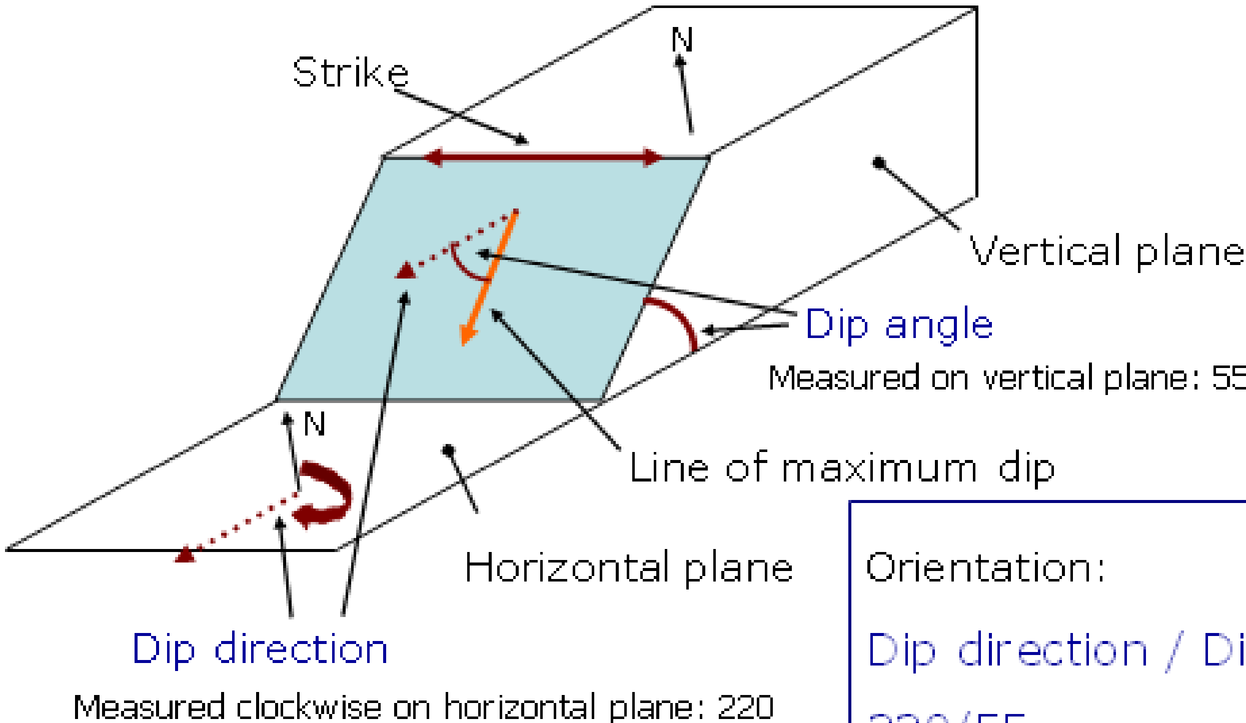


Figure 2.6 Equal area projections of plane and line: (a) plane projected as great circle and corresponding pole; (b) line projected as pole.

Orientation

Attitude of discontinuity in space. Described by the dip direction α (azimuth) and deep ψ of steepest declination in the plane of discontinuity. Example: dip direction/dip (015°/35°)

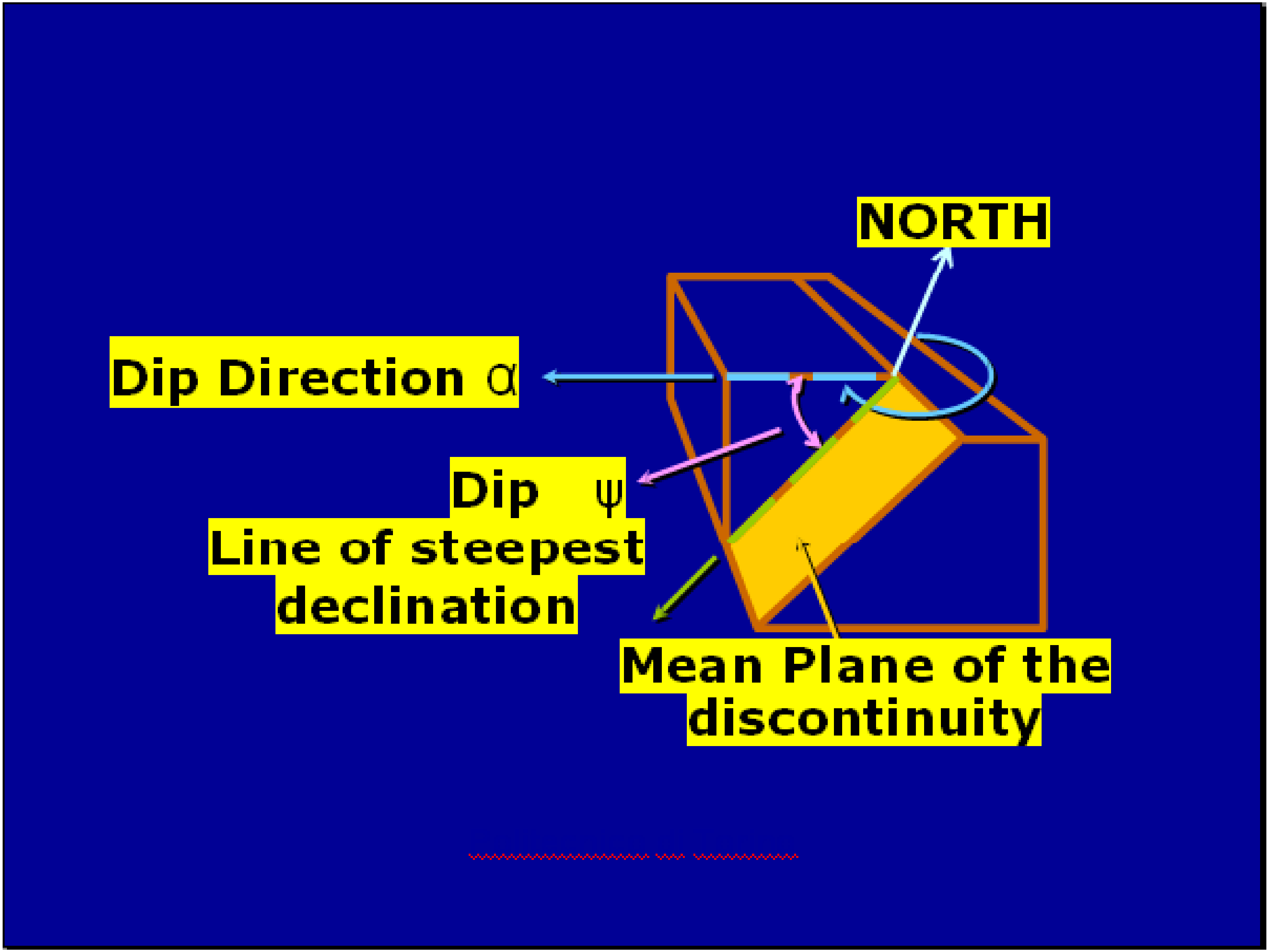
Geometrical Properties of Rock Joints



Orientation:

Dip direction / Dip

220/55


NORTH
Dip Direction α
Dip ψ
Line of steepest declination
Mean Plane of the discontinuity

Geometrical Properties of Rock Joints

A geological compass to measure dip and direction of joint plane

An electronic geological compass

Geological compass used for measuring the orientation of a discontinuity plane

It allows reading directly in terms of dip and dip direction

Geometrical Properties of Rock Joints

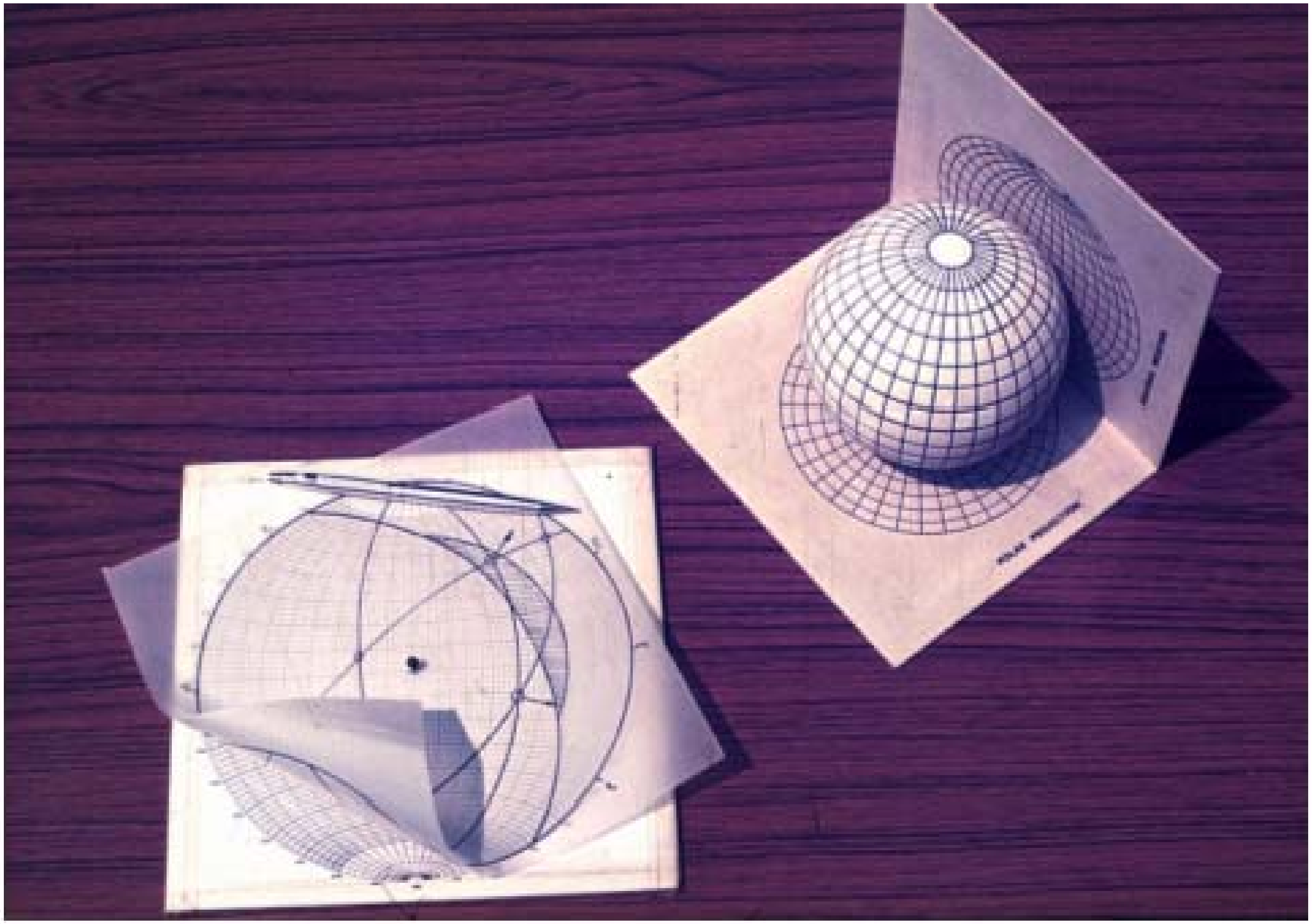
Joint Plane Orientation

Dip direction and strike direction are always perpendicular. Dip direction/dip format is generally used, e.g., 210/35, or 030/35. Sometimes, dip/strike format is used, e.g., 120/35SW (=dip direction/dip 210/35), or 120/35NE (=dip direction/dip 030/35). Normal (pole) to the plane is perpendicular to the plane. Orientation of the normal is given by:
trend of normal = dip direction of the plane ± 180,
plunge of normal = 90 – dip.

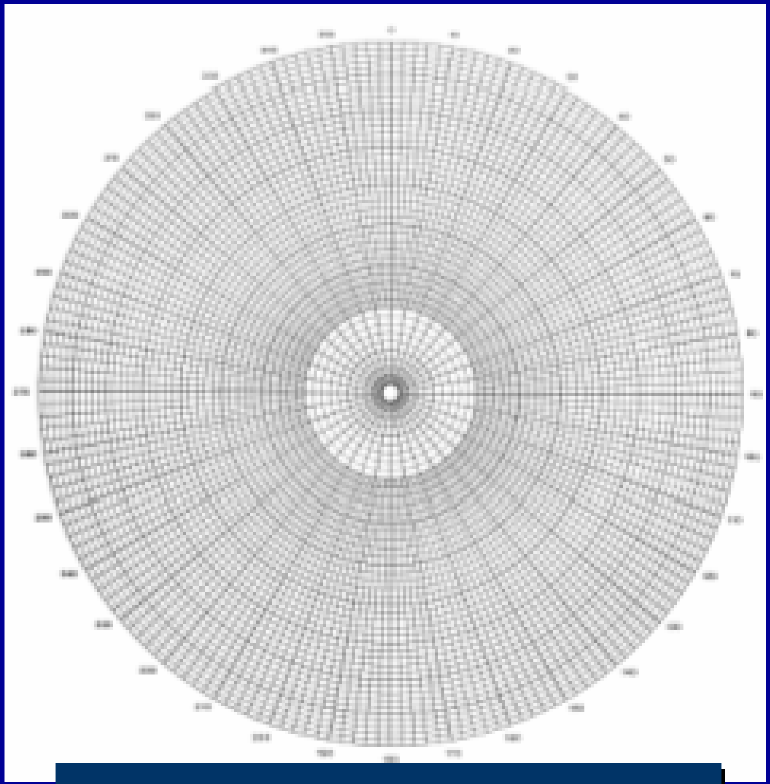
Geometrical Properties of Rock Joints

Joint Plane Orientation

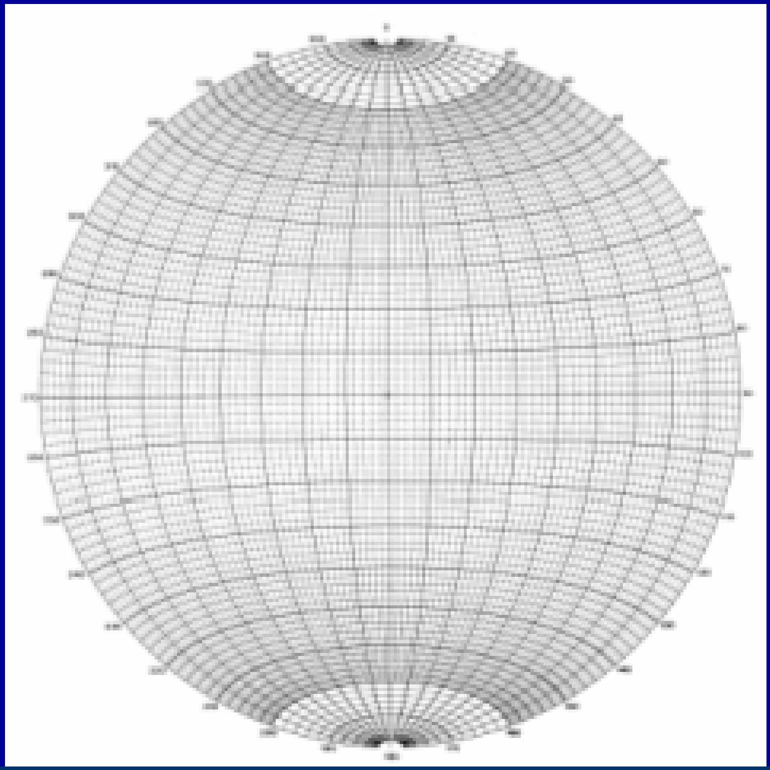
Orientation of a joint plane can be represented graphically using hemispherical projection method. The projection method is to represent a 3D plane by a 2D presentation. Use the projection, joint orientation data can be assessed in 2D form. It can be used to analyse large number of joint data and examine the rock slope stability and slide of rock block in underground excavation.



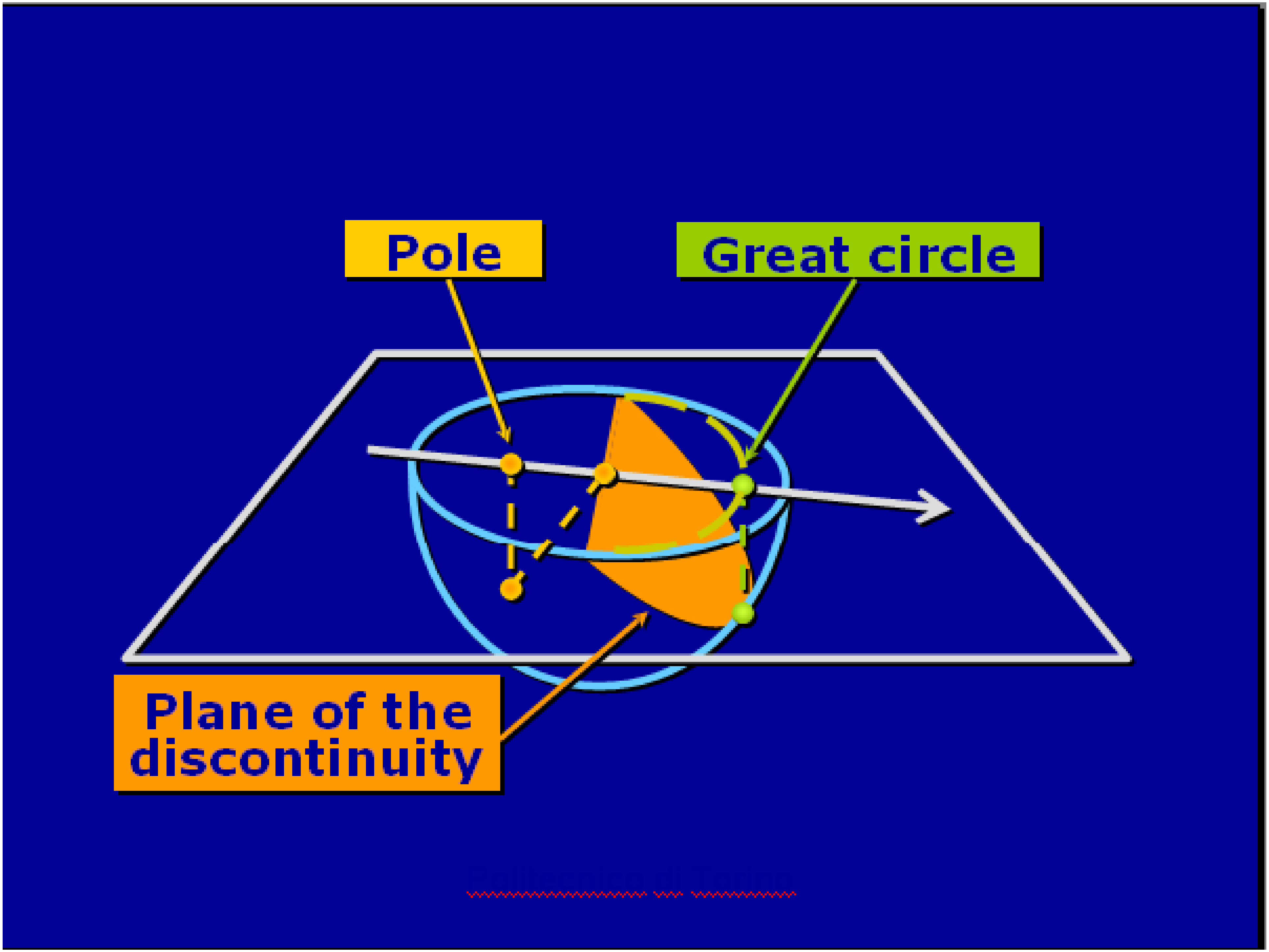
Spherical projections plot and analyze joint orientation data

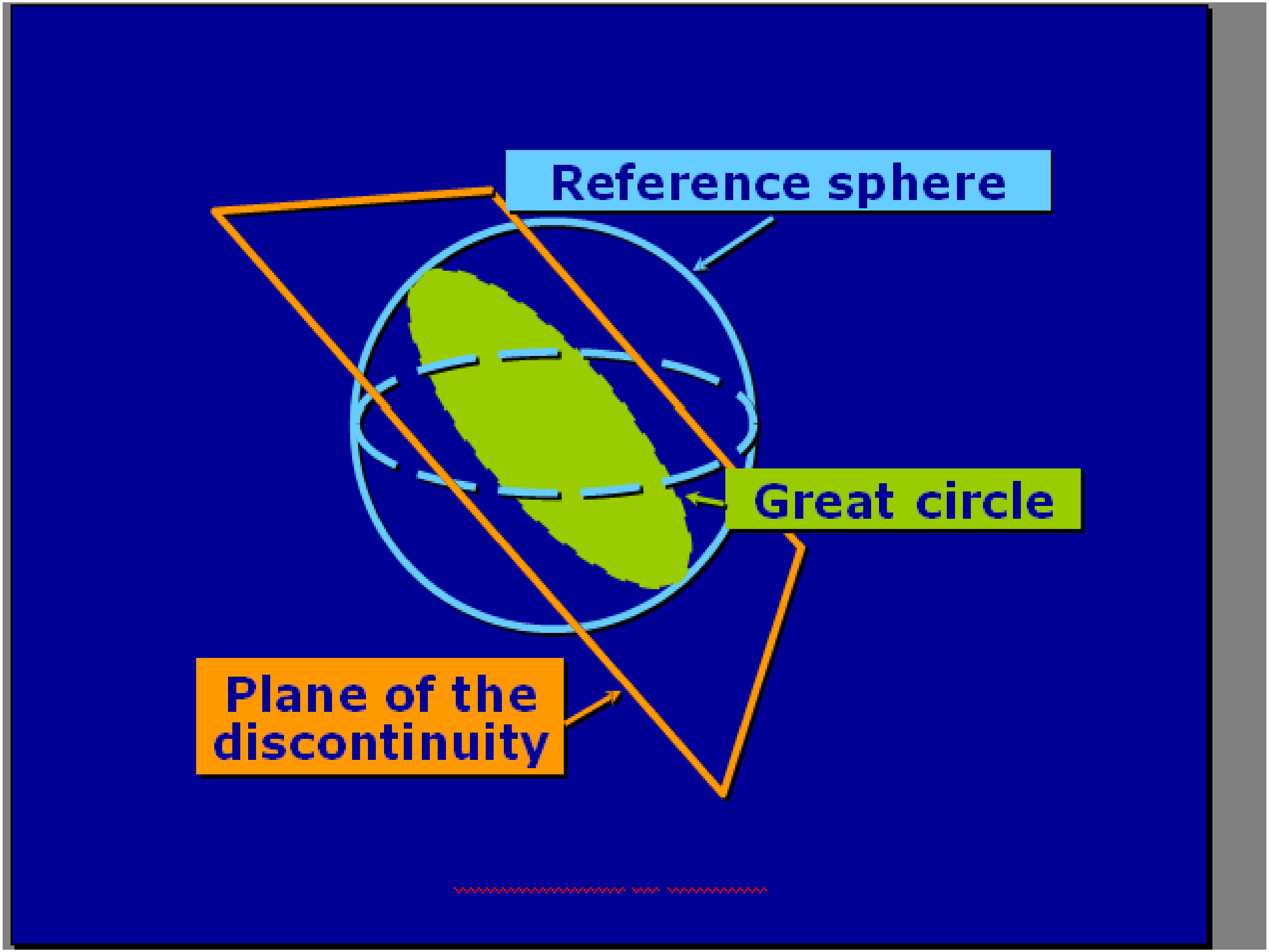


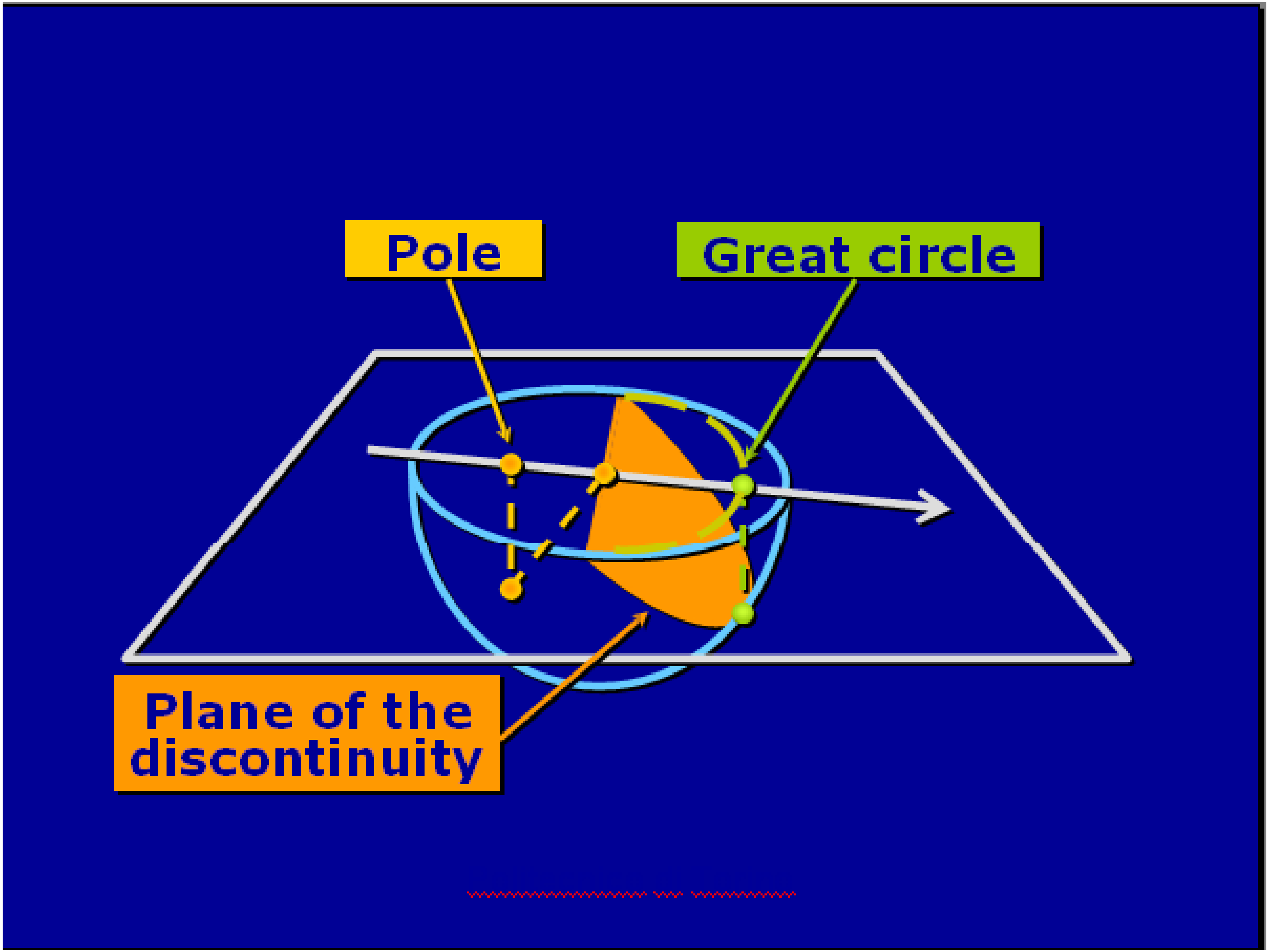
Polar equal-area stereonet



Equatorial equal-area stereonet


Pole
Great circle
Plane of the discontinuity


Reference sphere
Great circle
Plane of the discontinuity


Pole
Great circle
Plane of the discontinuity

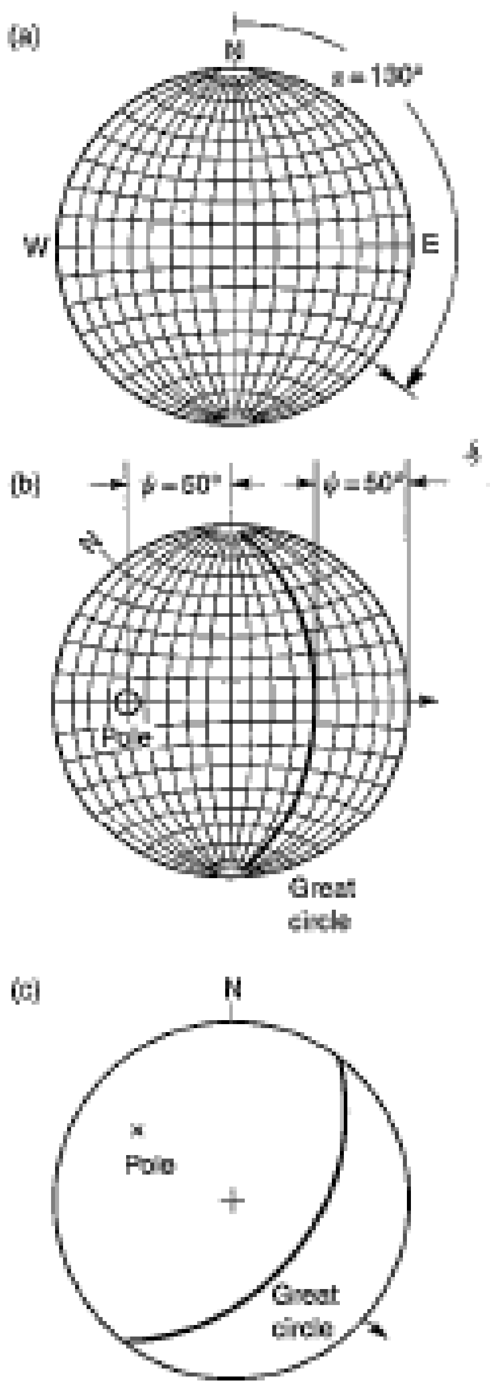


Figure 2.13 Construction of great circles and a pole representing a plane with orientation 50 (dip)/130 (dip direction) on an equal area net: (a) with the tracing paper located over the stereonet by means of the center pin, trace the circumference of the net and mark the north point. Measure off the dip direction of 130° clockwise from north and mark this position on the circumference of the net; (b) rotate the net about the center pin until the dip direction mark lies on the W–E axis of the net, that is, the net is rotated through 40° counterclockwise. Measure 50° from the outer circle of the net and trace the great circle that corresponds to a plane dipping at this angle. The position of the pole, which has a dip of (90–50), is found by measuring 50° from the center of the net as shown, or alternatively 40° from the outside of the net. The pole lies on the projection of the dip direction line which, at this stage of the construction, is coincident with the W–E axis of the net; (c) the tracing is now rotated back to its original position so that the north mark on the tracing coincides with the north mark of the net. The final appearance of the great circle and the pole representing a plane dipping at 50° in a dip direction of 130° is as illustrated.

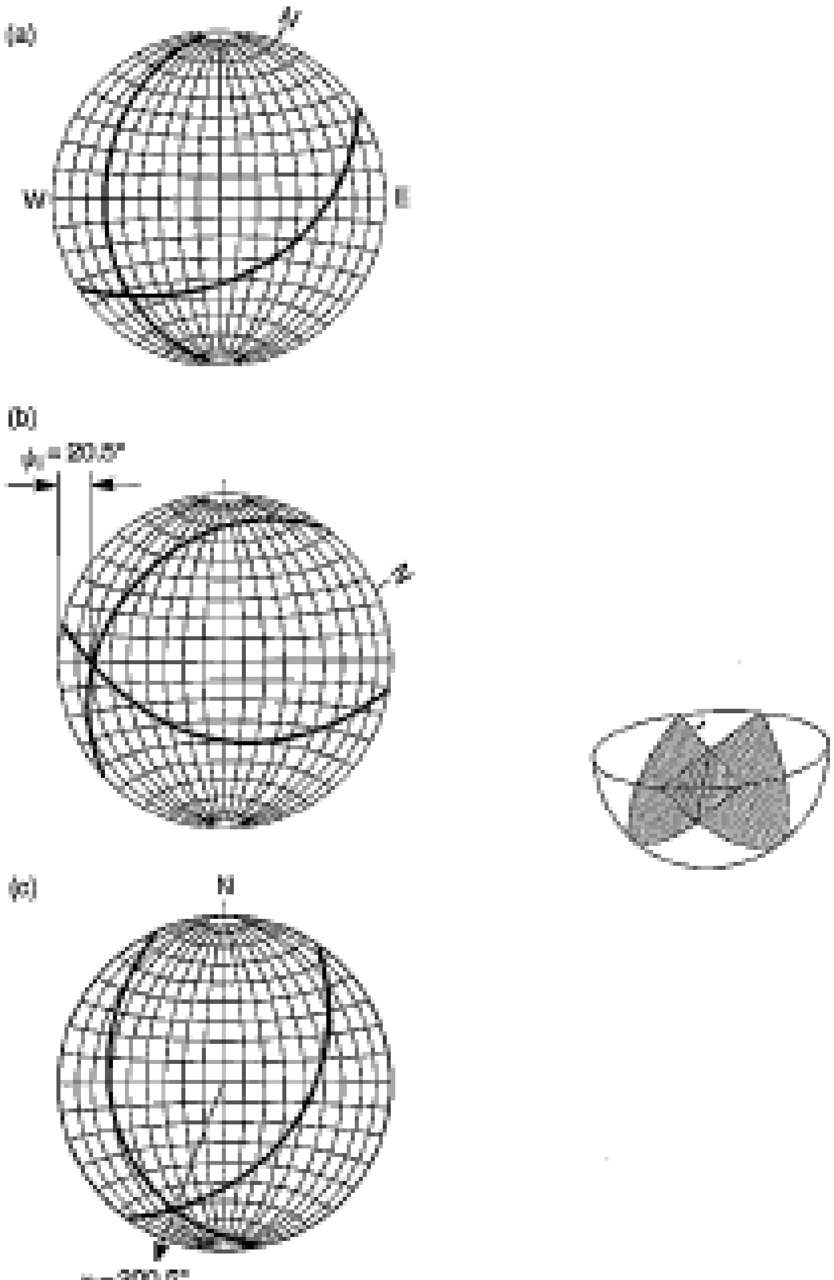


Figure 2.14 Determination of orientation (plunge and trend) of line intersection between two planes with orientations 50/130 and 30/250: (a) the first of these planes has already been drawn in Figure 2.13. The great circle defining the second plane is obtained by marking the 250° dip direction on the circumference of the net, rotating the tracing until the mark lies on the W–E axis and tracing the great circle corresponding to a dip of 30°; (b) the tracing is rotated until the intersection of the two great circles lies along the W–E axis of the stereonet, and the plunge of the line of intersection is measured as 20.5°; (c) the tracing is now rotated until the north mark coincides the north point on the stereonet and the trend of the line of intersection is found to be 200.5°.

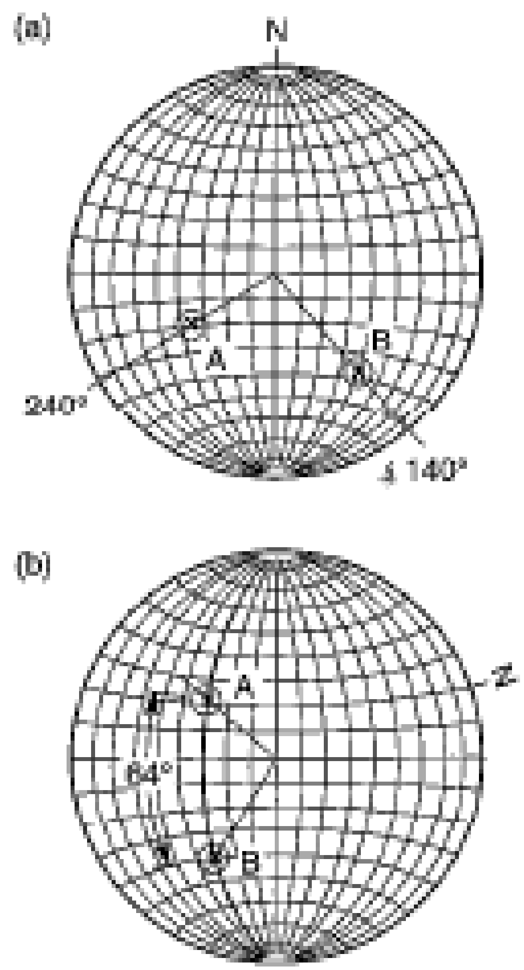
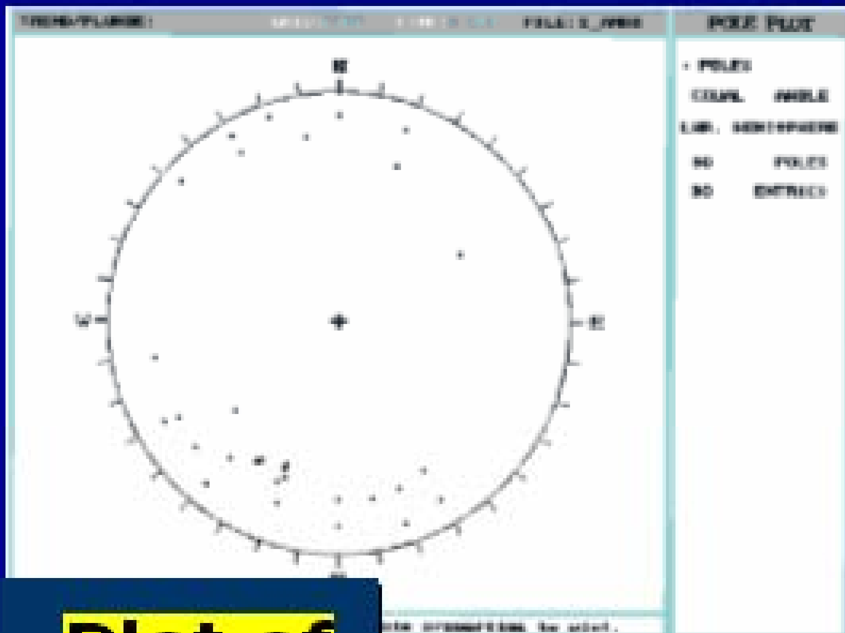


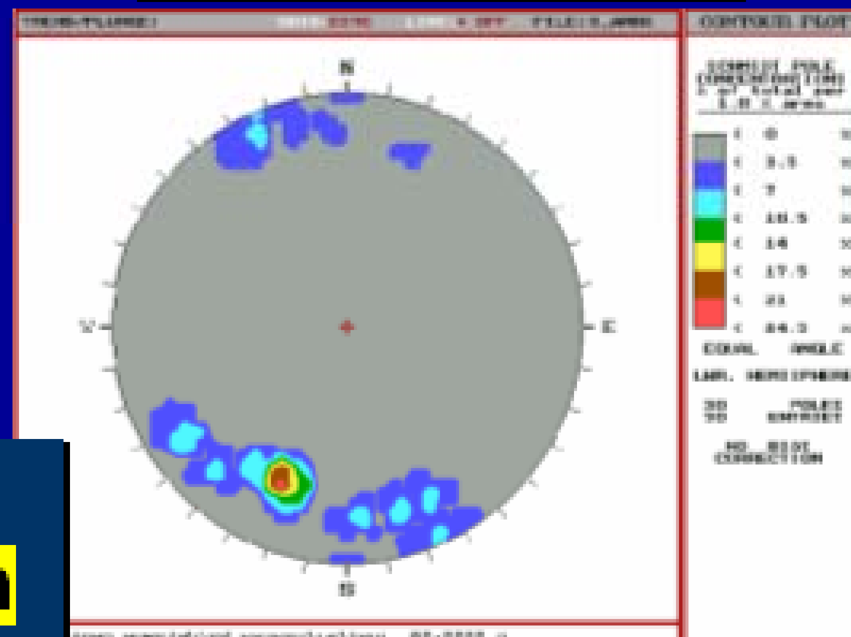
Figure 2.15 Determination of angle between lines with orientations 54/240 and 40/140: (a) the points A and B that define the poles of these two lines are marked on the stereonet as described in Figure 2.13 for locating the pole; (b) the tracing is rotated until the two poles lie on the same great circle on the stereonet. The angle between the lines is determined by counting the small circle divisions between A and B, along the great circle; this angle is found to be 64°. The great circle on which A and B lie defines the plane that contains these two lines. The dip and direction of this plane are 60° and 200° respectively.

Example

Computer analysis of structural data

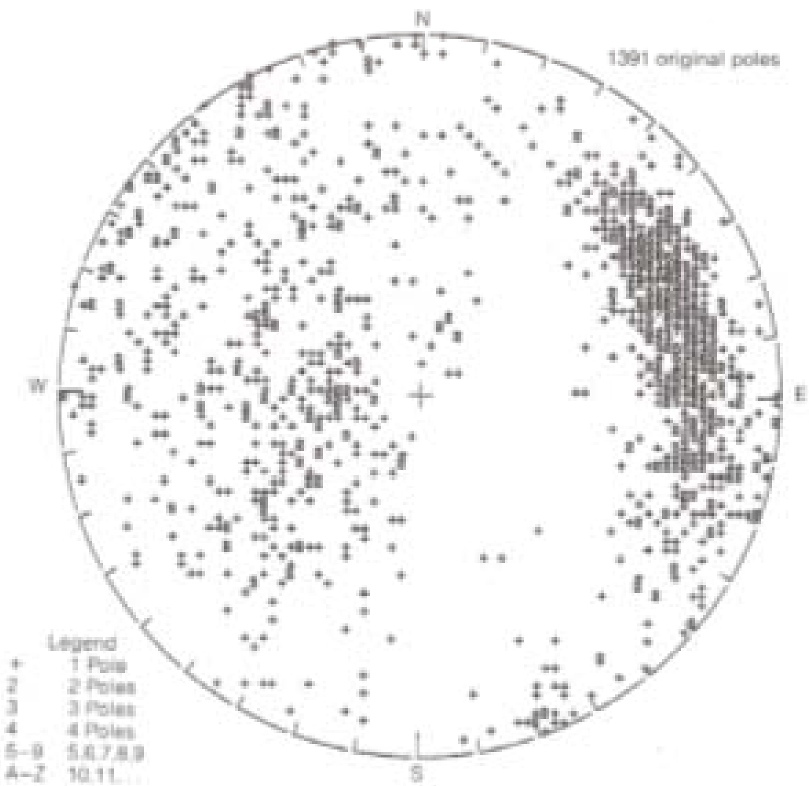


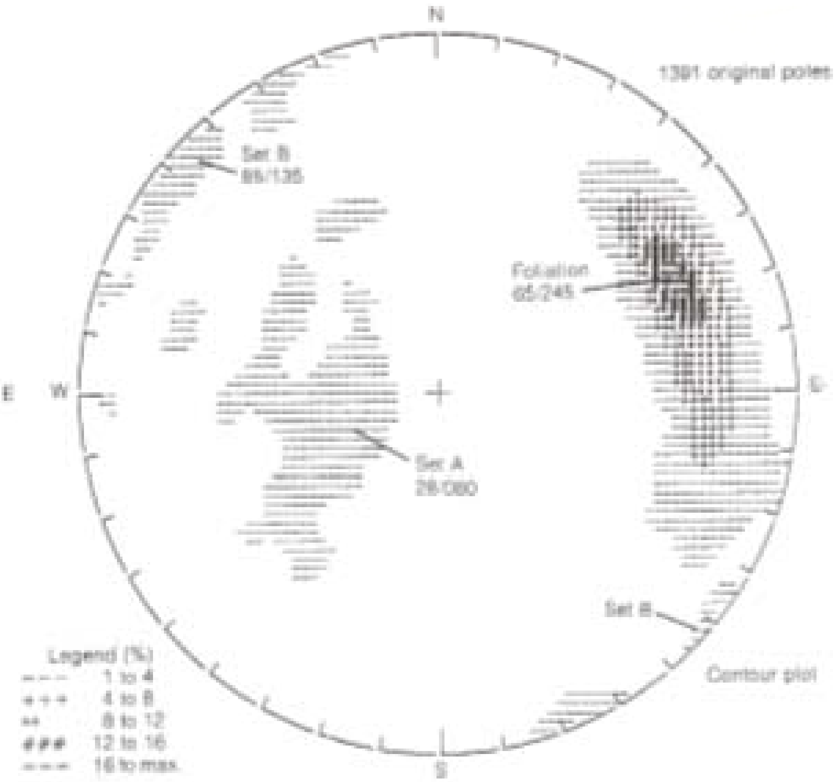
Plot of poles

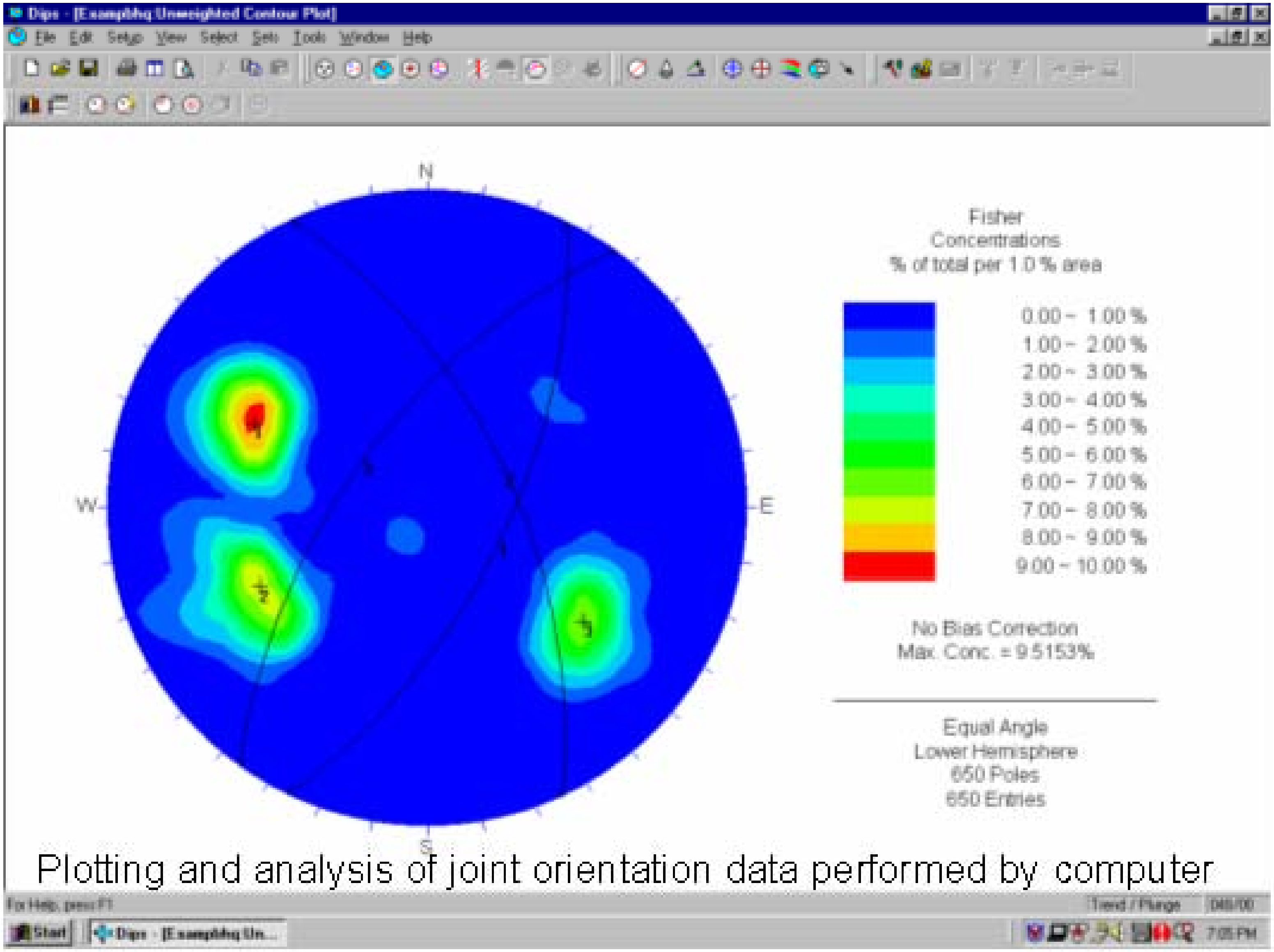


Contour diagram

Geometrical Properties of Rock Joints

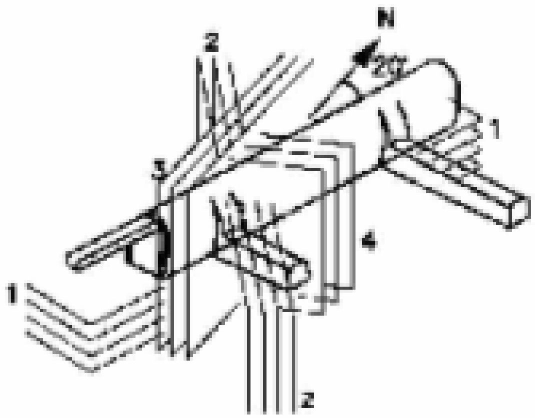


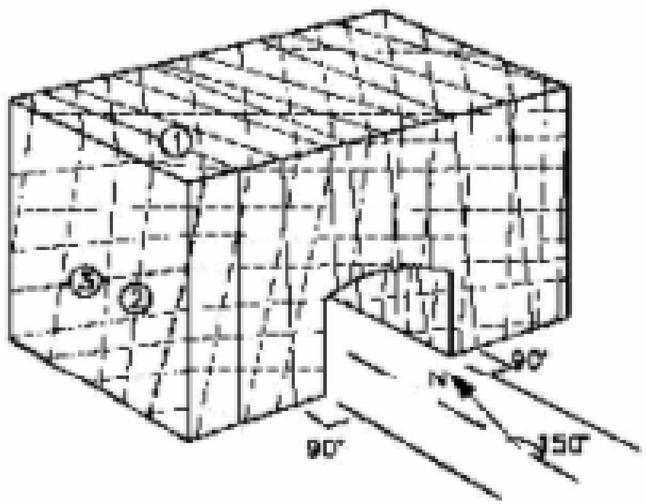


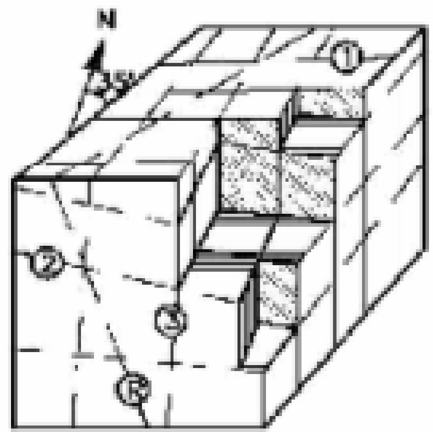


Plotting and analysis of joint orientation data performed by computer

Perspective views and block diagrams for engineering structures







Geometrical Properties of Rock Joints

Joint Spacing, Frequency, Block Size, and RQD

Fracturing degree of a rock mass is controlled by the number of joint in the rock mass. More joints mean that less average spacing between joints. Joint spacing controls the size of individual rock blocks. It controls the mode of failure and flow. For example, a close spacing gives low mass cohesion and circular or even flow failure.

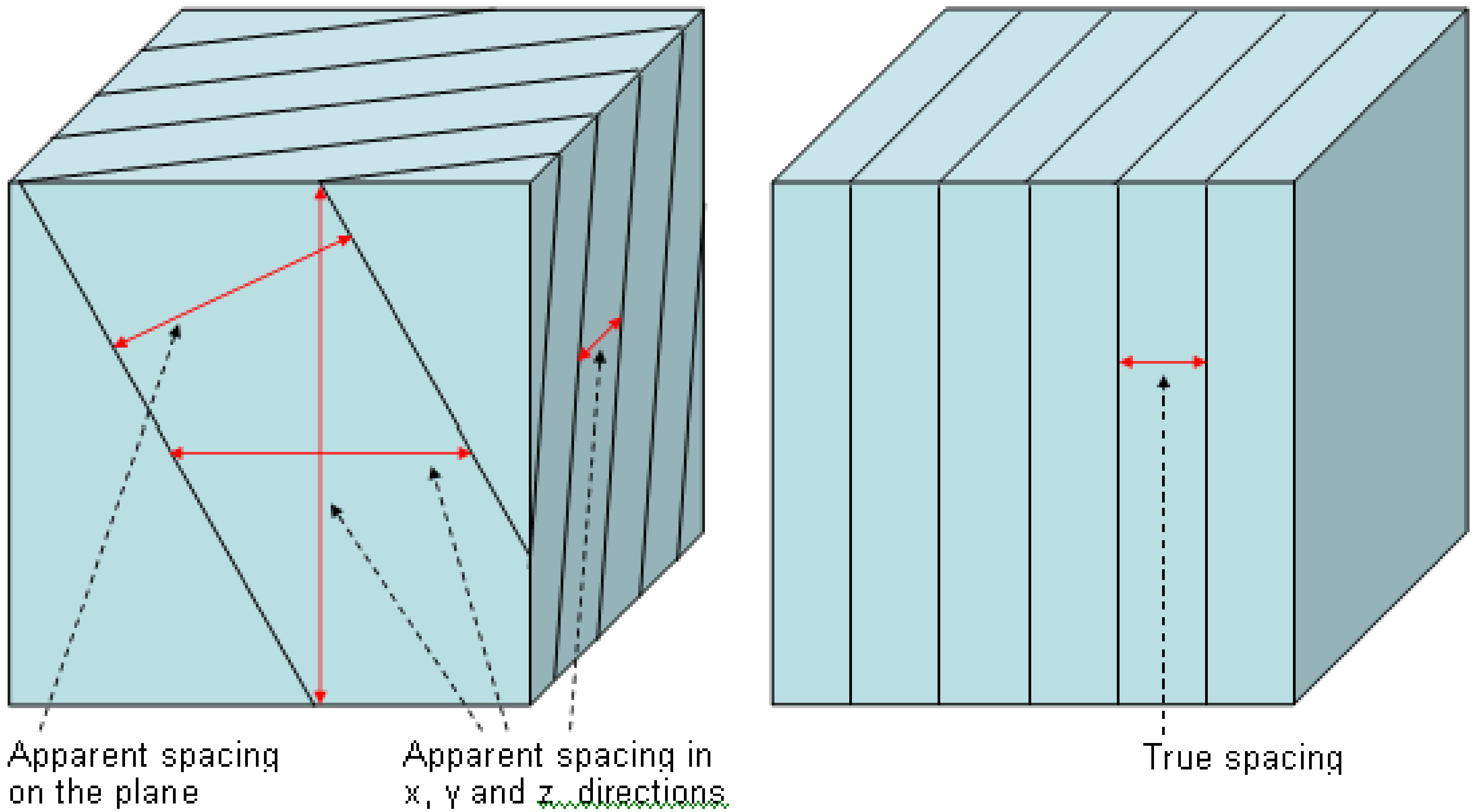
Geometrical Properties of Rock Joints

Joint Spacing

Joint spacing is the perpendicular distance between joints. For a joint set, is usually expressed as the mean spacing of that joint set. Often the apparent spacing is measured.

Measurements of joint spacing are different on different measuring faces and directions. For example, in a rock mass with mainly vertical joints, measurements in vertical direction have far greater spacing then that in horizontal direction.

Geometrical Properties of Rock Joints



Geometrical Properties of Rock Joints

Classification of joint spacing

Description	Joint Spacing (m)
Extremely close spacing	< 0.02
Very close spacing	0.02 – 0.06
Close spacing	0.06 – 0.2
Moderate spacing	0.2 – 0.6
Wide spacing	0.6 – 2
Very wide spacing	2 – 6
Extremely wide spacing	> 6

Geometrical Properties of Rock Joints

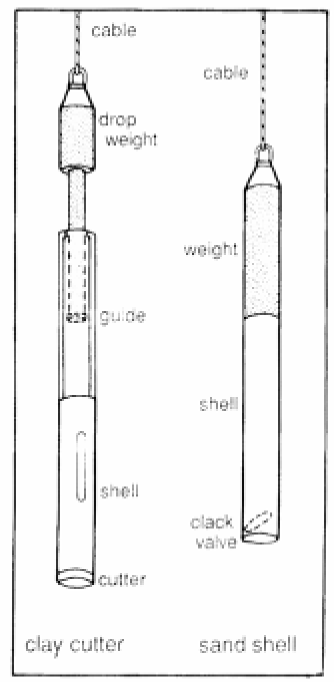
Joint Frequency

Joint frequency (λ), is defined as number of joint per metre length. It is therefore simply the inverse of joint spacing (s_j), i.e.,

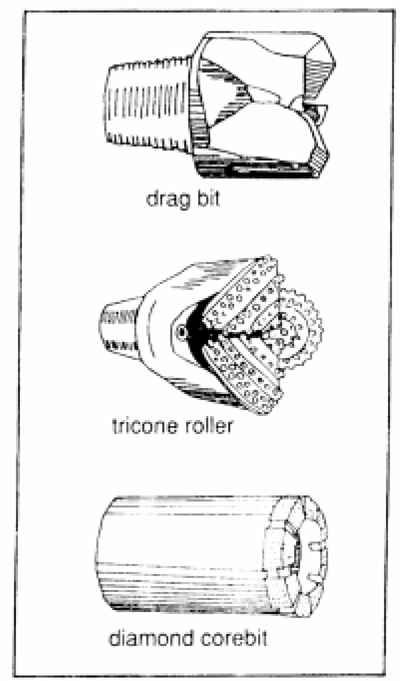
$$\lambda = 1 / s_i$$

Site investigation boreholes

- Percussion drilling
  - soils/soft clay rocks
  - core recovery
- Rotary coring
  - soil or rock >100m deep
  - core recovery
- Rock probing
  - rotary percussion rig
  - soil or rock
  - no core recovery



Alternative shells for light percussion drills



Alternative drill bits for rock penetration

Rotary rig

Core bit

Core drilling

Rock core


NORWEST HOLST SOIL ENGINEERING LIMITED
SITE HUYTON
CONTRACT F11841
No. BH. 101 BOX 2
DEPTH 6.80 m to 9.60 m
8.10
9.60


1529 GEOLOGICAL AND ROCK INVESTIGATION AT JURONG ISLAND HDD2-2 BOX-15
CR LENGTH(M) TCR(%) SCR(%) RQD(%) DATE
90 188.90-191.90 100 100 97 07-04-04
91 191.90-194.10 98 98 98 07-04-04
92 194.10-195.90 97 97 94 07-04-04
93 195.90-197.05 98 98 98 07-04-04
HDD2-2 191.90
HDD2-2 194.10
HDD2-2 195.90
HDD2-2 197.05

Total Core Recovery (R)

$$R = \frac{\text{Summed length of core recovered}}{\text{Length drilled}}$$

<u>Depends upon:</u>

- quality of the rock mass?
- stability of/lack of vibration in, the drill rig
- choice of core barrel/skill of the operator

Rock Quality Designation (RQD) or Modified Core Recovery

$$RQD = \frac{\Sigma x_i}{L}$$

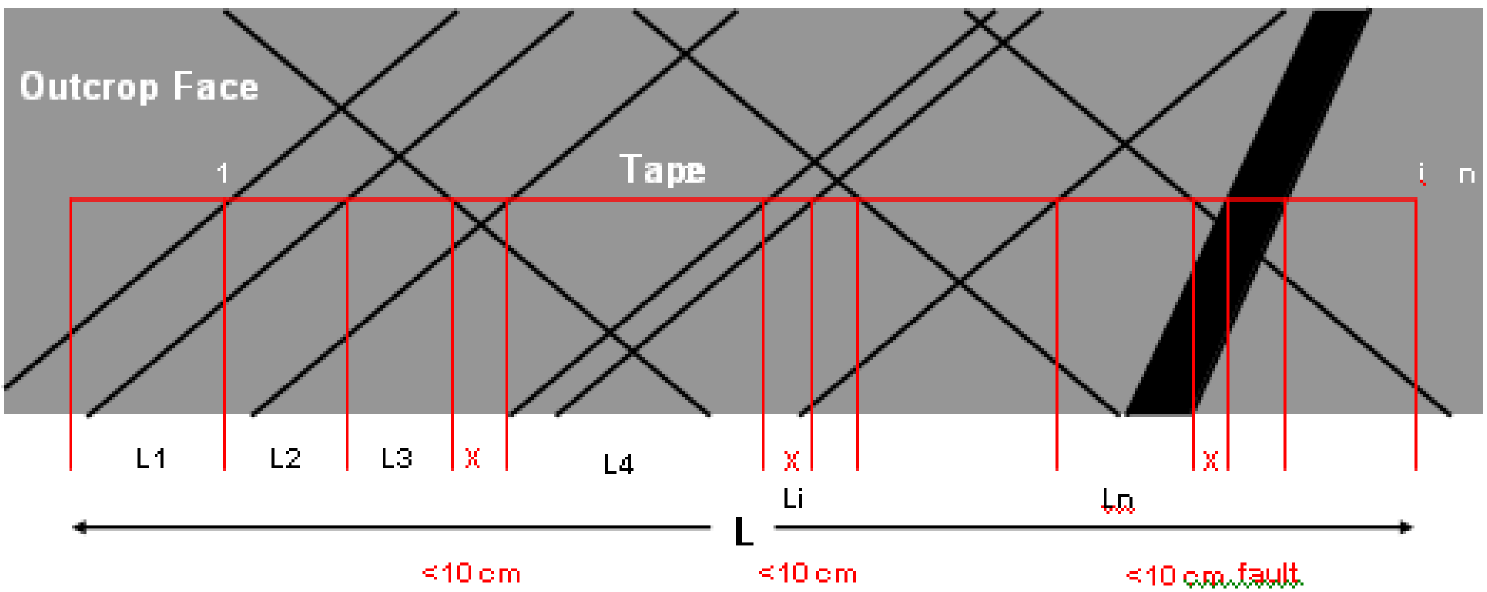
x_i = lengths of individual pieces of core $\geq$ 10 cm

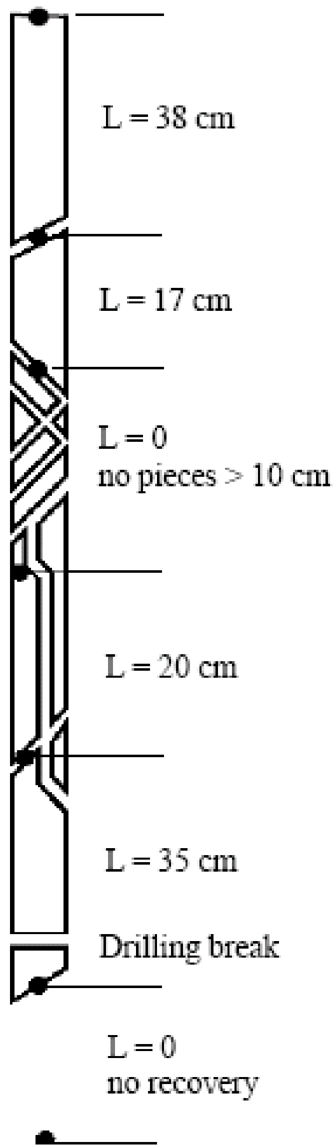
L is the total length of the drill run

Geometrical Properties of Rock Joints

$$RQD = (L1 + L2 + \ldots + Ln) / L \times 100\%$$

$$\lambda = \text{number of joints / length} = n / L$$





Total length of core run = 200 cms

$$RQD = \frac{\Sigma \text{ Length of core pieces} > 10 \text{ cm length}}{\text{Total length of core run}} \times 100$$

$$RQD = \frac{38 + 17 + 20 + 35}{200} \times 100 = 55\ \%$$

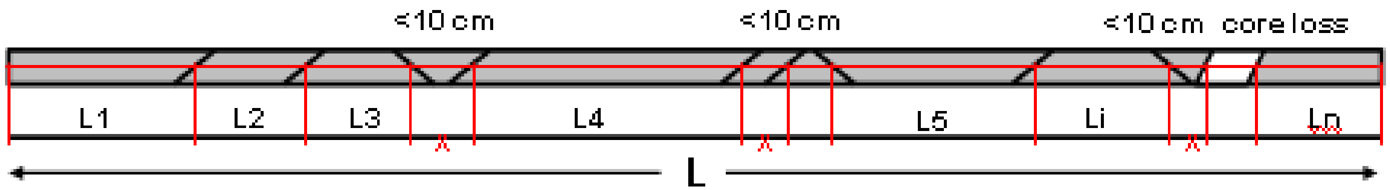
Figure 4.1: Procedure for measurement and calculation of *RQD* (After Deere, 1989).

Geometrical Properties of Rock Joints

RQD

Rock Quality Designation (RQD) is defined as the percentage of rock cores that have length equal or greater than 10 cm over the total drill length.

$$RQD = \Sigma Li / L \times 100\%, \quad Li > 10 \text{ cm}$$



$$RQD = (L1 + L2 + \ldots + Ln) / L \times 100\%$$

Geometrical Properties of Rock Joints

RQD can be correlated to joint frequency (λ):

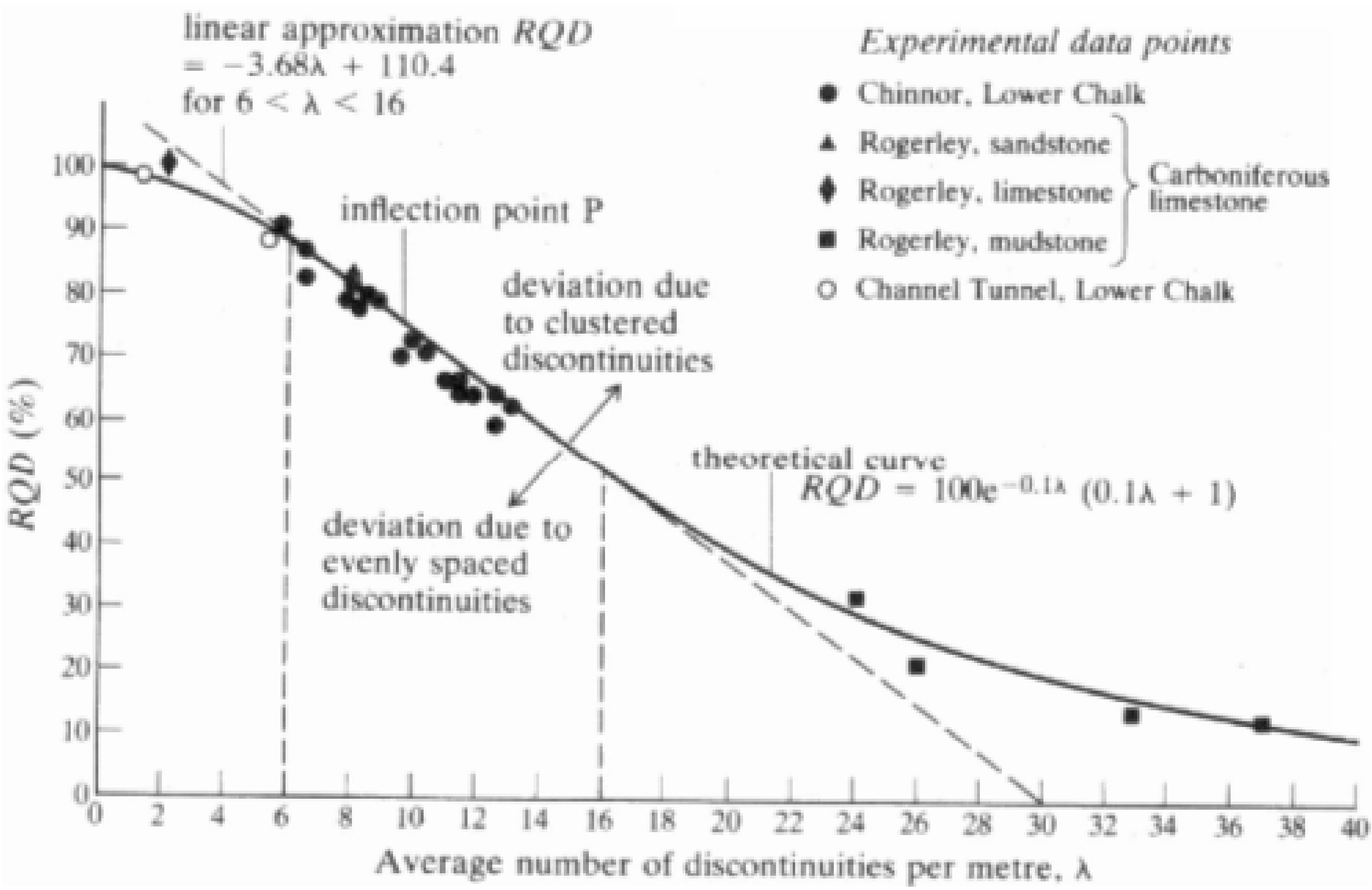
$$RQD = 100\,(0.1\lambda + 1)\,e^{-0.1\lambda}$$

For λ = 6 and 16/m, it can be approximated by:

$$RQD = 110.4 - 3.68\lambda$$

RQD was initially proposed as an attempt to describe rock quality, in reality, it only describes fracturing degree, but not other properties such as joint alteration, groundwater and rock strength.

Geometrical Properties of Rock Joints



Geometrical Properties of Rock Joints

Block Size and Volumetric Joint Count

Joint space also defines the size of rock blocks. When a rock mass contains more joints numbers, the joints have lower average spacing and smaller block size.

RQD can be related to volumetric joint count Jv by:

$RQD = 115 - 3.3\ Jv$, for Jv between 4.5 and 30.

$Jv < 4.5$, $RQD = 100\%$, $Jv > 30$, $RQD = 0\%$.

Indirect Methods of determination of RQF

Seismic Method -

RQD= $(V_f / V_l)^2 * 100$

Ratio of velocity in the field to that in the lab

Volumetric Count -

RQD = $115 - 3.3 * J_v$

where J_v is a measure of number of joints within a unit volume of rock mass

Geometrical Properties of Rock Joints

ISRM suggested block size designations

Designation	Volumetric Joint Count, joints/m^3
Very large blocks	< 1
Large blocks	1 – 3
Medium-sized blocks	3 – 10
Small blocks	10 – 30
Very small blocks	> 30
Crushed rock	> 60

Geometrical Properties of Rock Joints

Joint Surface Roughness and Matching

A joint is an interface of two contacting surfaces. The surfaces can be smooth or rough; they can be in good contact and matched, or they can be poorly contacted and mismatched.

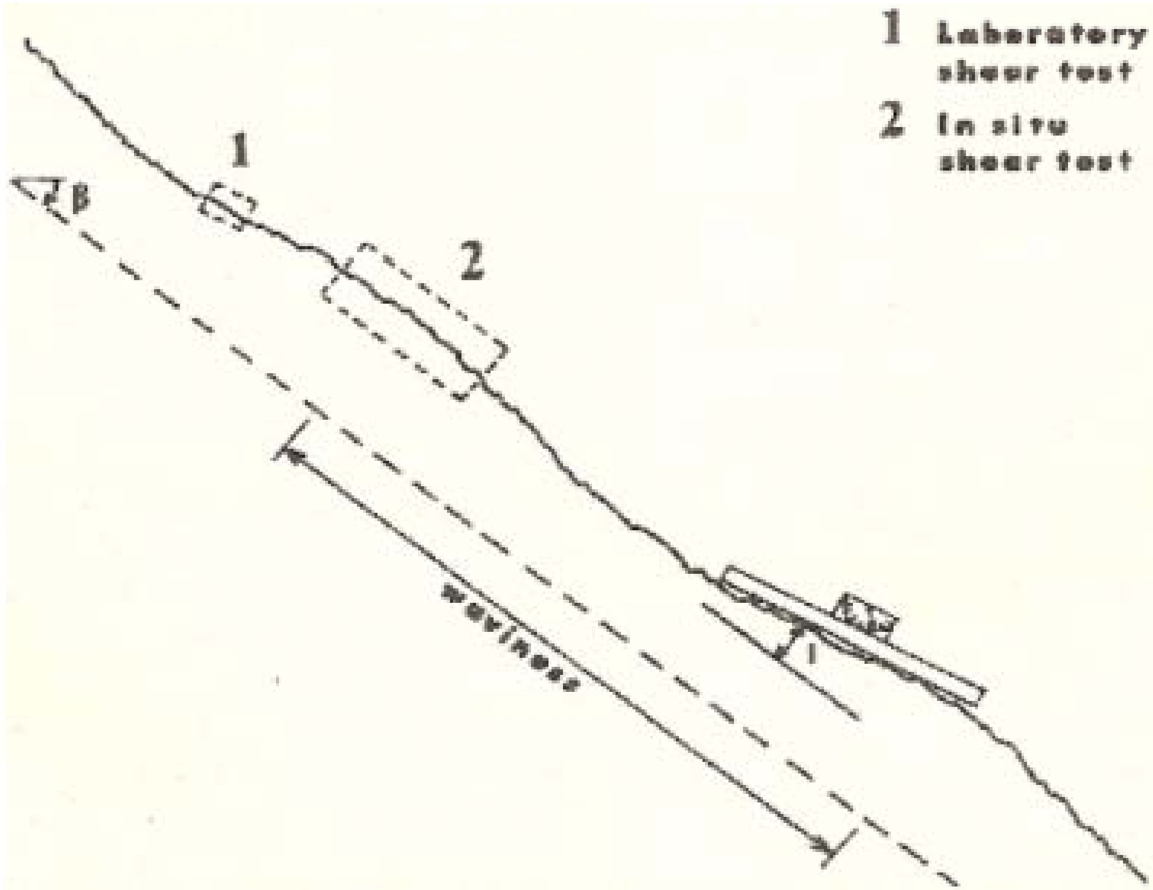
The condition of contact also governs the aperture of the interface. The interface can be filled with intrusive or weathered materials.

Geometrical Properties of Rock Joints

Joint Roughness

Joint surface roughness is a measure of surface unevenness and waviness relative to its mean plane. The roughness is characterised by large scale waviness (undulation) and small scale unevenness (irregularity) of a joint surface. It is the principal governing factor the direction of shear displacement and shear strength, and in turn, the stability of potentially sliding blocks.

Geometrical Properties of Rock Joints

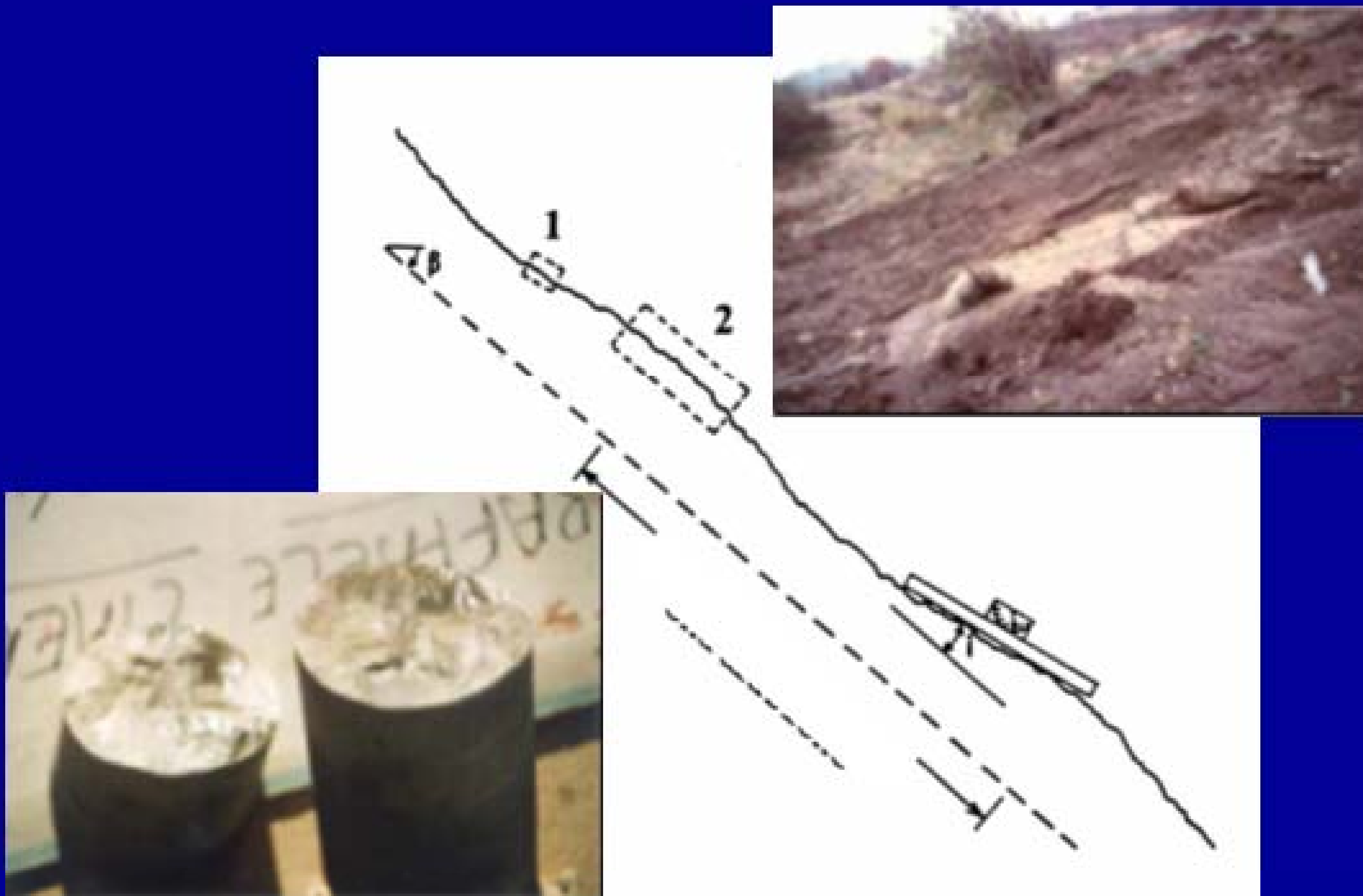


Geometrical Properties of Rock Joints

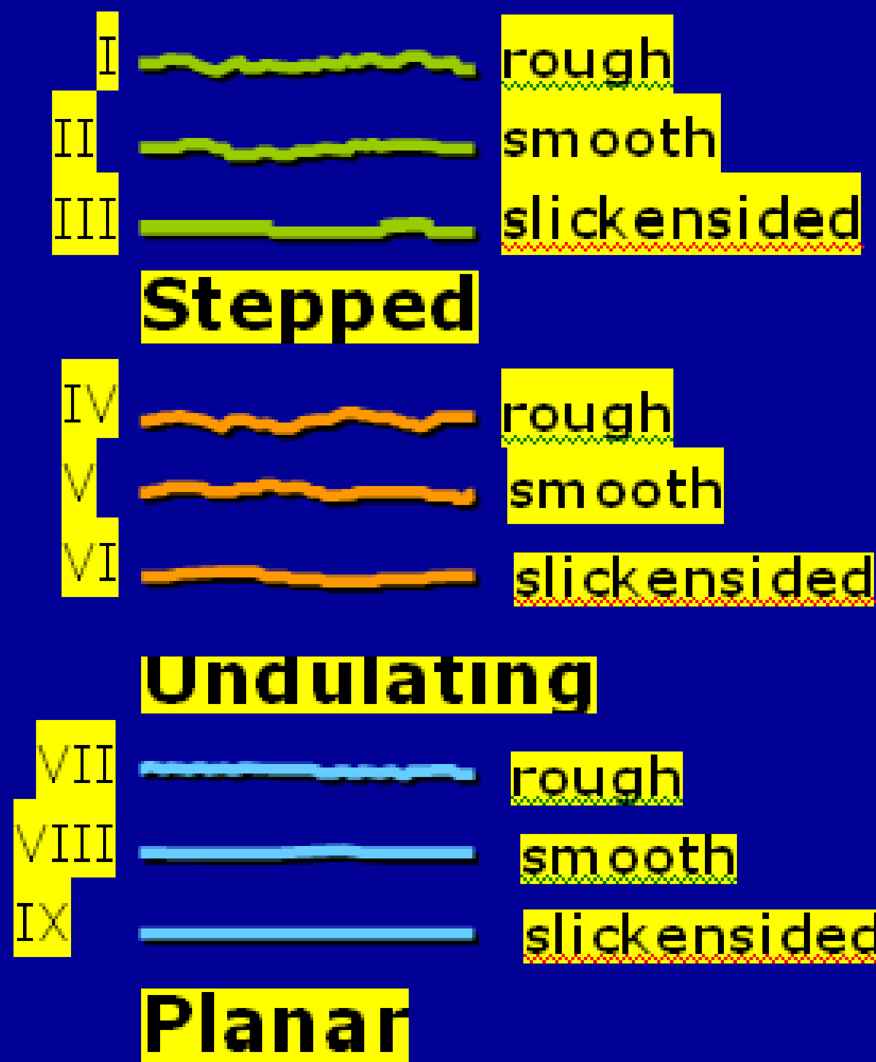
Joint Roughness

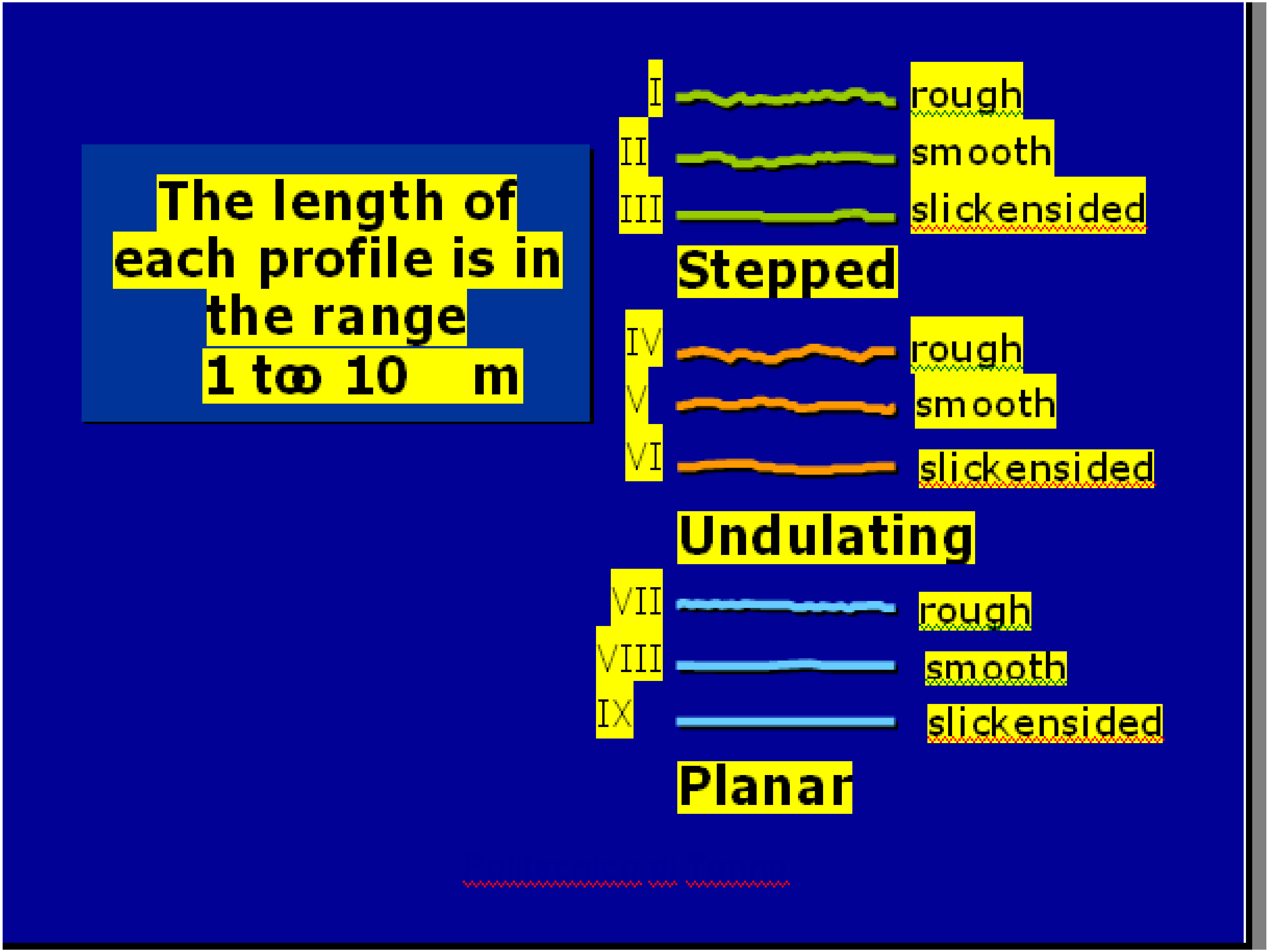
Roughness should first be described in metre scale (step, undulating, and planar) and then in centimetre scale (rough, smooth, and slickensided), as suggested by ISRM. It is not a quantitative measure.

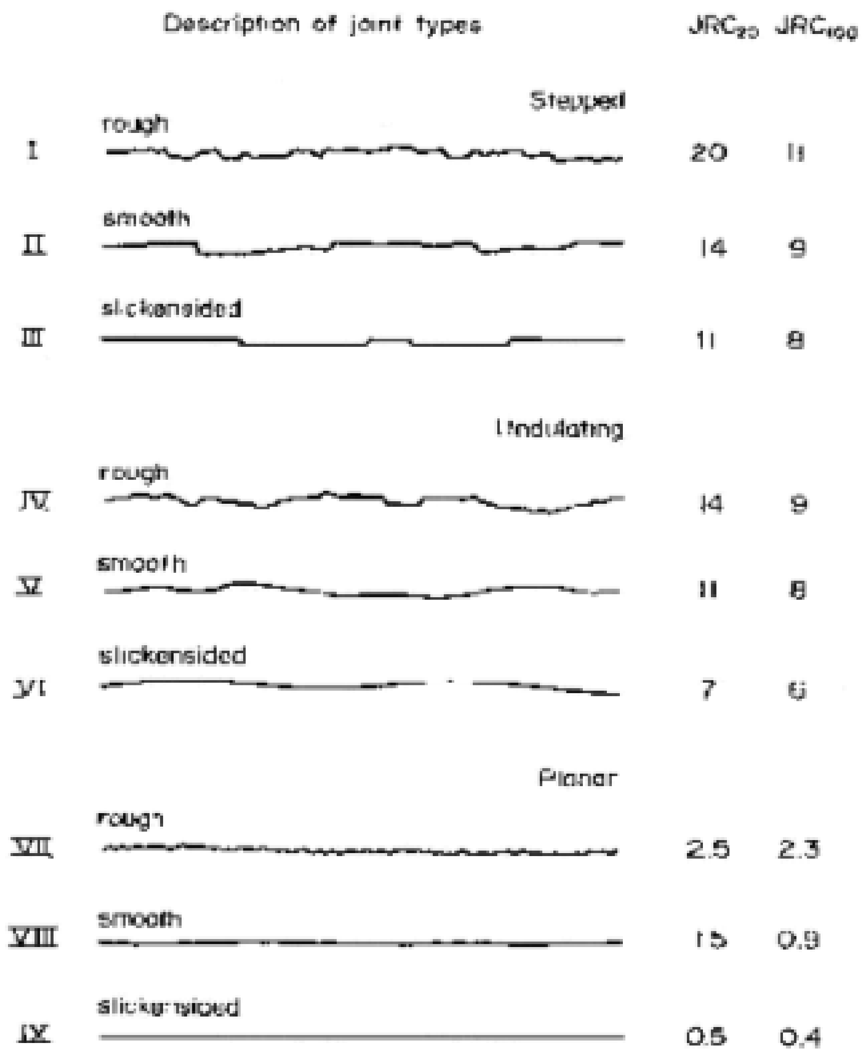
Joint Roughness Coefficient (JRC) is a quantitative measure of roughness, varying from 0 for the smooth flat surface to 20 for the very rough surface. Joint roughness is affected by geometrical scale.


1
2

Typical roughness profiles and suggested nomenclature




The length of each profile is in the range 1 to 10 m
I
rough
II
smooth
III
slickensided
Stepped
IV
rough
V
smooth
VI
slickensided
Undulating
VII
rough
VIII
smooth
IX
slickensided
Planar



JRC number is obtained by directly comparing the actual joint surface profile with the typical profile in the chart.

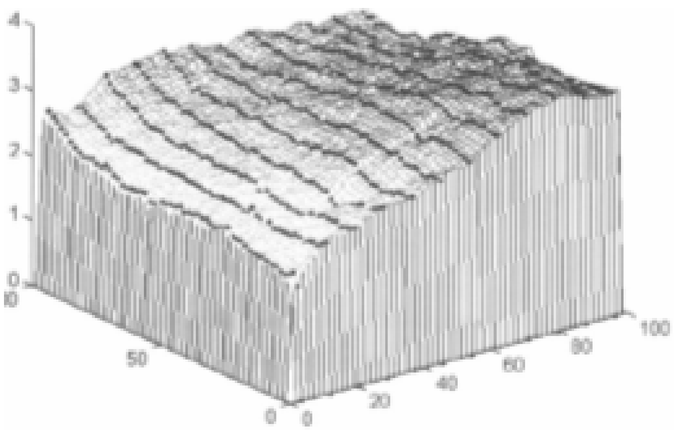
JRC_{20} is the profile for 20 cm and JRC_{100} for 100 cm. The value of JRC decreases with increasing size.

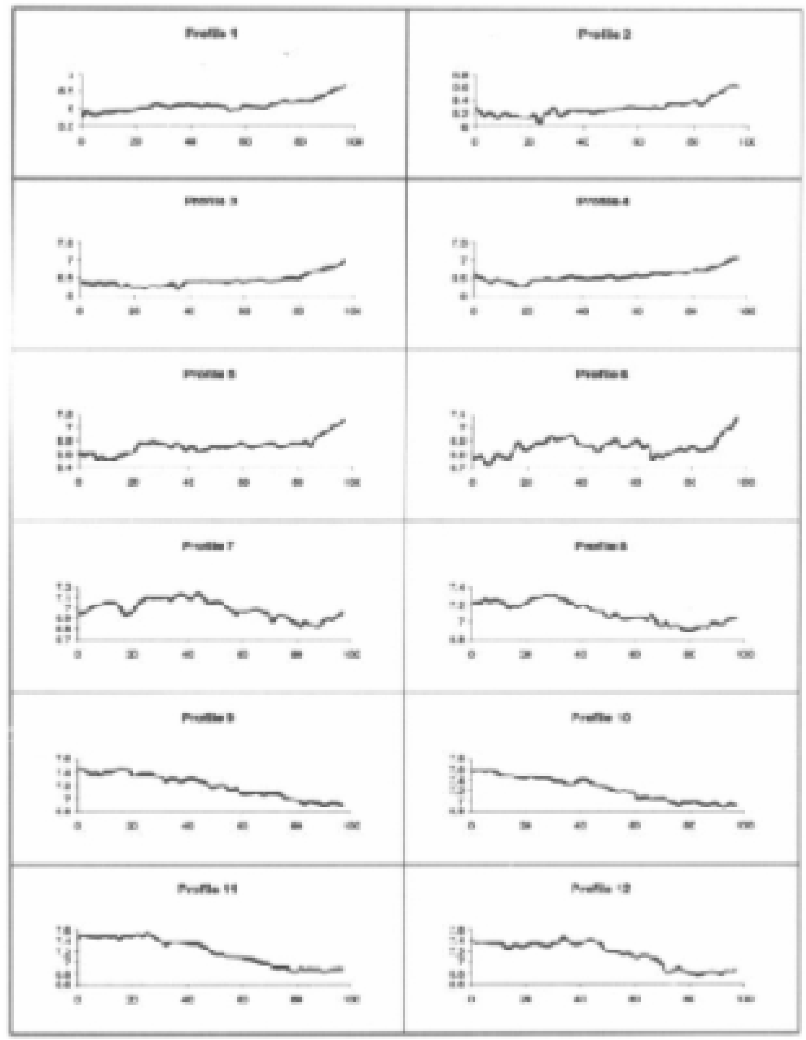
Geometrical Properties of Rock Joints

Joint Roughness in 3D

In realty, profiles of joint surfaces are 3D features. ISRM and JRC descriptions are 2D based. It is therefore suggested to take several linear profiles of a surface for the description and JRC indexing.

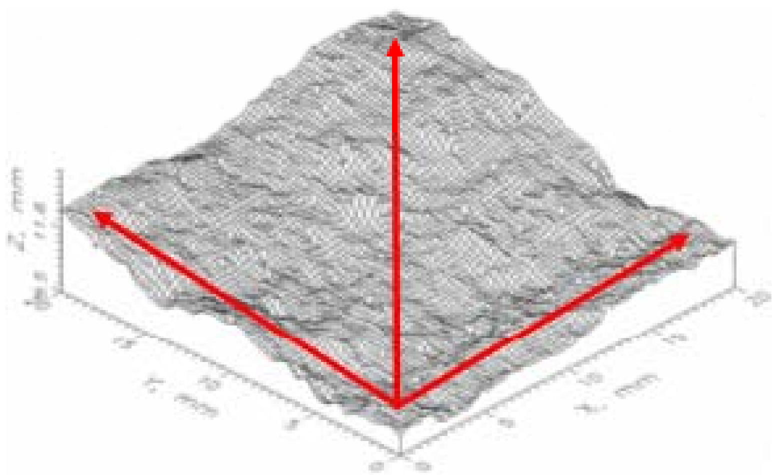
Joint surface is a rough profile that can be described by statistic method and fractal. Fractal method is applicable not only in 2D (linear profile), but also in 3D (surface plane profile). It is a useful tool to quantify the surface profile.



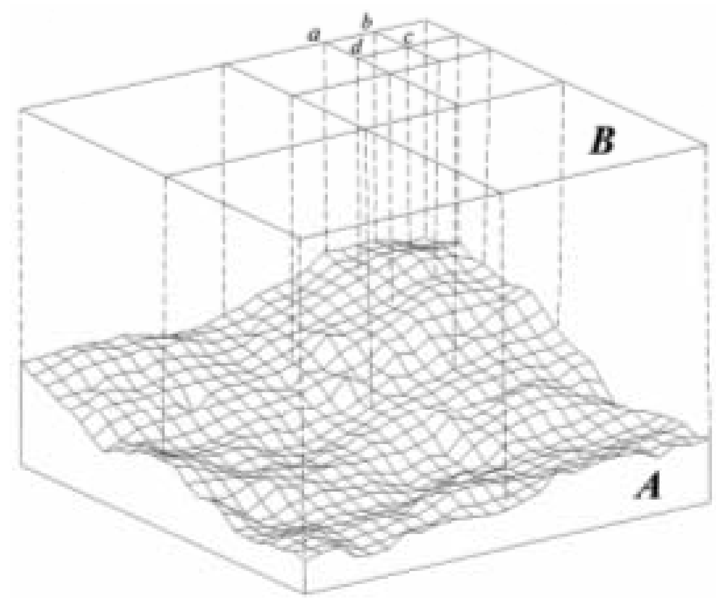


A joint surfaces is 3D. Each 2D measurement may give defferent linear profiles.

Geometrical Properties of Rock Joints



A joint surfaces in 3D, also noting change of linear profiles in directions.

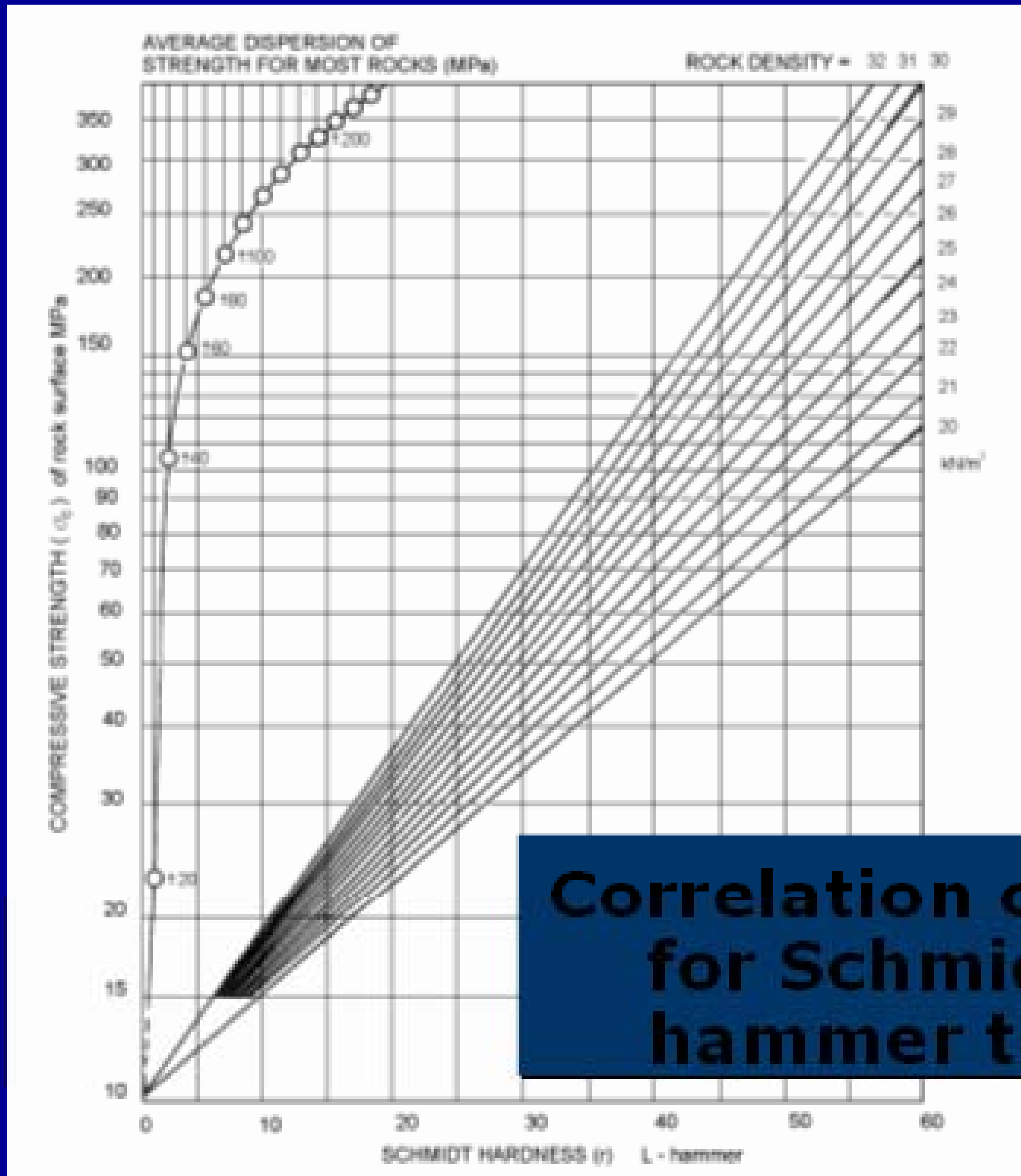


Calculating fractal for a 3D surface profile.

Wall strength

It is the compressive strength of the rock comprising the walls of of a discontinuity. It is a very important component of shear strength and deformabilty, especially if the walls are in direct rock to rock contact as in the case of unfilled joints

Correlation chart for Schmidt hammer test

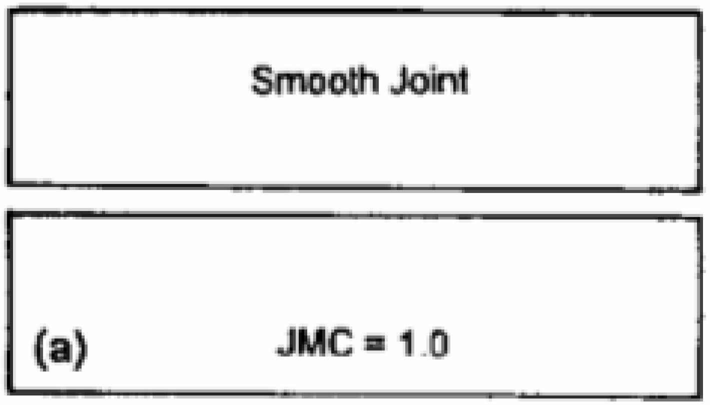


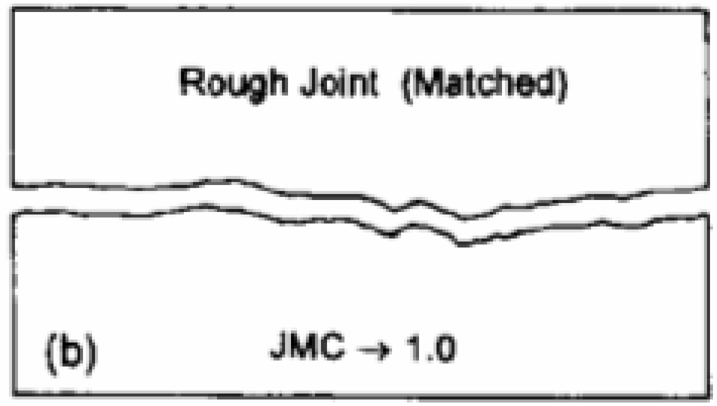
Geometrical Properties of Rock Joints

Joint Matching

A joint is an interface of two surfaces. Properties of a joint are also controlled by the relative positioning of the two surfaces, in addition to the profiles. For example, joints in fully contacted and interlocked positions has little possibility of movement and is also difficult to shear, as compared to the same rough joints in point contact where movement can easily occur. Often, joints are differentiated as matched and mismatched. A Joint Matching Coefficient (JMC) has been suggested.

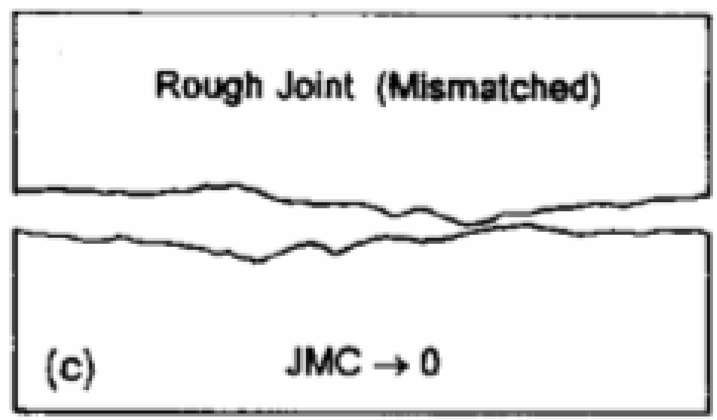
Geometrical Properties of Rock Joints





JMC is 1 for completely matched joint and two surfaces fully in contact.

JMC is 0 for completely mismatched joint and two surfaces in contact at a few points only.

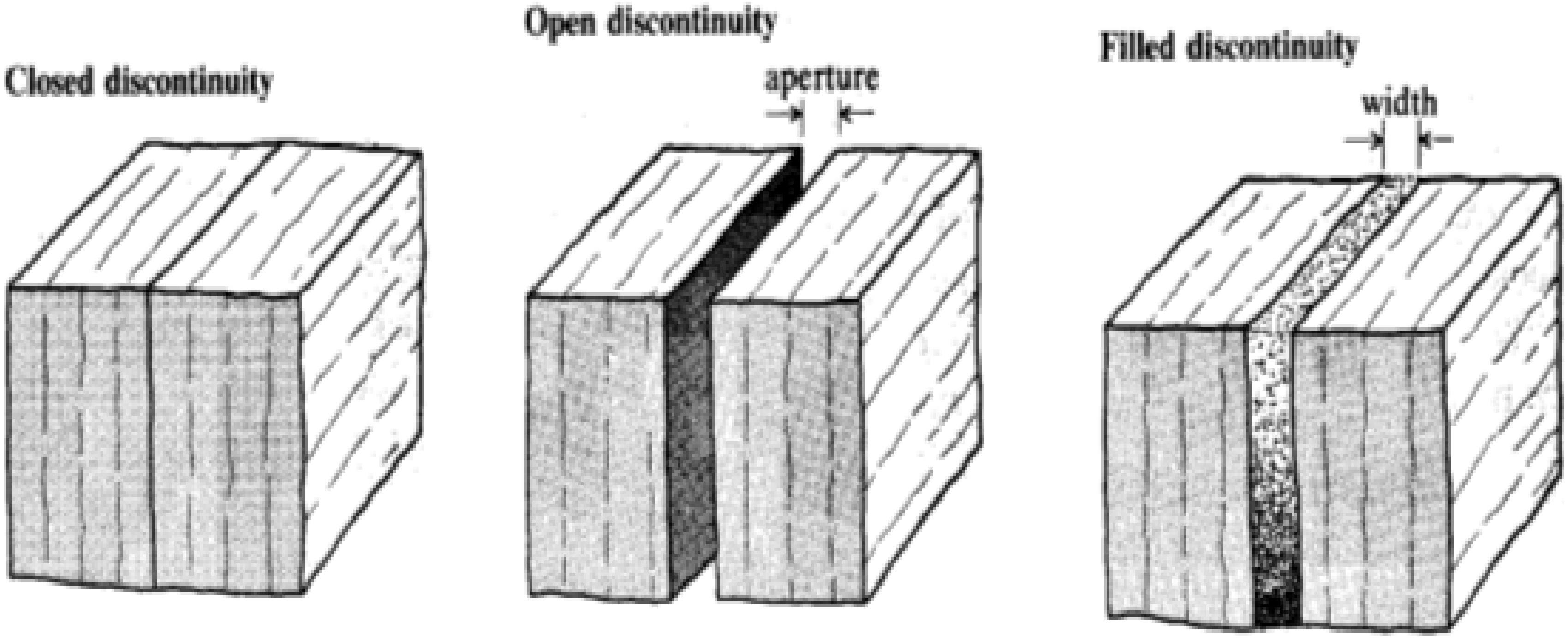


Geometrical Properties of Rock Joints

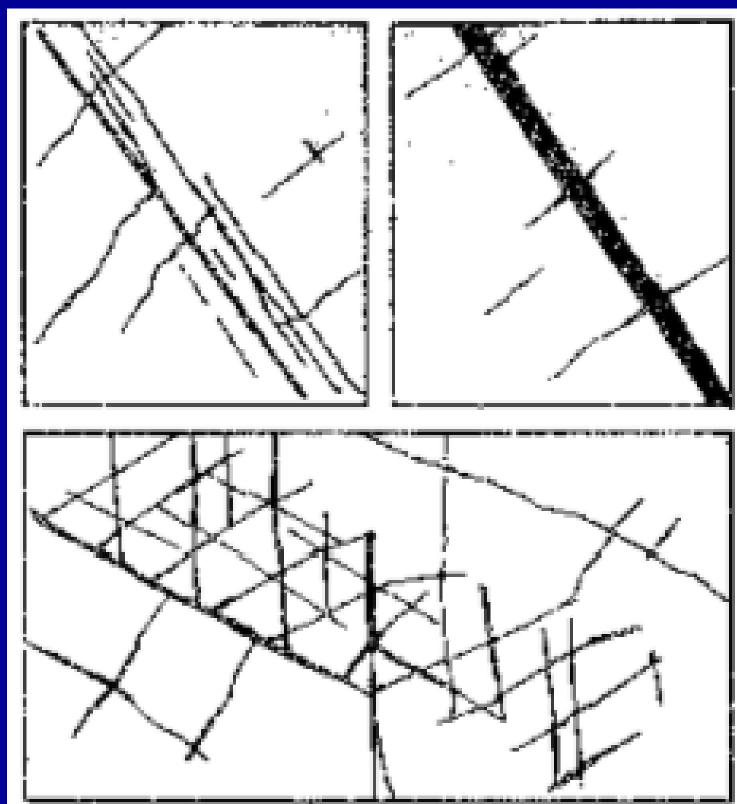
Joint Aperture and Filling

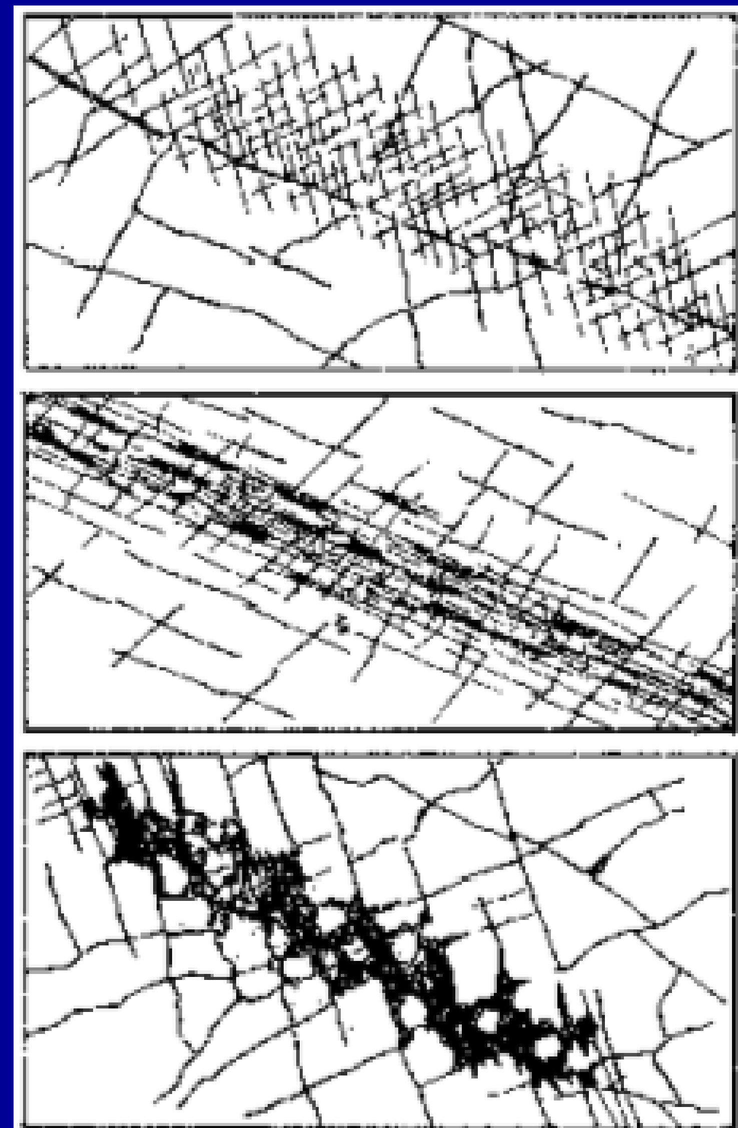
In a natural joint, it is very seldom that the two surfaces are in complete contact. There usually exists an opening or a gap between the two surfaces. The perpendicular distance separating the adjacent rock walls is termed as aperture. Joint opening is either filled with air and water (open joint) or with infill materials (filled joint). Open or filled joints with large apertures have low shear strength. Aperture also associates with flow and permeability.

Geometrical Properties of Rock Joints



Examples of field sketches of filled discontinuities





Geometrical Properties of Rock Joints

Classification of discontinuity aperture

Aperture	Description	
< 0.1 mm	Very tight	
0.1 ~ 0.25 mm	Tight	"Closed feature"
0.25 ~ 0.5 mm	Partly open	
0.5 ~ 2.5 mm	Open	"Gapped Feature"
2.5 ~ 10 mm	Widely open	
1 ~ 10 cm	Very widely open	
10 ~ 100 cm	Extremely widely open	"Open feature"
> 1 m	Cavernous	

Geometrical Properties of Rock Joints

Joint Aperture and Filling

Aperture can be the real aperture and equivalent hydraulic aperture. The later is particularly important when permeability is concerned.

Filling is material in the rock discontinuities separating the adjacent rock surfaces. In general, properties of the filling material affect shear strength, deformability and permeability of the discontinuities.

Seepage

Water seepage through rock masses results mainly from flow through water conducting discontinuities (secondary permeability)

Example of water seepage through discontinuities

Mechanical and Hydraulic Properties

Key Mechanical and Hydraulic Properties of Rock Joints

Normal Stiffness – deals with normal load and normal displacement

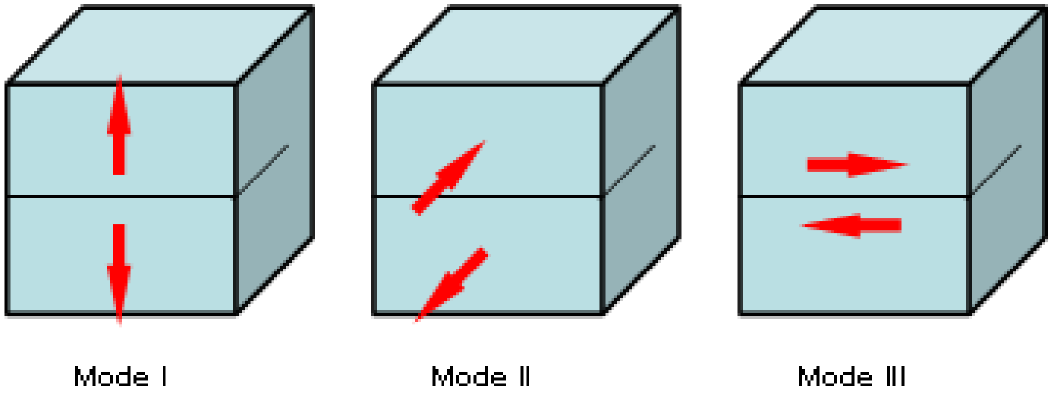
Shear Strength – deals with shear stress, shear displacement and dilation

Permeability – deals with flow and hydraulic conductivity

Strength and Deformation

Fracture Toughness

Fracture toughness of rock materials measures the effectiveness of rock fracturing. It is typically measured by a toughness test. There are three fracture mode: (Mode I), (Mode II) (Mode III).



Strength and Deformation

Fracture Toughness
Correspondingly, there are three fracture toughness, K_{IC}, K_{IIC} and K_{IIIC}.

In rock mechanics, Mode I is associated with the crack initiation and propagation in a rock material.

Granite	0.11 – 0.417
Dolerite	>0.41
Gabbro	>0.41
Basalt	>0.41
Sandstone	0.027 – 0.041
Shale	0.027 – 0.041
Limestone	0.027 – 0.041
Gneiss	0.11 – 0.41
Schist	0.005 – 0.027
Slate	0.027 – 0.041
Marble	0.11 – 0.41
Quartzite	>0.41

Mechanical and Hydraulic Properties

Stress and Deformation at Discontinuity

Stresses are often disturbed by a discontinuity. For a rock fracture with opening, normal stress on the fracture walls is zero and there are stress concentrations on the contact points. The stress field is no longer the same as in the continuous material.

For a closed joint, the stress field may be continuous although strain may not.

Mechanical and Hydraulic Properties

Stress and Displacement at Discontinuity
Displacement at discontinuity is not continuous. For example, at a fracture plane, sliding or shear displacement may occur. There may be much greater normal displacement at fracture than those of the material.

Discontinuities can range from a fully-welded interface to an opening containing different material. The mechanics of are vary different.

Mechanical and Hydraulic Properties

Stress and Displacement at Discontinuity

For a fully-welded interface between two different materials, it has the continuities both is stress and displacement. Discontinuity is the change of materials at the interface.

For a fully-contacted smooth interface, the interface representing a weak plane of shearing.

For a locally-contacted fracture with gaps, both stress and displacement are discontinuous.

Mechanical and Hydraulic Properties

Normal Stiffness and Displacement

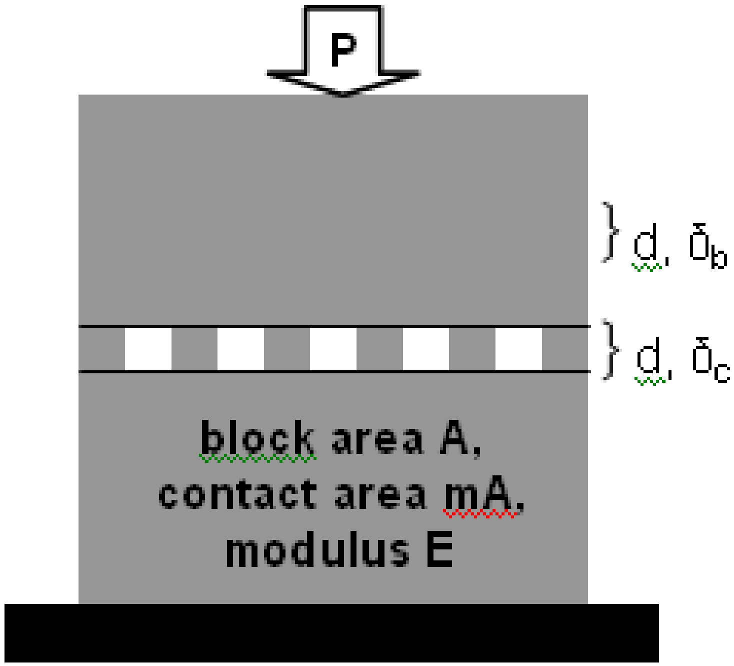
Normal stress and displacement of fully-contact discontinuity is continuous and therefore can be dealt with continuum approach.

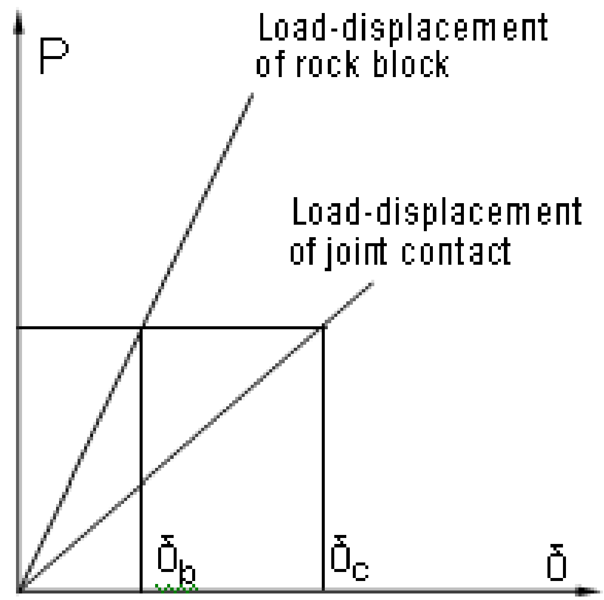
For locally-contacted fractures, there are voids between the two sides, stress-displacement function is discontinuous.

(a) An idealised pillar-contacted fracture

(b) An idealised prism-contacted fracture

Mechanical and Hydraulic Properties





Assume block and contact have the same material, m is between 0 and 1. Contact area does not change and fail.

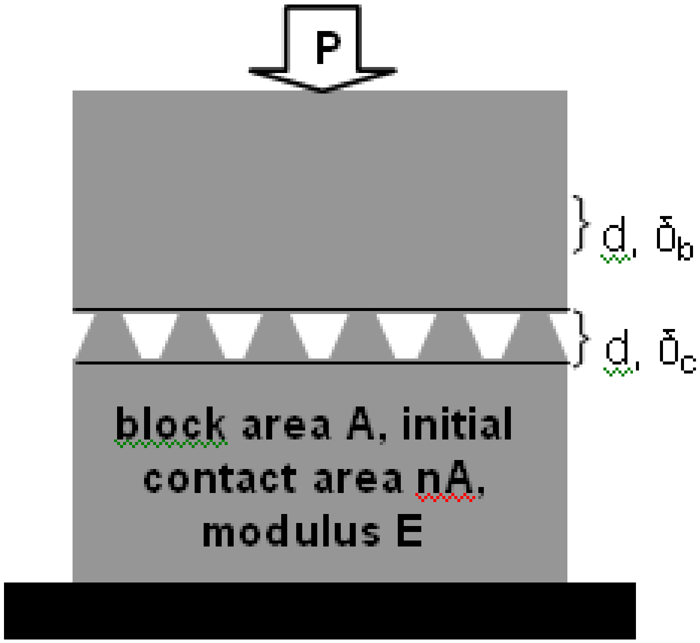
$\delta_b = (P\ D) / (A\ E)$

$\delta_c = (P\ D) / (m\ A\ E)$

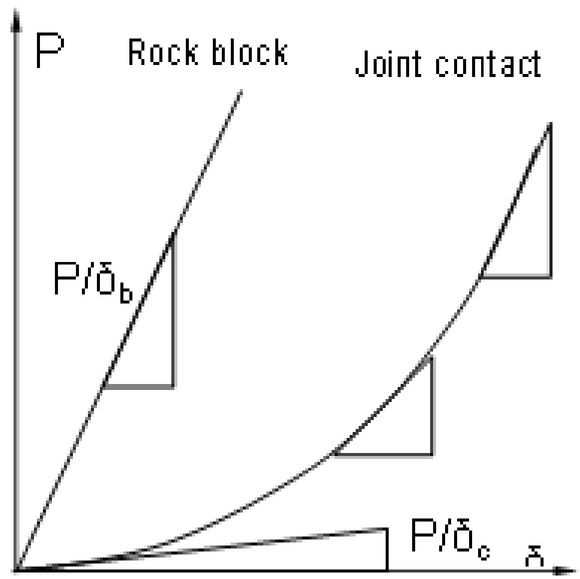
δ

P/δ

Mechanical and Hydraulic Properties



Assume block and contact have the same material, n is between 0 and 1. Contact area increases with contact closure, but does not fail.



At initial condition

$P/\delta_c = nP/\delta_b$

At complete closure

$P/\delta_c = P/\delta_b$