2 Fractures and Discontinuities

2.1 Introduction

From the hydrogeological point of view, fractures and discontinuities are amongst the most important of geological structures. Most rocks possess fractures and other discontinuities (Fig. 2.1) which facilitate storage and movement of fluids through them. On the other hand, some discontinuities, e.g. faults and dykes may also act as barriers to water flow. Porosity, permeability and groundwater flow characteristics of fractured rocks, particularly their quantitative aspects, are rather poorly understood. Main flow paths in fractured rocks are along joints, fractures, shear zones, faults and other discontinuities.

There is a great need to understand hydraulic characteristics of such rocks, in view of: (a) groundwater development, to meet local needs; and (b) as repositories for nuclear and other toxic wastes.

There could be multiple discontinuities in fractured rocks along which groundwater flow takes place. A number of factors including stress, temperature, roughness, fracture geometry and intersection etc. control the groundwater flow through fractures. For example, fracture aperture and flow rate are directly interrelated; non-parallelism of walls and wall roughness lead to friction losses; hydraulic conductivity through fractures is inversely related to normal stresses and depth, as normal stress tends to close the fractures and reduce the hydraulic conductivity.

It has also been noted that fracture permeability reduces with increasing temperature. As temperature increases with depth, thermal expansion in rocks takes place which leads to reduction in fracture aperture and corresponding decrease in permeability. Further the permeability is also affected by cementation, filling, age and weathering (see Chap. 8).

Parallel fractures impart a strong anisotropy to the rock mass. On the other hand, greater number of more interconnected fractures tends to reduce anisotropy. Further, larger fracture lengths, greater fracture density and larger aperture increase hydraulic conductivity.

Therefore, summarily, for hydrogeological studies, it is extremely important to understand and describe the structure of the rock-mass and quantify the pattern and nature of its discontinuities (van Golf-Racht 1982; Sharp 1993; Lee and Farmer 1993; de Marsily 1986).

2.2 Discontinuities—Types, Genetic Relations and Significance

Discontinuity is a collective term used here to include joints, fractures, bedding planes, rock cleavage, foliation, shear zones, faults and other contacts etc. In this discussion using a genetic approach, we group discontinuities into the following categories:

1. Bedding plane
2. Foliation including cleavage
3. Fractures (joints)
4. Faults and shear zones, and
5. Other geological discontinuities.

2.2.1 Bedding Plane

Primary bedding and compositional layers in sedimentary rocks form the bedding plane. Usually, it is the most significant discontinuity surface in all sedimentary rocks such as sandstones, (Fig. 2.1b) siltstones, shales etc., except in some massive sandstones or

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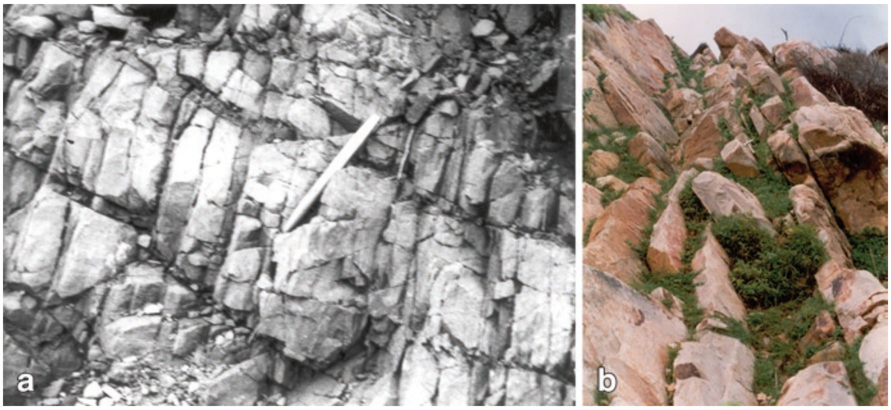


Fig. 2.1 Examples of fractured rocks; **a** Metamorphic rocks (meta-argillites) in Khetri Copper Belt, India. Several sets of fractures including shear planes are developed; some of the fractures possess infillings. **b** Sandstones of Vindhyan Group, India; bedding planes constitute the dominant discontinuity surfaces. (Photograph (b) courtesy of A.K. Jindal)

limestones. Bedding plane can be readily identified in the field owing to mineralogical-compositional-textural layering.

Bedding plane, being the most important discontinuity, imparts anisotropy and has a profound influence on groundwater flow in the vadose zone. The groundwater flow is by-and-large down-dip (Fig. 2.2).

Folds are flexures in rocks formed due to warping of rocks. Although a wide variety of folds are distinguished, the two basic types are anticlines (limbs dipping away from each other) and synclines (limbs dipping towards each other). Folding leads to change or reversal in dip directions of beds, and this affects groundwater flow. Further, folding is accompanied by fracturing of rocks. In an anticline, the crest undergoes higher tensional stresses and hence develops open tensile fractures, which may constitute better sites for groundwater development.

2.2.2 Foliation

Foliation is the property of rocks, whereby they break along approximately parallel surfaces. The term is restricted to the planes of secondary origin occurring in metamorphic rocks. Foliation develops due to parallel-planar alignment of platy mineral grains at right angles to the direction of stress, which imparts fissility. The parallel alignment takes place as a result of recrystallisation during regional dynamothermal metamorphism, a widespread and common phenomenon

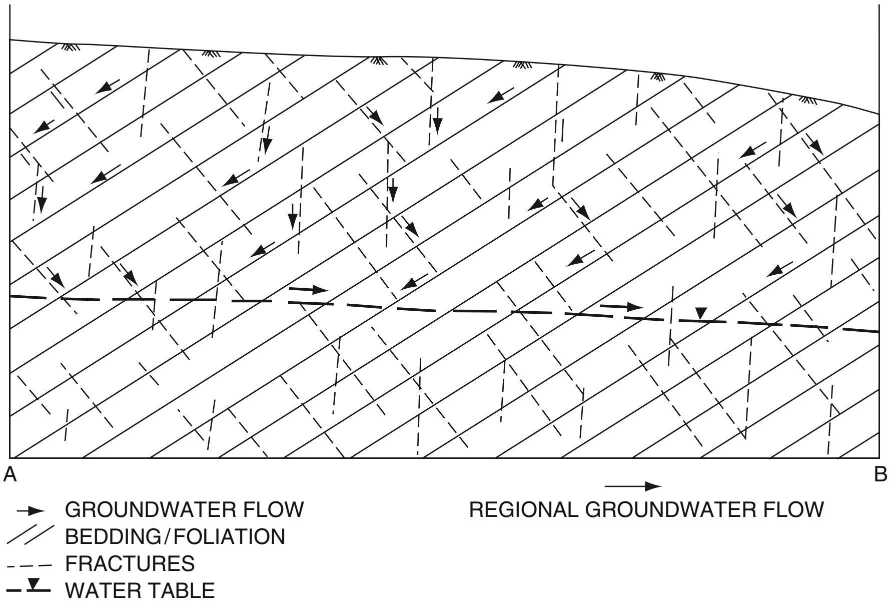


Fig. 2.2 Schematic diagram showing the role of bedding planes and fractures on groundwater movement in the vadose zone

in crystalline rocks. *Rock cleavage* is almost a synonymous term. It is also used for planes of secondary origin along which the rock has a tendency to break in near-parallel surfaces. Some terms are used for specific metamorphic rocks. Thus, the term *slaty cleavage* is used for rock cleavage in slates; *schistosity* is used for schists and *gneissosity* for gneisses. Foliation planes may or may not be parallel to bedding. Foliation that is parallel to the bedding is often referred to as bedding foliation. Fracture cleavage is produced by closely-spaced jointing. In many schistose rocks, shear cleavages are developed due to closely spaced shear-slip planes, known as slip-cleavage. In a folded region, the foliation often developed parallel to the axial plane of folds is called the axial plane foliation.

Foliation in metamorphic rocks has a profound influence on groundwater movement, possessing quite the same role as bedding in the sedimentary rocks, both being the most significant discontinuities in the respective rock categories (e.g. see Fig. 2.2).

2.2.3 Fractures and Joints

2.2.3.1 Introduction and Terminology

Fractures, also called joints, are the planes along which stress has caused partial loss of cohesion in the rock. It is a relatively smooth planar surface representing a plane of weakness (discontinuity) in the rock. Conventionally, a fracture or joint is defined as a plane where there is hardly any visible movement parallel to the surface of the fracture; otherwise, it is classified as a fault. In practice, however, a precise distinction may be difficult, as at times within one set of fractures, some planes may show a little displacement whereas others may not exhibit any movement. Slight movement at right angles to the fracture surface will produce an open fracture, which may remain unfilled or may get subsequently filled by secondary minerals or rock fragments.

'Fracture zones' are zones of closely-spaced and highly interconnected discrete fractures. They may be quite extensive (length > several kilometres) and may even vary laterally in hydraulic properties.

Fracture-discontinuities are classified and described in several ways using a variety of nomenclature, such as: joints, fracture, fault, shear, gash, fissure, vein etc.

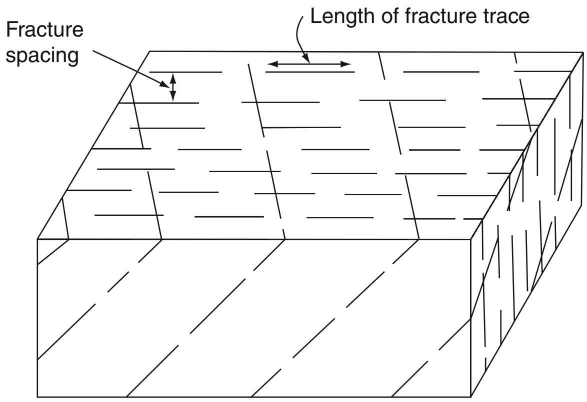


Fig. 2.3 Two sets of fractures are schematically shown in the block. An individual fracture has limited spatial extent and is discontinuous in its own plane. Fracture spacing and fracture trace length are indicated for one set

Generally, the term fracture is used synonymously with joint, implying a planar crack or break in rock without any displacement. The terms fault and shears are used for failure planes exhibiting displacement, parallel to the fracture surfaces. Gash is a small-scale open tension fracture that occurs at an angle to a fault. Fissure is a more extensive open tensile fracture. A filled-fissure is called a vein.

An individual fracture has a limited spatial extent and is discontinuous in its own plane (Fig. 2.3). On any outcrop, fractures have a certain trace lengths and fracture spacings. By mutual intersection, the various fracture sets may form interconnected continuous network, provided that the lengths of the joints in the different sets are much greater than the spacings between them (see Fig. 2.18). The interconnectivity of fractures leads to greater hydraulic conductivity.

2.2.3.2 Causes of Fracturing

Although fractures are extremely common and widespread in rocks, geologically they are still not well-enough studied (Price and Cosgrove 1990). Complex processes are believed to be involved in the origin of fractures, which are related to geological history of the area. Fractures are created by stresses which may have diverse origin, such as: (a) tectonic stresses related to the deformation of rocks; (b) residual stresses due to events that happened long before the fracturing; (c) contraction due to shrinkage because of cooling of magma or dessication of sediments; (d) surficial movements such as landslides or movement of glaciers; (e) erosional unloading of deep-seated rocks; and (f) weathering, in which dilation may lead to irregular extension cracks and dissolution may cause widening of cavities, cracks etc.

2.2.3.3 Types of Fractures

Firstly, fractures may be identified into two broad types: (a) systematic, which are planar, and more regular in distribution; and (b) non-systematic, which are irregular and curved (Fig. 2.4). The non-systematic fractures meet but do not cross other fractures and joints, are curved in plan and terminate at bedding surface. They are minor features of dilational type and develop in the weathering zone. Curvilinear pattern is their general characteristic. Parallel systematic fractures are treated as a set of fractures.

Geometric classification—Considering the geometric relationship with bedding/foliation, the systematic fractures or joints are classified into several types. Strike joints are those that strike parallel to the strike of the bedding/foliation of the rock. In dip joints, the strike direction of joints runs parallel to the dip direction of the rock. Oblique or diagonal joints strike at an angle to the strike of the rocks. Bedding joints are essentially parallel to the bedding plane of the associated sedimentary rock.

Depending upon their extent of development, fractures may be classified into two types: first-order and second-order. First-order fractures cut through several layers of rocks; second-order fractures are limited to a single rock layer. Further, depending upon the strike trend of fractures with respect to the regional fold axis, fractures are designated as longitudinal (parallel), transverse (perpendicular) or oblique ones (see Fig. 2.7 later).

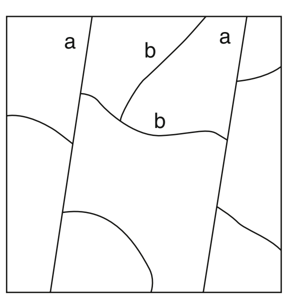


Fig. 2.4 Systematic and non-systematic types of fractures

Genetic classification—Genetically, the systematic fractures can be classified into three types:

1. *Shear fractures*, which may (or may not) exhibit shear displacement and are co-genetically developed in conjugate sets with a dihedral angle $2i > 45°$.
2. *Dilational fractures*, which are of tensile origin, commonly, developed perpendicular to the bedding plane, and are open fractures with no evidence of shear movement.
3. *Hybrid fractures*, which exhibit features of both shear and dilational origin. They may occur in conjugate sets with a dihedral angle $2i < 45°$. They are open (extension!), may be partly filled with veins, and may also exhibit some shear displacement.

The physical stress conditions under which these three types of fractures develop are illustrated by the Mohr diagram in Fig. 2.5. The curve ABC is a Mohr envelope. The stress circles touching the Mohr envelope at A, B and C points indicate different failure conditions of the rock. In condition 'A', the principal maximum compressive stress is negative, i.e. extensional, and therefore it leads to a dilational failure. In condition, 'C', a typical conjugate shear failure takes place, such that the dihedral angle $2i > 45°$. 'B' represents a condition that there is a positive maximum principal compressive stress and a negative minimum principal compressive stress, i.e. the effective normal stress perpendicular to the fracture plane is negative (extensional). This can be attributed to high fluid pressure conditions at depth. Hence, there is a tendency for such shear fractures to open and also get filled with minerals. Typically, in such hybrid shear-extension fractures, the dihedral angle is $2i < 45°$.

Conjugate shear fractures developing at greater depths are of ductile nature and possess a large 2i (~90°). On the other hand, conjugate brittle shears develop at a shallower depth and possess a smaller 2i (~60°). Further, brittle deformation causes derivative shears of several orders to form successively deviating trends, which cause a spread in the trends of conjugate shears (Ruhland 1973). The process of shearing is also accompanied by tensile deformation. Thus, brittle deformation may produce fractures of different magnitude and direction in successive orders. In a rock mass fractured by three orders of brittle deformation, tensile

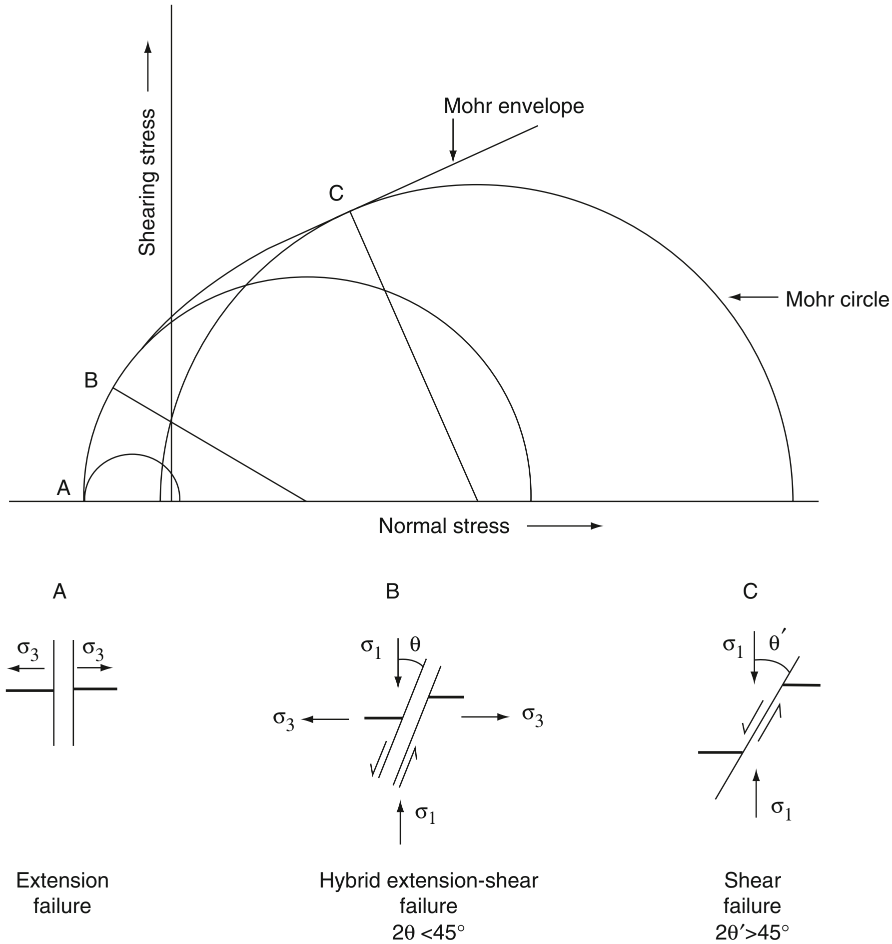


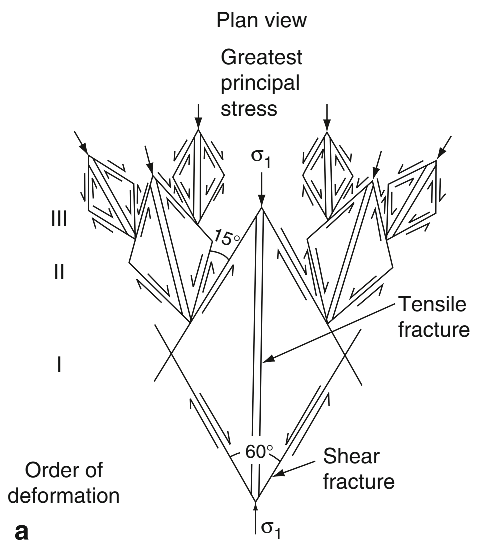
Fig. 2.5 Basic genetic types of fractures: *A* extension fracture; *B* hybrid extension-shear fracture; *C* shear fracture. The Mohr diagram indicates the stress conditions for these failures. σ_1 and σ_3 are the maximum and minimum principal compressive stresses respectively

fracturing may spread over a range of about 75° and shear fracturing over a range of nearly 135° (Fig. 2.6).

2.2.3.4 Discrimination Between Shear and Extension Fractures

The rheological principles indicate that there is no sharp categorization between extension and shear fractures. In fact, all gradations from one category to the other take place. However, from hydrogeological point of view, it is important to distinguish between shear and extension joints as dilational joints are more open and possess greater hydraulic conductivity than shear joints. Discrimination between shear and tension joints may be difficult, particularly in complexly deformed areas. However, the following features may help in their discrimination:

1. Shear joints may exhibit displacement parallel to the plane of the joints, which is absent in the case of extension joints.
2. Shear joints commonly occur in conjugate sets which may be indicated by a statistical analysis.
3. In field, slickensides and other criteria of relative movement may be observed in the case of shear joints.
4. Generally, extension joints are open and shear joints are tight.
5. The orientation of the joints with respect to the bedding/foliation and or fold-axis can provide information on shear vs. tensile origin of fractures, as shear joints occur in oblique conjugate sets whereas extension joints occur as longitudinal and transverse joints forming an orthogonal pair (Fig. 2.7).
6. The cumulative trend diagram of fractures may also provide information on the related stress field,



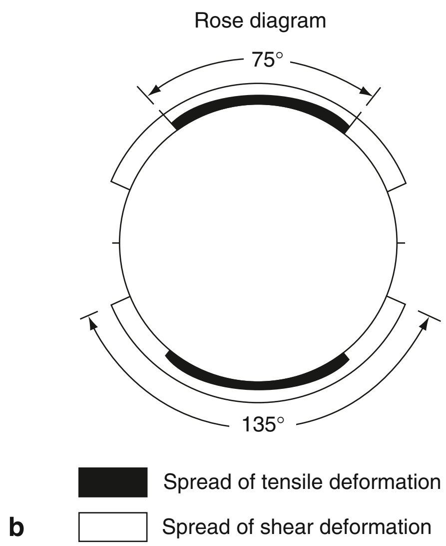


Fig. 2.6 Scheme of brittle deformation of a homogeneous rock mass. The rose diagram illustrates the ranges of orientations of tensile and shear fractures due to three orders of deformation. (After Ruhland 1973)

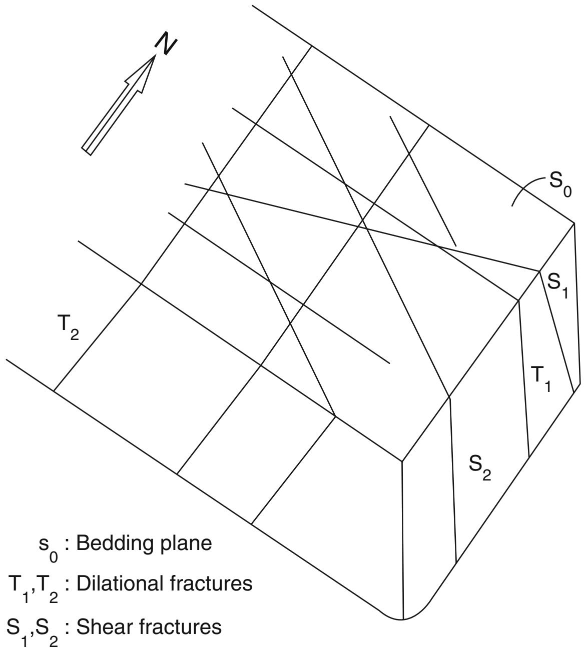


Fig. 2.7 Development of four sets of fractures in the case of simple dipping strata (see also Fig. 2.9)

and therefore the likely trends of shear and extension fractures; the maximum principal compressive stress bisects the dihedral angle of conjugate shear fractures and is parallel to the tensile fracture.

A field example of large-scale tensional and shear fractures extending for several kilometres is given in Fig. 2.8 where tensional fractures appear as wide open and shear joints are characterized by relative displacements.

2.2.3.5 Orientation of Fractures vis-à-vis Regional Structure

Ideally, in the case of simple-dipping strata, four sets of fractures (systematic) develop (Fig. 2.7). S_1 and S_2 form a conjugate set of shear fractures and T_1 and T_2 are extension fractures. All these fractures are perpendicular to the bedding plane and contain the intermediate principal compressive stress σ_2.

Figure 2.9 shows a simplified ideal relationship between fractures and folds. σ_1 is the maximum principal compressive stress perpendicular to the fold-axis (b). A conjugate set of oblique trending right-lateral and left-lateral shear fractures develops. There are two sets of extension fractures, one longitudinal and the other transverse to the fold-axis, both being mutually orthogonal.

During folding, bending of a bed causes extension on the convex side and compression on the concave side (Fig. 2.10). This results in extension fractures and normal faults on the crests of anticlines. Less commonly, thrust faults also develop in the inner areas of compression.

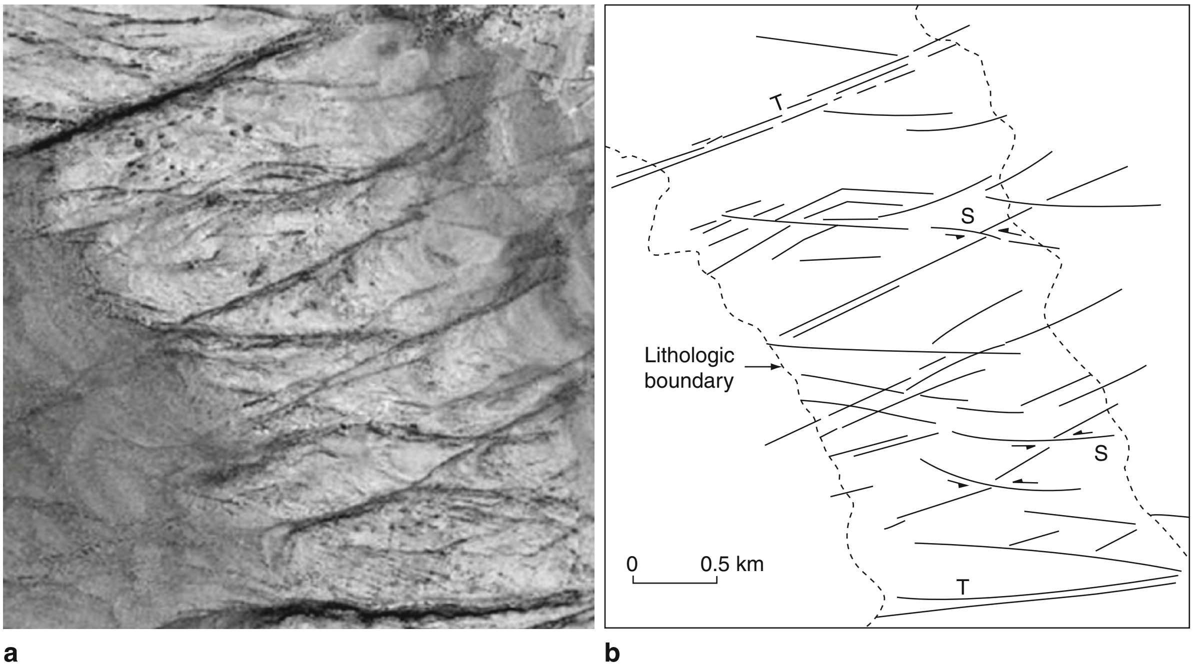


Fig. 2.8 **a** Example of large-scale tensional and shear fractures extending for several kilometres in a part of the Precambrian Cuddapah basin, India; black-and-white image generated from GoogleEarth. **b** Interpretation map of the above image; fractures marked *T* are wide open tensional fractures that are vegetated implying groundwater seepage, *S* are shear fractures exhibiting lateral relative displacement at places

2.2.3.6 Other Types of Fractures

Sheeting joints: These joints are generally flat, somewhat curved and nearly parallel to the topographic surface, often developed in granitoid rocks. They are closely developed near to the surface, and their spacing increases with depth. They are generated due to release of overburden stress.

Columnar joints: Joints of this type are tension fractures generated due to shrinkage in rocks. Shrinkage may occur due to cooling or dessication. Igneous rocks contract on cooling. Mud and silt shrink because of

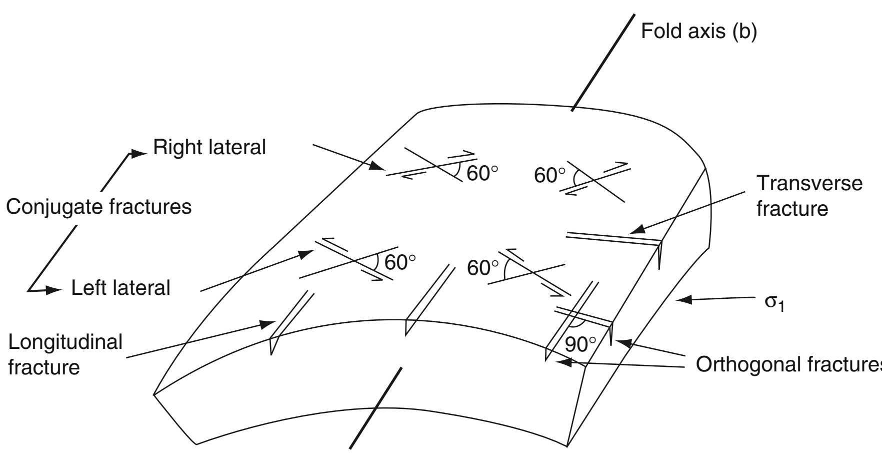


Fig. 2.9 Ideal relationship between major joint sets in a folded bed. There are two sets of conjugate shear fractures and two sets of mutually orthogonal dilational fractures. All the fractures are shown vertical

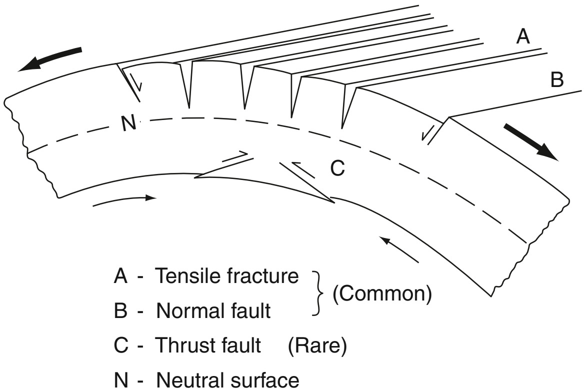


Fig. 2.10 Development of extensional fractures and normal faults on the crest and the upper axial zone of an anticline. Thrust faults may also develop, occasionally, in the inner area of compression

dessication. As a result, polygonal and columnar joints develop. The columns are generally a few centimetres to a metre in diameter, and several metres long (high). Frequently, the columns are four, five or six sided in shape (see Fig. 14.5).

2.2.4 Faults and Shear Zones

Rupture and shear movement due to stresses leads to faulting. The stress in rocks is mostly a result of mountain building tectonic activity. From a hydrogeological point of view, faults and shear zones constitute very important types of discontinuities in rocks. Faults are planes and zones of rupture along which the opposite walls have moved past each other, parallel to the surface of rupture. The orientation of a fault plane is defined in terms of strike and dip, as that of any other plane in structural geology. Faults vary in dimension from a few millimetres long with minor displacement to several hundred kilometres in strike lengths with movement of several tens of kilometres.

2.2.4.1 Terminology

In describing faults, a range of terminology is used; only some of the more important terms are introduced

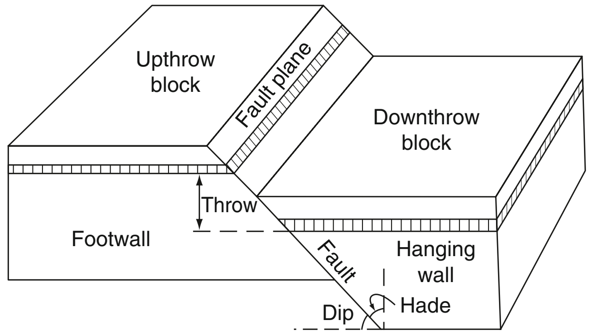


Fig. 2.11 Common terms used in describing a fault

here (see e.g. Billings 1972; Price and Cosgrove 1990). The fault block above the dipping fault plane is called *hanging wall*; the block below the faults plane is called *footwall* (Fig. 2.11). The angle which a fault plane makes with the vertical plane parallel to the strike of the fault is called *hade*; it is complement of the dip. In many instances the displacement is distributed through a zone, called the fault zone, which may be a few centimetres to hundreds of metres wide. Faults may exhibit simple translational or rotational movements. Slip is the relative displacement as measured on the fault surface. Strike-slip and dip-slip are the displacements along the strike direction and dip direction respectively on the fault plane. *Throw* is the vertical displacement caused by the fault. The blocks which have moved up and down are called *upthrow* and *downthrow blocks*, respectively.

Shear zones are generally filled with broken and crushed rocks, which may be embedded in clay matrix. Shear zones tend to be more extensive and continuous than joints.

2.2.4.2 Classification

Faults are classified in various ways in the literature. Some classifications are based on geometrical relations between the fault plane and country rocks. Genetically, faults are classified into three types: (a) normal, (b) reverse and (c) strike-slip. They are related to the stress conditions (Fig. 2.12).

In the case of a normal fault, hanging wall moves relatively downward. Normal faults are generally high-angle faults caused when σ_1 is vertical. Reverse faults are generally low-angle (gently dipping) faults

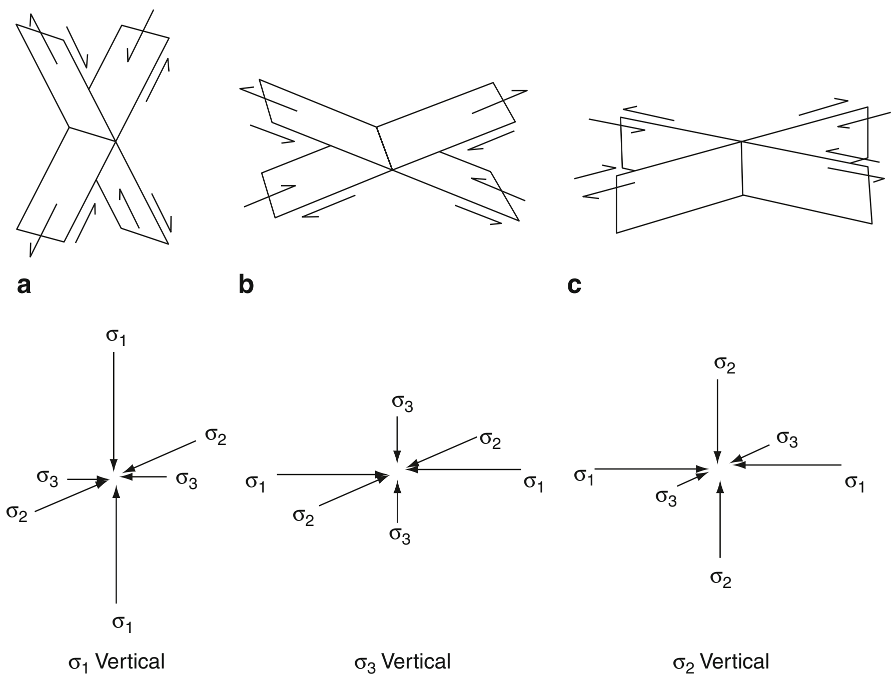


Fig. 2.12 The basic genetic types of faults: **a** normal, **b** reverse and **c** strike-slip. Orientations of principal compressive stresses are also shown

caused when σ_3 is vertical. It is characterised by the relative upward movement of the hanging wall. Strike faults are vertical faults marked by movement only in the strike direction of the fault. These are caused when σ_2 is vertical.

2.2.4.3 Recognition of Faults in the Field

A number of criteria are used to decipher the presence of faults, though in a specific case only some of the features may be present. Some of the more important criteria include: (a) displacement of key beds; (b) truncation of beds and structures; (c) repetition and omission of strata; (d) presence of features indicating movement on fault surface such as slickensides, mylonite, breccia, gouge, grooving etc; (e) evidence of mineralisation, silicification, along fault zones; (f) physiographic features such as fault scarps, offset ridges, etc; (g) alignment such as springs alignment, pond alignment, vegetation alignment, rectilinearity of a stream; (h) indication of sudden anomalous changes in river course, such as knick points, offset of streams, anomalous or closed meanders etc.; (i) erosional features such as triangular facets, unpaired terraces etc.

Investigations for faults may be made in outcrops, road cuttings, mines or other excavations, where smaller faults could often be directly observed. A larger fault, on the other hand, may be identified on stratigraphic and physiographic evidences, and particularly on remote sensing images, as only small segments of the fault may be exposed in field, and the feature may be largely covered under soil, debris or vegetation (see Sect. 4.8.11).

2.2.4.4 Effect of Faults on Groundwater Regime

Faults may affect groundwater regime in numerous ways, some of the more important being the following:

1. It is well known that faults may have such effects as truncation, displacement, repetition or omission of beds. In this light, the distribution and occurrence of aquifers may be affected by faults as locally an aquifer unit may get displaced/truncated/omitted (Fig. 2.13a, b).
2. A fault may bring impervious rock against an aquifer, which would affect groundwater flow and distribution (Fig. 2.13a).

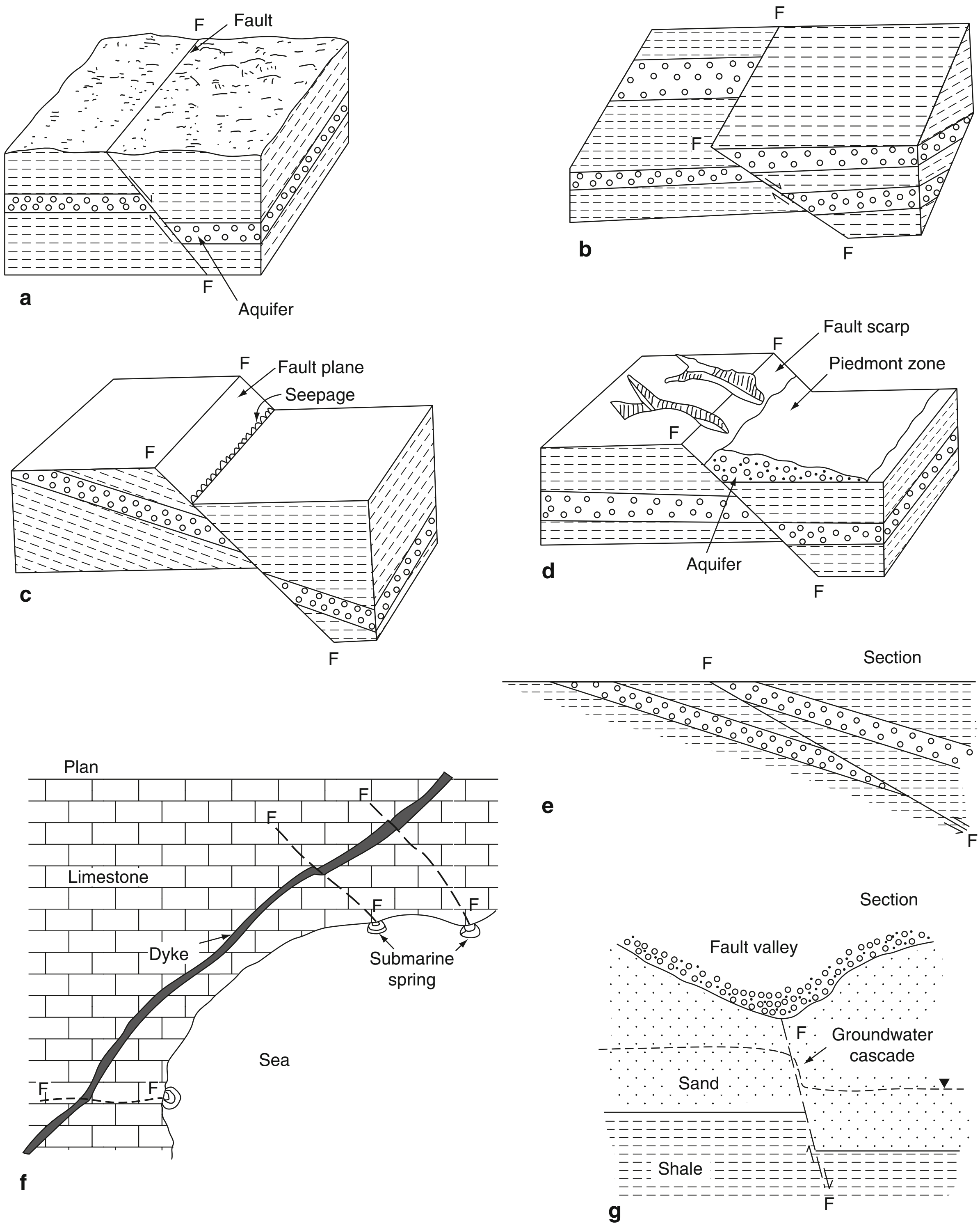


Fig. 2.13 Effects of faults on aquifers (for details see text)

3. Truncation of an aquifer by a fault may lead to seepage and formation of a spring line along the fault (Fig. 2.13c).
4. A fault may lead to a scarp; intensive erosion of the upthrow block and deposition of extensive piedmonts on the downthrow block may follow; the piedmont deposits may serve as good aquifers (Fig. 2.13d).
5. An aquifer may get repeated in a borehole due to thrust faulting; further it may also get re-exposed on the surface for recharge (Fig. 2.13e).
6. Vertical dykes, veins etc. which generally act as barriers to groundwater flow, may be breached by faults and this may produce local channel-ways across the barrier (Fig. 2.13f).
7. A fault may lead to a groundwater cascade (Fig. 2.13g).
8. Faults create linear zones of higher secondary porosity; these zones may act as preferred channels of groundwater flow, leading to recharge/discharge.
9. A fault may lead to inter-basinal subsurface flow.
10. A fault zone, when silicified, may act as a barrier for groundwater flow.

Figures 2.14 and 2.15 give field examples of extensive faults with strike length of kilometres, showing displacements of beds and marked by preferential alignment of vegetation indicating groundwater seepage.

Fig. 2.14 Faults displacing the sedimentary layers of sandstones and shales (Vindhyan Super Group, near Chittaurgarh, India). The terrain has a semi-arid climate. Note the preferential growth of vegetation along fault zones related to the seepage of groundwater. Sedimentary layering is also marked by vegetation banding. Black-and-white image from GoogleEarth

2.2.5 Other Geological Discontinuities

In addition to the above structural features, there could be other geological boundaries such as unconformities and intrusive contacts which may act as discontinuities.

Unconformity is a surface of erosion and nondeposition separating overlying younger strata from the underlying older rocks. Conglomerate beds and palaeosols usually occur along the unconformity surface which often forms good aquifers. An unconformity implies that a hydrologeological unit may get laterally pinched out and spatially replaced by another unit (Fig. 2.16).

Intrusive contacts are other geological boundaries of significance in the context of hydrogeology. Intrusive bodies occur in a variety of shapes and sizes, such as batholiths, dykes, sills etc. Their relation with the host rocks could be concordant, transgressive, or discordant. The igneous plutonic bodies crystallize under high pressure and temperature; they are devoid of primary porosity. Therefore, hydrogeological characters

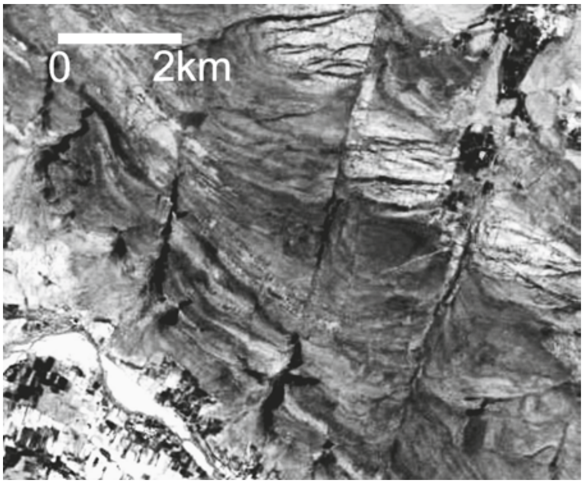


Fig. 2.15 Large-scale parallel faults running for several kilometres displacing the sedimentary layers of Cuddapah basin, India. Note the vegetation alignment along the southern parts of fault zones related to the seepage of groundwater. Black-and-white image from GoogleEarth

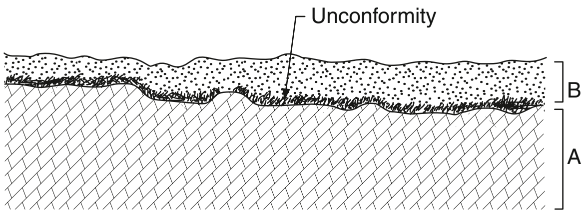


Fig. 2.16 Development of an aquifer along an unconformity between two impervious beds *A* and *B*

of the host rocks and intrusive rocks may be vastly different from each other. Hence, igneous contacts act as regional boundaries from a hydrogeological point of view.

2.3 Fracture Characterization and Measurements

A fractured rock mass can be considered to be made up of three basic components: (a) fracture network, (b) matrix block and (c) infillings along the fractures, if present (see Fig. 2.1). A single fracture or discontinuity plane is characterised by its orientation, genetic nature (shear/tensile), persistence and aperture etc. Several fracture planes of the same type create a fracture set. They have certain spacing (frequency). Several intersecting intercommunicating fracture sets create a fracture network which facilitates fluid flow. Thus, it is extremely important to characterize discontinuities and make their measurements, for a meaningful application. The various important parameters are summarised in Table 2.1.

The concept of Representative Elementary Volume (REV) is very important and may be introduced here. REV is the minimum rock mass volume which has the hydraulic and or mechanical properties similar to those of the rock mass. For mechanical properties, a sample size of a few cubic meters may be sufficient for approaching a REV; however, in case of hydraulic flow, REV may be substantially larger, and in some cases, it may not even exist due to strong anisotropy and spatial variability of rock characters.

2.3.1 Number of Sets

Several sets of discontinuities are often developed in a rock mass, three to four sets being most common. Number of sets of discontinuities in a exposure can be statistically determined by contouring the pole-plots (see Fig. 2.18). Relevant data as orientation, spacing, length, aperture etc. has to be collected for each set of discontinuity.

2.3.2 Orientation

Orientation is the parameter to define a single fracture plane in space, using angular relationships, as for any

Table 2.1 Parameters for discontinuity characterization

Parameter	Description
1. Number of sets	Number of sets of discontinuities present in the network
2. Orientation	Attitude of discontinuity present in the network
3. Spacing	Perpendicular distance between adjacent discontinuities of the same set
4. Persistence	Trace length of the discontinuity seen in exposure
5. Density	
– linear	Number of fractures per unit length
– areal	Cumulative length of fractures per unit area of exposure
– volumetric	Cumulative fractured surface area per unit bulk rock volume
6. Fracture area and shape	Area of fractured surface and its shape
7. Volumetric fracture count	Number of fractures per cubic metre of rock volume
8. Matrix block unit	Block size and shape resulting from the fracture network
9. Connectivity	Intersection and termination characteristics of fractures
10. Aperture	Perpendicular distance between the adjacent rock-walls of a discontinuity, the space being air or water-filled
11. Asperity	Projections of the wall-rock along the discontinuity surface
12. Wall coatings and infillings	Solid materials occurring as wall coatings and filling along the discontinuity surface

geological planar surface. It is defined in terms of dip direction (angle with respect to north) and dip amount (angle with horizontal). The orientation is expressed in terms of a pair of numbers, such as 25°/N 330°, implying a plane dipping at 25° in the direction 330° measured clock-wise from the north. In field, inaccuracies often creep-in the measurements, and therefore statistical analysis is desirable.

Rose diagram is a method of displaying the relative statistical prevalence of various directional trends, e.g. strike direction of fractures, lineaments etc. It can be prepared for parameters such as number or length, i.e. number of joints direction-wise, or length of joints direction-wise. Frequently, the directions are grouped in 10° interval. Frequency in a group-interval is represented along the radial axis, the length of petals becoming a measure of relative dominance of the trend. The strike petals possess a mirror image about the centre of the rosette. Data on the magnitude of dip cannot be incorporated in the rosette, and may however be shown outside the circumference (Fig. 2.17). *Histogram plot* is another way to represent the relative prevalence of the trends.

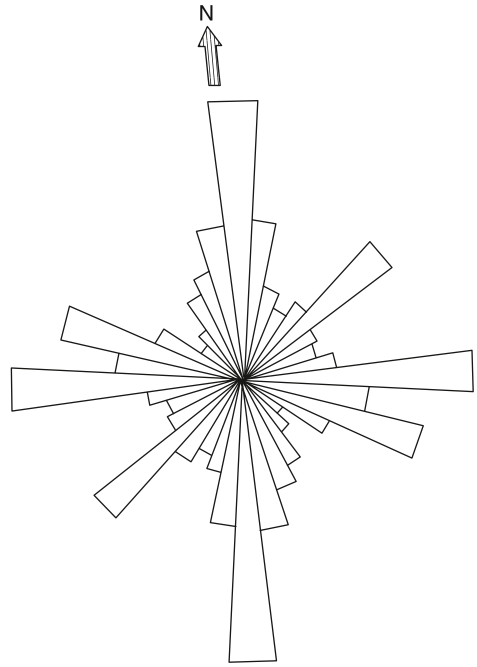


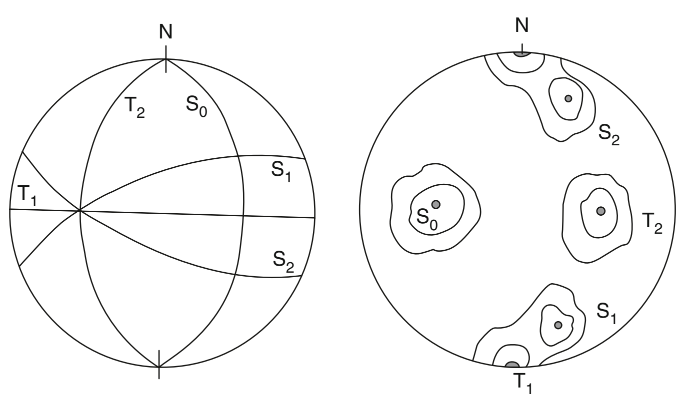
Fig. 2.17 Rose diagram of strike trends of discontinuities showing their relative prevalence

Spherical projection: For representing orientation of geological planar surfaces, the method of stereographic equal-area projection is frequently employed, as it accurately shows the spatial distribution of data. Basic concepts on great-circle plots and π-pole plots to represent planes can be found in any standard text on structural geology (e.g. Billings 1972; Price and Cosgrove 1990). The method of plotting pole has a relative advantage over the great-circle method in that clusters of poles and their relative concentrations can be readily ascertained on such plots by contouring. Schmidts-net is often used for density contouring to provide information on highest concentration, i.e. the most dominant fracture plane. Figure 2.18 gives an example.

It may be important to find the over-all effect of various discontinuities. The mean direction of a group of poles can be represented by a simple vector-sum of all the constituting poles, following Fisher distribution. Similarly a resultant vector can be calculated

Sr. No.	Surface	Strike	Dip direction	Dip amount
1	S_0	N - S	E	45°
2	T_1	E - W	Vertical	–
3	T_2	N - S	W	45°
4	S_1	N 68°-N 248°	N 338°	80°
5	S_2	N 112°-N 292°	N 202°	80°

a Fracture orientation data



b Great circle diagram **c** π-Pole diagram

Fig. 2.18 **a** Orientation data of discontinuities. S_0 is bedding plane, T_1 and T_2 are tensile fractures and S_1 and S_2 are shear fractures. Their great-circle and π-pole diagrams are shown in figures (**b**) and (**c**) respectively

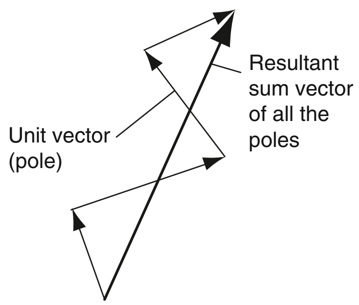


Fig. 2.19 Principle of determining the mean pole direction as the resultant vector sum of all the vectors (poles), following Fisher method

by summing all the clusters, to give a net directional effect of all the sets of discontinuities (Fig. 2.19).

It may be mentioned here that only selected and not all of the discontinuities present may play a significant role in fluid movement in the rock mass. Therefore, selection and data integration ought to be done judiciously. Further, Sharp (1993) gave a more useful concept for integration of discontinuity trend, frequency and aperture data to make hydraulic zonation maps (see Sect. 7.2.5).

2.3.3 Spacing (Interval)

Systematic joints are roughly equidistant and possess parallelism, and therefore, the parameter statistical spacing has significance. It describes the average (or modal) perpendicular distance between two adjacent discontinuities of the same set. It has a profound influence on rock mass permeability and groundwater flow. Fracture spacing is reciprocal of the fracture frequency or linear fracture density. It also controls fracture intensity and matrix block size.

Fracture separation (f_s) is related to lithology and thickness of the bed (b), and is given as (Price and Cosgrove 1990):

$$f_s = Y \cdot b \tag{2.1}$$

where Y is a constant related to lithology. Modelling and theoretical approaches also show that fracture spacing and bed thickness should have a linear relationship, for a given lithologic material.

By spreading a tape in any convenient direction on an outcrop face, average apparent spacing (f_{sa}) between fractures of a set can be measured. This measurement has to be corrected for angular distortion (θ) to give the value of true fracture interval, perpendicular to the fracture orientation. The correction angle (θ) equals the angle between the direction of tape alignment and the pole to the fracture plane, and can be easily computed using a stereographic net (Fig. 2.20). The true fracture spacing (f_s) can be obtained from the measured fracture spacing (f_{sa}) as:

$$f_s = f_{sa} \cdot cos\theta \tag{2.2}$$

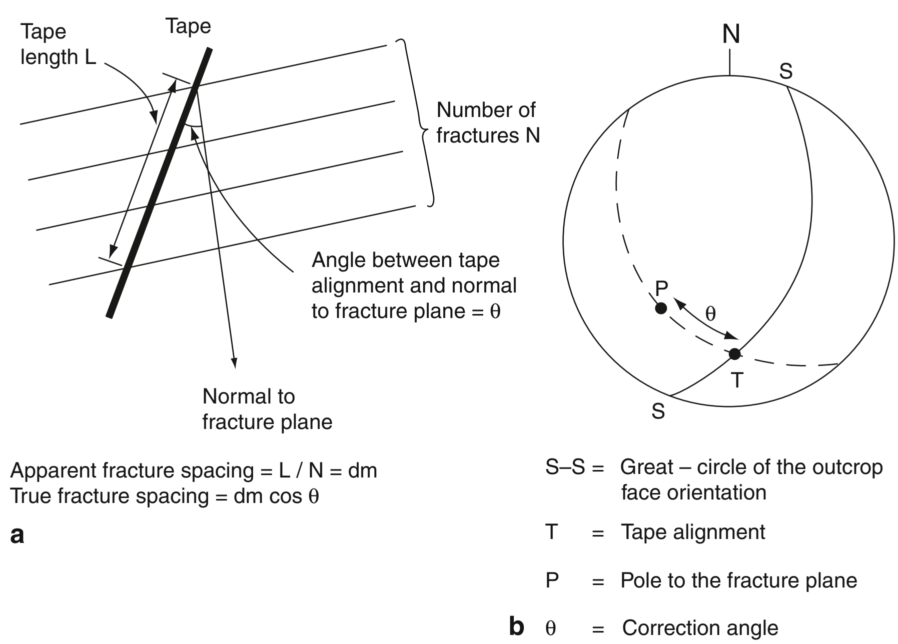


Fig. 2.20 Spacing of fractures and computation of true fracture spacing. **a** Measurements in field for apparent fracture spacing. **b** Angle of correction, i.e. the angle between the line of tape alignment and pole to the fracture plane, computed by stereographic method

Further, it has been reported that fairly reliable estimates of fracture spacing can also be given by the P-wave velocity using seismic refraction techniques (see Sect. 5.6).

2.3.4 Persistence (Fracture Length)

Fracture persistence or length is a measure of the extent of development of discontinuity surface (Fig. 2.21). This carries the notion of size and controls the degree of fracturing. It is a crude measure of the penetration length of a fracture in a rock mass. Fracture trace length is also related to fractured surface area. As some of the discontinuities are more persistent and continuous than others, it becomes a very important parameter in controlling groundwater flow.

Persistence is rather difficult to quantify, as it would differ in the dip and strike directions. It can be measured by observing the discontinuity trace length in an exposure, in both dip and strike directions.

The observed trace length may be only an apparent value of the true trace length due to various types of bias creeping in the data during measurements in exposures, drifts, excavations, benches etc. For example, the biases could be like: (a) inability to recognize fracture traces shorter than a certain threshold length will lead to a bias (truncation of the histogram); (b) inability to measure full length of the traces owing to incomplete exposures in drift-walls, excavations etc. will lead to recording of censored length data; (c) the observed length of fracture trace depends on the relative orientation between the fracture plane and the exposure face; (d) in the sampling area or scanline, a stronger discontinuity is more likely to appear than a weaker one. Considering such aspects, methods for estimating the true trace length are discussed by a few workers (e.g. Pahl 1981; Laslett 1982; Chiles and de Marsily 1993).

2.3.5 Fracture Density

Fracture density is measured for each set of fracture set separately and corresponds to the degree of rock fracturing. It can be described in three ways: linear, areal and volumetric, depending upon whether the measurement/computation corresponds to length (1D), area (2D) or volume (3D) aspect, respectively.

1. Linear fracture density (1D fracture density, d_1) is the average number of fractures of a particular set, per unit length measured in a direction perpendicular to the fracture plane. It equals fracture frequency (F_f) and is the reciprocal of fracture spacing.
2. *Areal fracture density* (2D fracture density, d_2) is a way to quantify persistence of the discontinuity. It is the average fractured length (of traces) per unit area on a planar surface.
3. Volumetric fracture density (3D fracture density, d_3) is the average fractured surface area per unit rock volume, created by all the fractures of a given set.

All types of fracture densities, d_1, d_2, and d_3 have the same dimension (L^{-1}). The volumetric density (d_3) is independent of direction and is a static parameter, like porosity. On the other hand, areal and linear densities are directional parameters and have bearing on fluid flow.

Both d_1 and d_2 depend on the orientation of the fractures vis-à-vis that of the scanline/exposure face. However, d_3 is independent of direction and can be estimated from a survey with boreholes or scanlines, with the help of proper weighting of the observed fractures (Chiles and de Marsily 1993). For computing the correct weighting factors, consider first the case of a borehole or a scanline survey (Fig. 2.22). The surveyed straight line can be considered as a cylinder of length L with a small section p, as in the case of a borehole. If n fractures intersect the survey line and i_i is the acute angle made by the *ith* fracture plane with the borehole, then the fracture surface within the

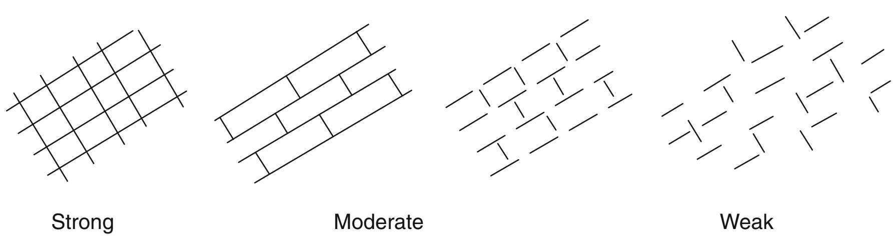


Fig. 2.21 Influence of persistence of discontinuity on the degree of fracturing and interconnectivity

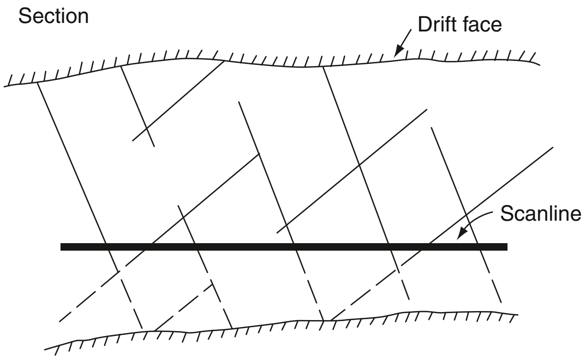


Fig. 2.22 Scanline method of discontinuity survey

cylinder is p/sini_i, for the *ith* fracture. Hence, 3D fracture density d_3 is:

$$d_3 = \frac{1}{L \cdot p} \sum_{i=1}^{n} \frac{p}{sin\theta_i} = \frac{1}{L} \sum_{i=1}^{n} \frac{1}{sin\theta_i} \qquad (2.3)$$

Thus, the weighting factor is related to the acute angle between the fracture plane and the scanline.

Similarly, considering the case of an areal survey, the exposure can be considered as a layer of area *S* and a small thickness *e*. Within the surveyed rectangle, if *n* fractures are traced on the exposure (Fig. 2.23), and *ith* fracture has a trace length l_i and makes an angle i_i with the exposure plane, then the fractured surface area for the *ith* fracture is $e \cdot l_i / \sin i_i$. Hence, 3D fracture density is:

$$d_3 = \frac{1}{S \cdot e} \left(\sum_{i=1}^{n} \frac{e \cdot l_i}{\sin \theta_i} \right) = \frac{1}{S} \left(\sum_{i=1}^{n} \frac{l_i}{\sin \theta_i} \right) \qquad (2.4)$$

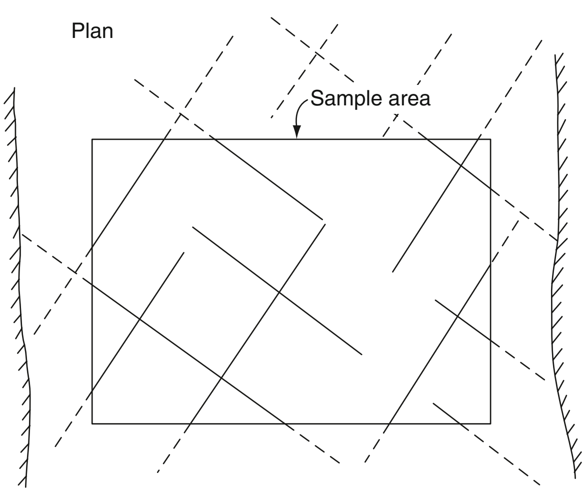


Fig. 2.23 Areal method of discontinuity survey

Thus, the weighting factor is related to acute angle and fracture trace length. If all the fractures have the same trace length, then *l* is constant. For parallel fractures, i_i can be replaced by *i*. For example, in an area in Bundelkhand granites (India), the 3D fracture density was computed using the scanline method at 64 observation sites. It is observed that d_3 in the area varies generally from about 6 m^{-1} to 21 m^{-1}, whereas there are smaller pockets of higher values of d_3, of the order of 31 m^{-1}. The variation in d_3 across the study area is shown in Fig. 2.24, where the magnitude of d_3 is plotted as a circle of appropriate radius.

With simplifications and assumptions, d_1, d_2 and d_3 can be interrelated; if fracture orientations are purely random, then (Chiles and de Marsily 1993):

$$d_1 = 1/2 \cdot d_3 \qquad (2.5)$$

$$d_2 = \pi/2 \cdot d_3 \qquad (2.6)$$

2.3.6 Fracture Area and Shape

Fracture area can be estimated from the strike trace length and dip trace length, assuming that the fractured surface has a certain regular shape, e.g. circular, square, elliptical, rectangular or polygonal. Out of these the case of circular discs is the simplest. Disc diameter D can be related to fracture surface area *A* as:

$$A = (\pi/4) \cdot \left(D^2 + S_D^2\right) \qquad (2.7)$$

where S_D is the standard deviation of disc diameter distribution. Statistical aspects on the bearing of fracture shape on area estimation are discussed by a few workers (e.g. Lee and Farmer 1993). The 3D density of disc centres τ, average disc surface area *A* and the 3D fracturation density d_3 are interrelated as:

$$d_3 = \tau \times A \qquad (2.8)$$

2.3.7 Volumetric Fracture Count

Volumetric fracture count (V_f) is the total number of fractures per cubic meter (m^3) of rock volume and is determined from the mean fracture spacing as:

$$V_f = 1/f_{s1} + 1/f_{s2} + 1/f_{s3} \cdots + 1/f_{si} \qquad (2.9)$$

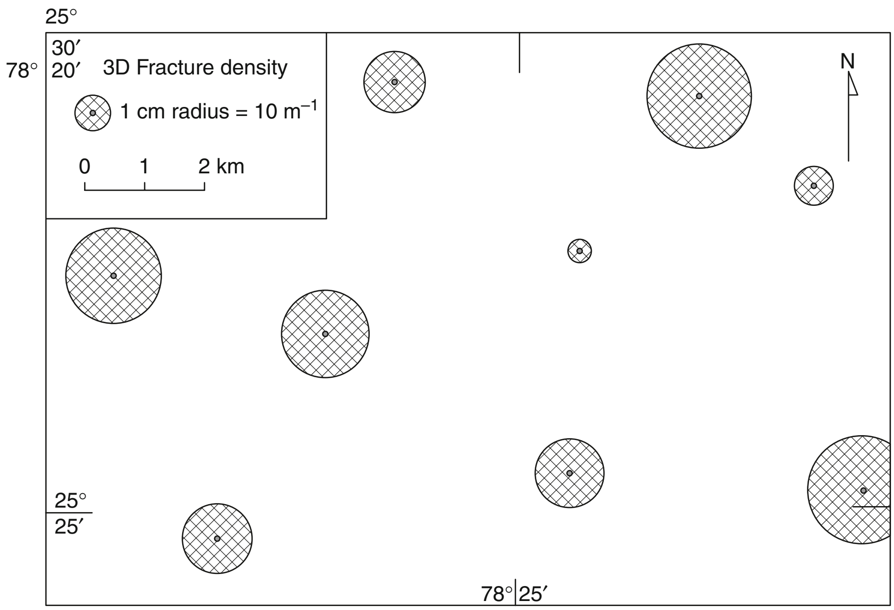


Fig. 2.24 Map showing variation in 3D fracture density in a part of Bundelkhand granites, Central India

where f_{si} is the mean fracture spacing of the *i*th fracture set in metres. This also carries the notion of fracture intensity which is defined as the number of discontinuities per unit length, measured along a line, area or volume. Volumetric fracture count has a direct bearing on the size of matrix blocks and the representative elementary volume (REV).

2.3.8 Matrix Block Unit

The rock block bounded by fracture network is called matrix block unit. Each matrix block unit can be considered to be hydrogeologically separated from the adjacent block. The shape of the matrix block unit could be prismatic, cubical or tabular, as governed by the orientation of fractures and their distribution (Fig. 2.25). For example, predominantly vertical fractures produce columnar and parellelopiped blocks (e.g. columnar joints in basalts); dominantly horizontal joints lead to plates and sheets (e.g. sheeting joints in granitoid rocks). These features impart hydraulic anisotropy to the geologic unit.

Consider an ideal case where beds are horizontal and fractures only vertical. It is known that fracture spacing and bed thickness are directly related (Eq. 2.1). It follows that a particular lithology has a tendency to develop block units of a certain shape, the block unit volume being dependent upon the bed thickness.

Block size is also related to the volumetric fracture count V_f. The maximum number of matrix blocks N_{bmax} can be expressed as (Kazi and Sen 1985):

$$N_{bmax} = \left(\frac{V_f}{3} + 1\right)^3 \tag{2.10}$$

Fractal concepts are also used to define fragmented rocks. It is found that for fragmented materials including rocks, there is a size-frequency relationship of the form:

$$N(r) \propto \left(r^{-D}\right) \tag{2.11}$$

where $N(r)$ is the number of fragments with a characteristic linear dimension greater than (r) and D is the

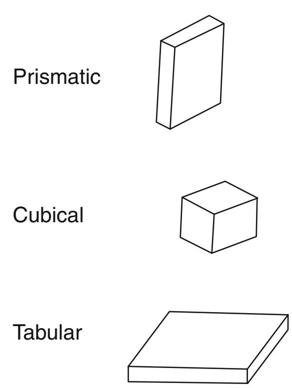


Fig. 2.25 Shape of matrix block units: prismatic, cubical and tabular

fractal dimension. It is believed that in future, fractal dimensions could be very useful in defining rock mass characteristics (e.g. Mojtabai et al. 1989; Ghosh 1990).

2.3.9 Fracture Connectivity

Discontinuities may exhibit differing termination and connectivity characteristics (Fig. 2.26a). Intersection of discontinuities is important as groundwater flow takes place through multiple fractures. Greater continuous inter-communication among the fracture network is provided by a higher degree of fracturing. Fracture connectivity increases with increasing fracture length and fracture density, as the chance of fracture intersection increases.

For evaluating connectivity it is necessary to study how the fractures terminate. Barton et al. (1987) classified fractures into three categories: abutting, crossing, and blind. The fractures of blind type do not intersect other fractures and remain unconnected. Laubach (1992) suggested that in many cases fracture connectivity may be gradual and that many fractures earlier classified as abutting, were really diffuse (interfingering type). He grouped fracture terminations into blind, diffuse and connected (which includes abutting). The data can be plotted in a ternary diagram to represent the bulk condition of fracture intersection in the rock mass (Fig. 2.26b). As an example, it is shown in the figure that most the joints in Bundelkhand granites (BG) are of connected type.

2.3.10 Rock Quality Designation (RQD)

RQD is a semi-quantitative measure of fracture density which can be estimated from core recovery data. RQD is defined as the ratio of the recovered core more than 4 in. (about 10 cm) long and of good quality to the total drilled length and is expressed as a percentage. Although RQD is mainly used in assessing the geomechanical properties of rocks, it is also considered to be an important parameter in assessing relative permeability.

2.3.11 Aperture

Aperture is the perpendicular distance separating the adjacent rockwalls of an open discontinuity, in which the intervening space is air or water-filled. Aperture may vary from very tight to wide. Commonly, subsurface rock masses have small apertures. Tensile stress may lead to larger apertures or open fractures. Often shear fractures have much lower aperture values than the tensile fractures.

Aperture may increase by dissolution, erosion etc. particularly in the weathered zone. It may decrease with depth due to lithostatic pressure, and there fracture wall compression strength is an important parameter governing aperture as lithostatic pressure tends to close the fracture opening. Table 2.2 gives aperture ranges as usually classified in rock mechanics.

Fracture aperture can be measured by various methods which include feeler gauge, flourescent dyes, impression packer, tracer test, hydraulic test etc. Readers may refer to Indraratna and Rajnith (2001) for details of various methods used for measurement of fracture aperture. Often, measurement of aperture in surface exposures is made with a vernier caliper or gauge and the measured opening is termed as the mechanical aperture. In the laboratory, fracture aperture can be estimated by impregnating rock samples

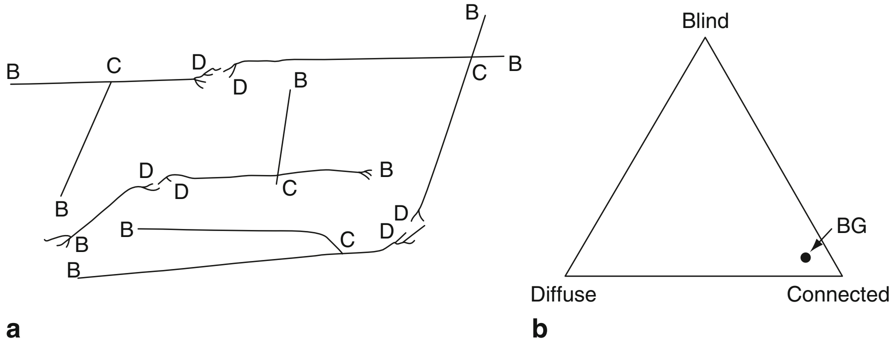


Fig. 2.26 Fracture connectivity. **a** Different types of fracture terminations: *B* blind; *C* crossing; *D* diffusely connected. **b** Ternary diagram of fracture terminations (After Laubach 1992); the point *BG* corresponds to data from Bundelkhand granites indicating high degree of fracture interconnectivity

Table 2.2 Aperture classification by size. (After Barton 1973)

Aperture (mm)	Term
<0.1	Very tight
0.1–0.25	Tight
0.25–0.50	Partly open
0.50–2.50	Open
2.50–10.0	Moderately wide
>10.0	Wide

with dyes or resin and by studying the thin sections under the microscope. This method can even be used in soft sediments viz. clay till (Klint and Rosenbem 2001). Lerner and Stelle (2001) have suggested two field techniques to estimate the in-situ spatial variation of fracture aperture: one is the conventional slug hydraulic testing using packers and in the second technique NAPL (sunflower oil) is injected into isolated fractures in a borehole.

The term 'equivalent aperture' is introduced to account for the variation in fracture which can be estimated from tracer test and hydraulic tests. The terms 'tracer aperture' and 'hydraulic aperture' are introduced by Tsang (1999) depending on the method of estimation. The hydraulic aperture is estimated from hydraulic tests based on the Cubic Law:

$$T_f \propto a^3 \tag{2.12}$$

where a is the fracture aperture and T_f is the transmissivity of the formation (also see Sect. 7.2.1).

The data on discontinuity sets with corresponding apertures is to be recorded. Asperities affect the aperture size and also render its measurement difficult in field. Therefore, when considering fluid flow, apertures are defined in terms of flow properties, as volumetric flow rate is governed by the cube of aperture. Aperture can be integrated with fracture density to give an integrated function representative of hydraulic conductivity (see Sect. 7.2.5).

2.3.12 Asperity

Fracture walls are not flat parallel smooth surfaces but contain irregularities, called asperities (Fig. 2.27). The asperity reduces fluid flow and leads to a local channelling effect of preferential flow. This reduces the

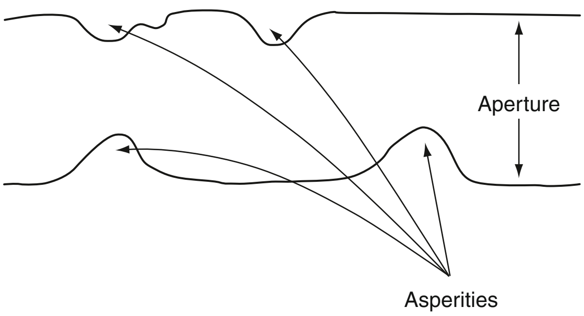


Fig. 2.27 Asperities in fracture walls

effective porosity and makes flow velocities irregular. Observations on asperities should be made for each type of fracture surface and measurement made. Mean height of asperities together with Reynolds number Re has a direct influence on flow regime, i.e. laminar vs. turbulent flow (Sect. 7.1.1).

2.3.13 Wall Coatings and Infillings

It is the solid material occurring between the adjacent walls of a discontinuity, e.g. clay, fault gouge, breccia, chert, calcite, etc. Filling material could be homogeneous or heterogeneous, and could partly or completely fill the discontinuity. The material may have variable permeability, depending upon mineralogy, grain size, width etc. The net effect of wall coatings and infillings is a reduced aperture.

2.4 Methods of Field Investigations

Methods of field investigations can be classified into two broad types (Jouanna 1993): 2D and 3D (Table 2.3). The 2D methods are based on observations made at rock surface, at surface or subsurface levels. They include scanline surveys, borehole surveys, and different types of areal surveys (Fig. 2.28). These methods give an idea of the hydrogeological properties at and around the site of observation.

The 3D methods are aimed at gathering information on the bulk volumetric properties involving inner structure of the fractured rock mass. There can be direct or indirect 3D methods. Brief descriptions of the various 2D and 3D methods are given below.

Table 2.3 Methods of field investigations

1. 2D Methods—Based on rock surface observations on lithology, structure, fractures, and their characteristics; made at surface or subsurface levels
   1.1 Scanline surveys
   1.2 Areal surveys—on outcrops, pits, trenches, adits, drift etc. including terrestrial geophotogrammetry and remote sensing
   1.3 Borehole surveys—including drilling, study of oriented cores, borehole logging, dipmeter, borehole cameras and formation microscanner methods
2. 3D Method—Investigations aimed at bulk volumetric properties of rock mass in 3D
   2.1 Hydraulic well tests
   2.2 Hydrochemical methods
   2.3 Geophysical methods including seismic, electrical, EM, gravity, magnetic and georadar

2.4.1 Scanline Surveys

Scanline surveys involve direct observation of rock features along a line on the rock surface, e.g. on an outcrop, drift face, excavation, adit etc. (Fig. 2.22). Scanlines are usually horizontal; however, vertical scanlines are preferred where fractures are mostly horizontal. Data on fractures obtained by sampling techniques such as along scanline (and also borehole) are strongly biased towards the fractures oriented perpendicular to the scanline/core and needs to be corrected for sampling bias by applying correction (Terzaghi 1965).

A suitable rock exposure or face is selected. A sample scanline is marked on the face, and its orientation (rake on the face) is recorded. Fractures intersecting the line are collected. Each fracture is represented by its trace which can be measured. Observations are made for various parameters, like: location of the fracture trace intersection with the scanline; orientation of the fracture and angle made with the scanline; termination type if seen and connectivity; alternatively, whether the fracture extends beyond the top of face/batter; fracture type and other relevant fracture characteristics.

2.4.2 Areal Surveys

Areal surveys can be treated as extension of the scanline surveys. They are used for surveying fracture characteristics on a rock surface area, e.g. on an outcrop, drift face, adit, tunnel etc. (Fig. 2.23). In field, an area is first demarcated on a rock surface for observation and statistical sampling. Detailed observations on fracture characteristics are made with-in the marked area where all the fractures data are collected.

Direct observations and field mapping at natural rock outcrops is an old established technique. Weathering, surficial cover, soil, vegetation etc. influence the accessibility and visibility of good outcrops. Excavations, pits and trenches are made to expose the fresh rocks at shallow depth for visual inspection. Subsurface direct observation can be made in adits and tun-

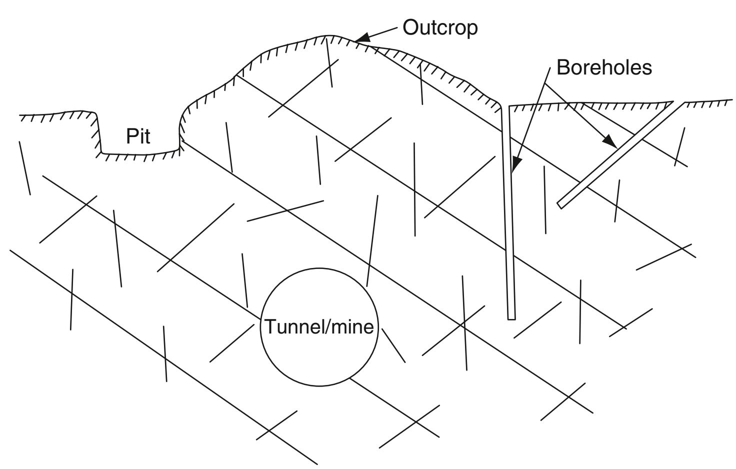


Fig. 2.28 The various 2D methods of field investigations

nels. Geological maps of rock faces exposed can be prepared and fracture characteristics measured.

Remote sensing includes study of photographs and images acquired from aerial and space platforms. This technique can give valuable information on geology, structure, fractures, lineaments etc. and forms an important mapping tool (Chap. 4). Further, stereo-photographs of rocks exposed in outcrops, scarps, excavations, etc. can be taken from a ground-based (terrestrial) platform. These stereo pairs can be studied and measurements of fracture characteristics can be done in laboratory.

2.4.3 Borehole Surveys

These are the only tools for direct observations of rock surface and features occurring at depth. A number of methods are available. As drilling is expensive, optimum combination of methods is employed for getting maximum information from drilling. In the case of vertical and sub-vertical fractures, inclined bores are preferred to intercept a number of such fractures. Study of drill cores, particularly oriented drill cores provides data on orientation of structures, fractures, their apertures as well as infillings. Further, borehole walls can be studied in several ways. Geophysical well logging is a standard technique, including electrical, caliper, radioactivity, magnetic logging etc. These give information on lithology and structure. Borehole televiewer provides images of the borehole walls with joints and fractures. Dipmeter and formation microscanner help measure orientation of structural features at depth in-situ (for drilling and well observation techniques, see Chap. 5).

It may be mentioned here again that data on fractures obtained by sampling techniques such as along scanline and borehole are strongly biased towards the fractures oriented perpendicular to the core/scanline and needs to be corrected for sampling bias by applying a correction (Terzaghi 1965).

2.4.4 3D Methods

As mentioned above, 3D methods are aimed to provide information on bulk volumetric properties of the fractured rock mass. These methods include hydraulic well tests, hydrochemical methods and geophysical techniques. The hydraulic well tests comprise pumping tests of various configurations and types, and give bulk volumetric assessment. Slug tests will give a first hand dependable information about the hydraulic conductivity at much lower costs than pumping tests (see Chap. 9). In hydrochemical methods various types of geochemical tracer studies and solute transport studies are carried out for bulk volumetric hydrogeological characterization (see Sect. 10.3). Further, a number of geophysical methods are used such as seismic, electrical, EM, gravity, magnetic and georadar. They are briefly described in Chap. 5 from a hydrogeological investigation point of view.

Summary

Most rocks possess fractures, broadly termed as discontinuities here, which facilitate storage and movement of fluids through the medium The discontinuities may be formed by planar surfaces such as bedding plane, foliation, fractures, faults shear zones etc. The common systematic fractures are of three main genetic origins: extensional, shear and hybrid. Faults can cause truncation or repetition aquifers and may lead to formation of springs and interbasinal subsurface flow. Discontinuities are characterized in terms of a number of parameters such as orientation, spacing, persistence, fracture and shape, connectivity, aperture coatings etc., and these data may be collected from field surveys by scanline method or areal surveys or in borehole observations.

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