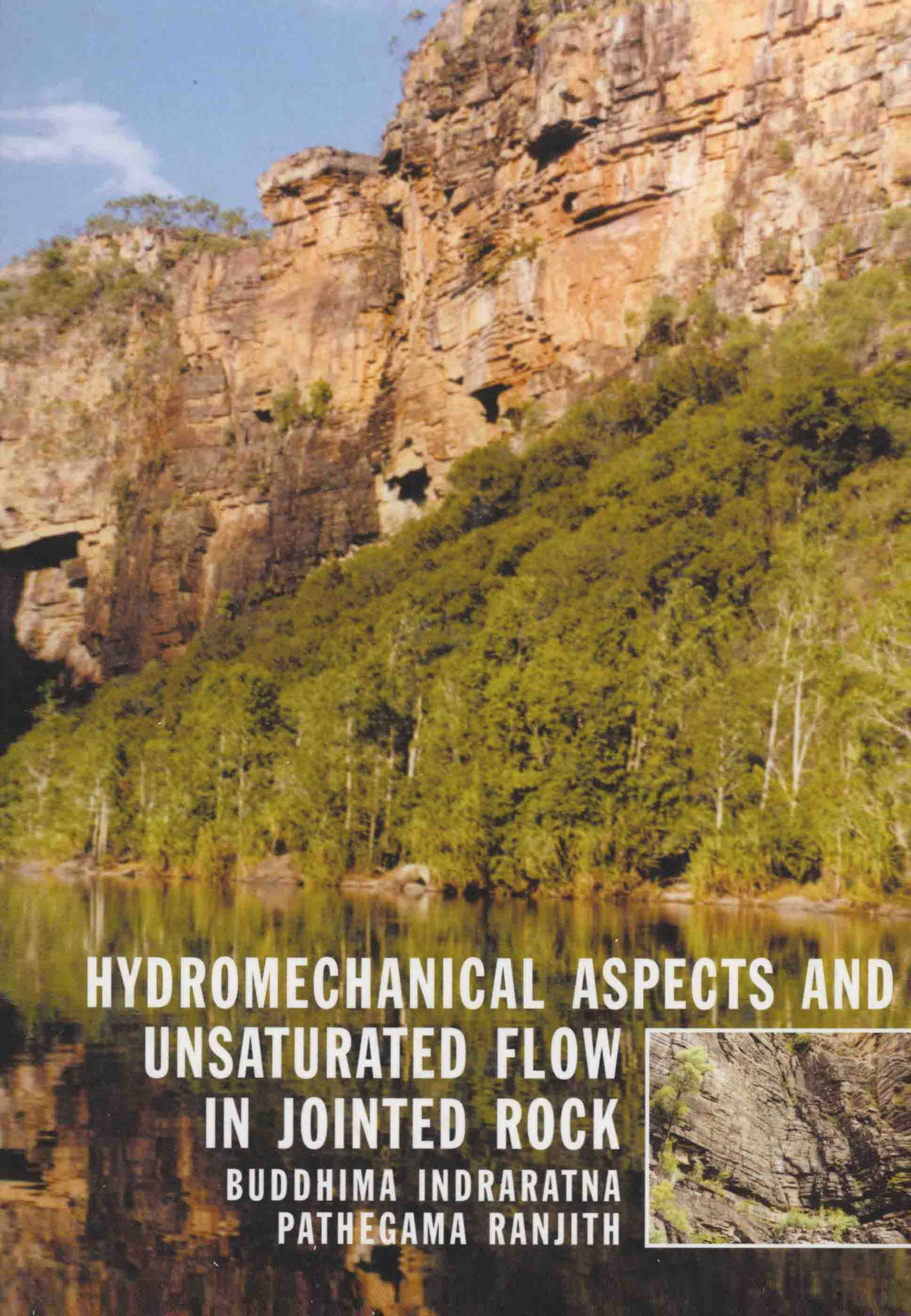

HYDROMECHANICAL ASPECTS AND UNSATURATED FLOW IN JOINTED ROCK

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Hydromechanical Aspects and Unsaturated Flow in Jointed Rock

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Preface

At present, due to the lack of proper understanding of unsaturated or multi-phase flows, it is often difficult to predict the risk of sudden groundwater inundation and gas outbursts in complex hydro-geological environments prevailing in underground mines and tunnels. For instance, in Australia, large reserves of coal and other minerals lie under tidal water, man-made reservoirs, rivers and the Pacific Ocean. Often, large volumes of groundwater are stored in sandstone aquifers above proposed mines and transport tunnels, while existing joints and fractures created by blasting and excavation provide ideal conduits for water to flow. The occurrence of methane pockets in coal seams and igneous activities that develop large amounts of gas such as carbon dioxide within complex hydro-geological regimes present obvious safety hazards, including human fatalities reported in the past due to methane explosion. The delays caused by water and gas ingress to underground sites carry adverse consequences in terms of stability, productivity and safety. In rock tunnels and mine openings, the cost of associated support systems is also considerable, and their installation can be time consuming.

During the past two decades, a number of numerical, analytical and experimental models have been developed for single-phase flow (i.e. water or gas only) through a single joint in rock. The single-phase flow theories can only provide rough estimates of flow rates and joint pressures. The compressibility of air and its sensitivity to temperature and its solubility in water make the analysis of two-phase flows a more challenging task. A realistic two-phase flow must be described by the characteristic components of each phase present in the mixture, their volume and mass ratio. Depending on the surface roughness and aperture along a rock joint, distinctly different water – gas flow patterns may result.

The fundamental aspects of rock joints have been addressed in a recent book, "Shear Behaviour of Rock Joints" by B. Indraratna and A. Haque, also published by Balkema, Rotterdam, in 2000. In this follow-up volume, the authors have provided a comprehensive background to hydro-mechanics of single- and two-phase flows with associated theories, mathematical and semi-empirical models. The book also includes a vivid description of the type of laboratory equipment utilized to simulate two-phase flows through jointed rock. The high pressure, two-phase triaxial equipment designed and built in-house is essentially the result of a five year project partly supported by industry, and the book describes the salient features of this novel facility, as well as highlighting the key experimental findings. A new mathematical model for two-phase flows developed by the authors is also presented in its initial form, while further modification of the theory is currently in progress. The experimental data obtained through laboratory testing have complemented some of the significant and fundamental concepts addressed in the book. Given the importance of construction and mining activities in jointed rock all over the world, this book will provide a useful reference for practicing geotechnical and mining engineers and researchers alike.

The completion of this book was made possible through the assistance of several national and international colleagues, who have reviewed the subject content presented in this volume on various occasions. The authors are particularly grateful to Dr. Winton Gale, Managing Director, Strata Control Technology (SCT), Wollongong and for the Australian Research Council for providing financial assistance for conducting research on unsaturated flow through rock joints. The authors are also thankful for the comments and criticisms of various colleagues, including Associate Prof. N. I. Aziz and Prof. R. N. Singh (Wollongong), Dr. A. Bhattacharya and Dr. V.S. Vutukuri (University of New South Wales), Dr. Chris Haberfield (Monash University), Dr. D.G. Toll (University of Durham) and Prof. P.H.S.W. Kulatilake (University of Arizona).

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Contents

CHAPTER 1

Characterisation of jointed rock mass

1.1 INTRODUCTION

In this introductory Chapter, a brief description of the rock types and properties, and joint characteristics is given. Various attempts have been made in the past to classify rock mass for important engineering applications underground and on the surface, such as design of mines, highway tunnels, slopes, dam foundations and nuclear waste storage plants. Classification of rocks can be made based on their mineral composition and their origin or types for engineering applications (Fig. 1.1). The geological classification provides mineralogical and chemical data, but it does not directly provide stress-strain characteristics of rocks, which are the most relevant in engineering applications. The existing rocks may be subjected to high pressure and temperature changes resulting in the metamorphic alteration of properties, structurally, mineralogically and texturally. Depending on the geological origin, i.e. stages of weathering, transportation, consolidation and alteration (Tucker, 1993), rocks are usually classified into three major groups, (a) igneous (b) sedimentary and (c) metamorphic rocks. Figure 1.2 shows the common rock types, which come under these principal categories. A simplified geological process is shown in Fig. 1.3.

Clayey and silty sediments are deposited and consolidated in layers to form sedimentary rocks, which are often stratified. Such interfaces are usually identified as 'bedding planes', along which movements and fluid flow can occur under certain circumstances. In underground coalmines, planes of weakness can be identified in inter-layered shale and sandstone deposits.

The principal chemical composition of different rocks can be found in the literature (Nockolds et al., 1978; Smith & Erlank, 1982). Depending on chemical composition and their grain size, some igneous rocks such as basalt display columnar fractures with hexagonal cross-sections. During the metamorphism process, fractures may develop within the rock mass and their extent depends on the temperature and pressure change. Based on the mineral grain shape, size and arrangement, metamorphic rocks have different structures such as banded, slaty and foliated (Santosh, 1991). Banded rocks such as gneiss permit relatively easy split through layers. When sedimentary rocks undergo metamorphism, the existing

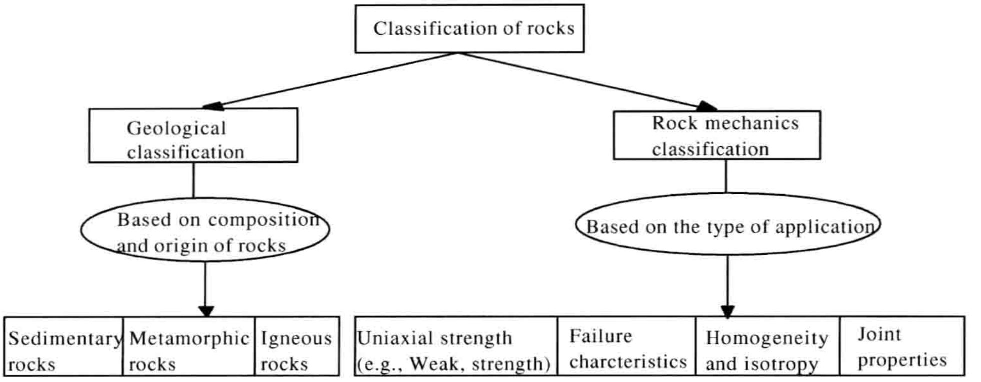


Figure 1.1. Principal classification systems of rocks.

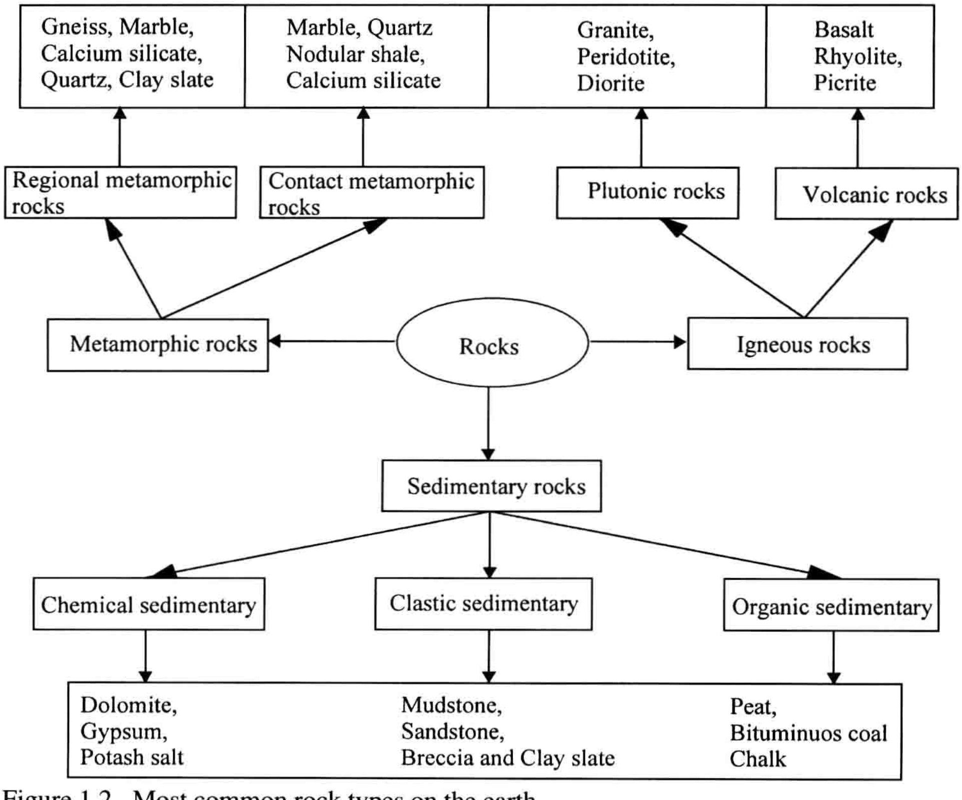


Figure 1.2. Most common rock types on the earth.

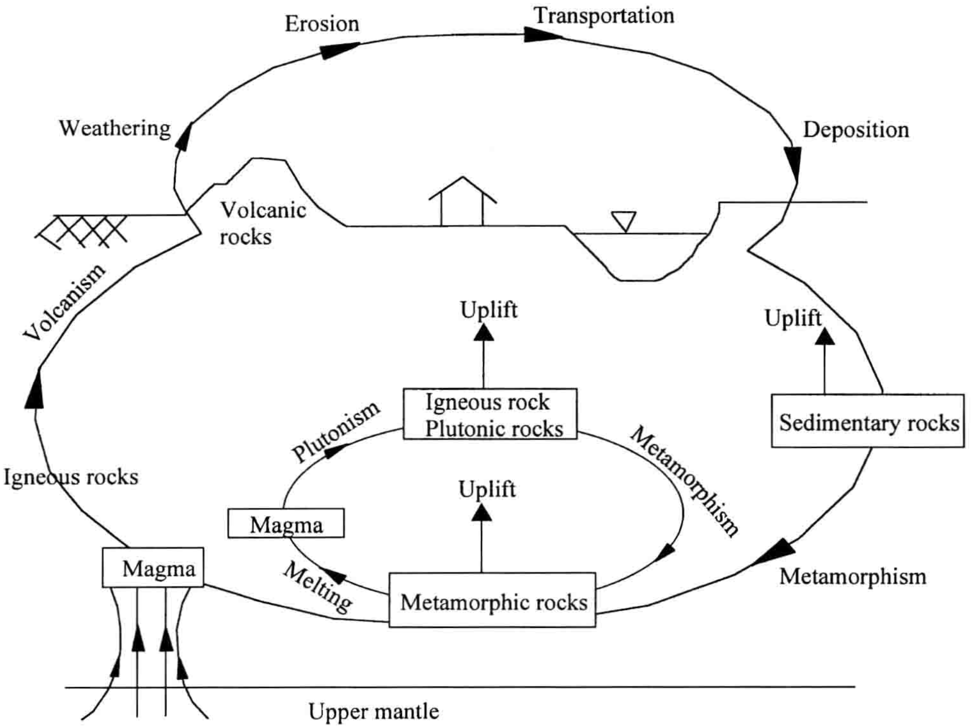


Figure 1.3. Simplified geological processes.

bedding planes in the sedimentary rocks may also be visible in the newly formed metamorphic rock. However, the bond between these layers is stronger than in sedimentary rocks. It is important to note that during excavation or blasting process, fractures may easily develop through bedding planes, which may then provide paths for fluid flow.

1.2 CLASSIFICATION SYSTEMS FOR ENGINEERING APPLICATIONS

Terzaghi (1946), Baron et al. (1960) and Coates (1964) attempted to classify rocks for different applications. Each classification system is based on the strength of rock mass and the geological features/structures such as joints, but little is usually said about rock-mass permeability. In Terzaghi (1946) rock mass classification for tunnels, 7 categories have been identified, as given below:

(1) Stratified rocks;
(2) Intact rocks;
(3) Moderately jointed rocks (e.g., vertical walls require no support);
(4) Blocky rocks (e.g., vertical walls require support);
(5) Crushed rocks;

(6) Squeezing rocks (low swelling capacity); and
(7) Swelling rocks (high swelling capacity).

As described by Coates (1964), one of the main deficiencies of the above classification system is that it does not give any information on the strength or permeability of rock mass. At shallow depth, blocky rocks might not require any support for vertical walls, whereas moderately jointed rocks may require support at greater depths, as well as effective water-proofing to prevent inundation.

Another classification system proposed by US Bureau Mines (1962) for underground openings, and recorded by Coates is described below. Rocks in underground mines have mainly been divided into two groups, namely (a) competent rocks (i.e., no support is required) and (b) incompetent rocks (i.e., support is required to prevent failure of an opening). Competent rocks are further subdivided into three classes, as massive elastic rocks (e.g., homogeneous and isotropic rocks with no significant jointing), bedded elastic rocks (e.g., homogeneous, isotropic beds with the bed thickness less than the span of the underground excavation) and massive plastic rocks (i.e., weak rock that may yield under relatively low stress).

The classification system suggested by Coates (1964) gives a better picture of the strength and failure characteristics of rocks. His method is based on 5 main characteristics of rock mass, as given below:

(1) Uniaxial compressive strength
  weak (<35 MPa)
  strong (between 35 and 175 MPa – homogeneous and isotropic rocks)
  very strong (> 175 MPa – homogeneous and isotropic rocks);
(2) Pre-failure deformation behaviour of rocks
  elastic
  viscous;
(3) Failure characteristics of rocks
  brittle
  plastic;
(4) Gross homogeneity
  massive
  layered (e.g. sedimentary rocks); and
(5) Continuity of rock mass
  solid (joint spacing >1.8 m)
  blocky (joint spacing <1.8 m)
  broken (passes through a 75 mm sieve).

It is clear that, while different classification systems are available, one must employ geological and rock mechanics classification models in conjunction to get a better understanding of the nature of a particular type of rock. The degree of jointing is the primary factor affecting permeability, hence the flow in to an excavation in a rock mass. Saturation of joints increases the internal hydraulic pressures, reducing the effective stress, hence the overall strength of rock mass.

1.3 FORMATION OF DISCONTINUITIES ON EARTH CRUST

In order to appreciate the hydro-mechanical aspects of jointed rock, a thorough understanding of the type of joints and discontinuity characteristics is required. Geological features in rock mass can be broadly divided into two groups, namely, (a) primary and (b) secondary. Primary features include original structures in the rock mass, which after being subjected to deformation and/or metamorphism, they are usually referred to as secondary structures.

Rocks during the process of development and the later formation of rock masses are usually subjected to a number of forces within the earth crust. These forces may be a single force or a combination of forces resulting from ground stresses, tectonic forces, hydrostatic forces, pore pressures, and temperature stresses. As a result of these forces and their magnitudes, rocks continuously undergo varying degree of deformation, resulting in the formation of different kinds of structural features (Fig. 1.4). For example, fractures or joints may initially develop within a rock mass, followed by dislocation of the fractured rock blocks. In some circumstances, these dislocated rock blocks move faster than the adjacent blocks, resulting in larger deformation between each rock block. Such structural features are referred to as faults. Both faults and joints are the result of the brittle behaviour of rock mass. Joints and faults can be easily identified from the component of displacement parallel to the structure. Joints usually have very small normal displacement, referred to as joint aperture. The estimation of joint aperture using various techniques under different stress conditions is discussed in detail in Ch. 3.

1.3.1 Joints and bedding planes

Joints in a rock mass are usually developed as families of cracks with probably regular spacing, and these joint families are referred to as joint sets. While the formation of joints is associated with the effect of differential stress, some joints are more prominent and well developed, extending for a considerable length (several kilometres), while others are minor joints having a length of only a few centimetres. In order to characterise joint sets it is necessary to consider their properties such as spacing, orientation, length, gap length and the apertures. Relative movement of joints is negligible in comparison to fault movements. Joints in a rock mass may be open or close or filled with some other material such as clay and silt. Open joints often provide fluid flow paths to other connected joints in the rock mass, and the quantity of fluid carried by each joint depends on the separation between joint blocks (joint aperture), joint geometry, hydraulic gradient and properties of fluid.

The fundamental geometrical observation of a joint includes the measurement of strike and dip. Based on the dip and the strike, joints are grouped into three classes: (a) dip joints, (b) oblique joints and (c) strike joints. However the classification based on the origin of joints is often more useful in various engineering

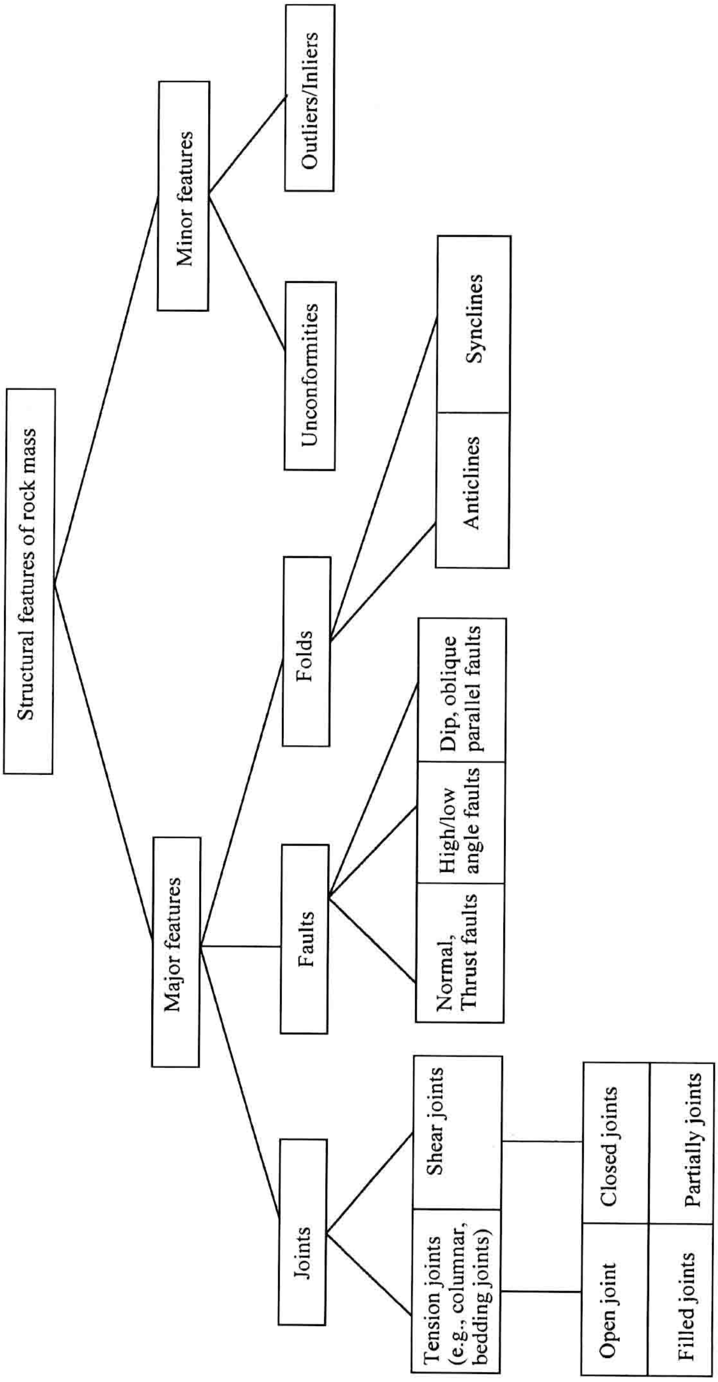


Figure 1.4. Common geological structural features in a rock mass.

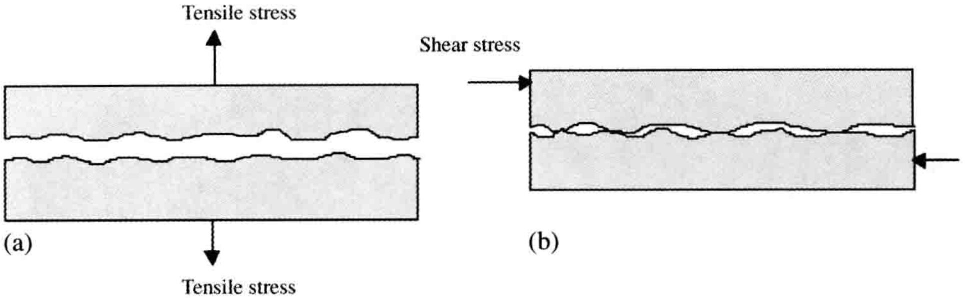


Figure 1.5. Genetic classification of joints. (a) Tension joint (e.g. igneous rocks) and (b) Shear joint (e.g. sedimentary rocks).

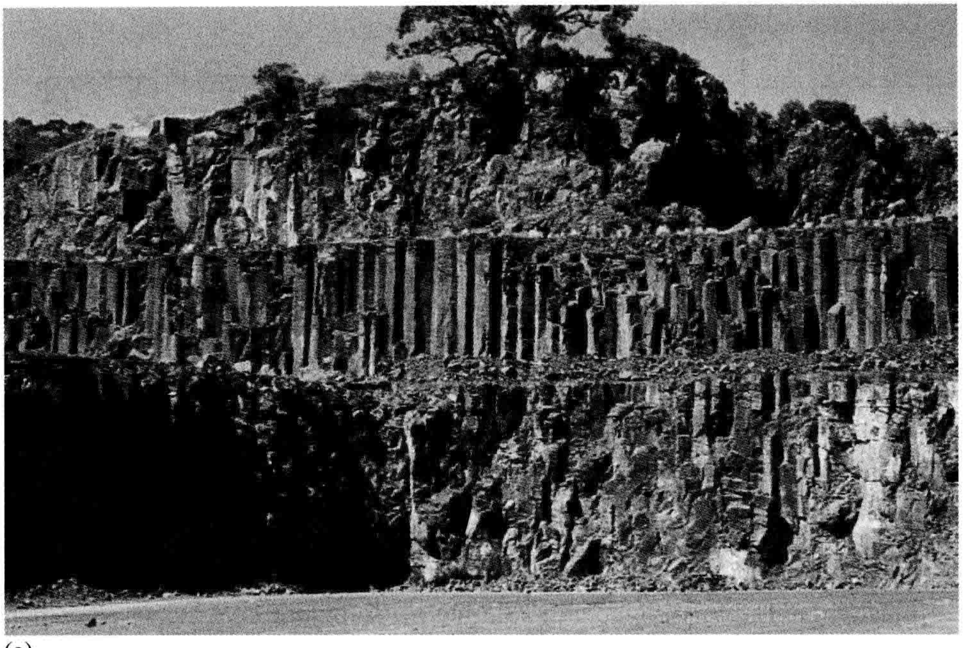
applications (Fig. 1.5). Based on the origin of joints, they are mainly grouped as follows:

(1) Tension joints; and

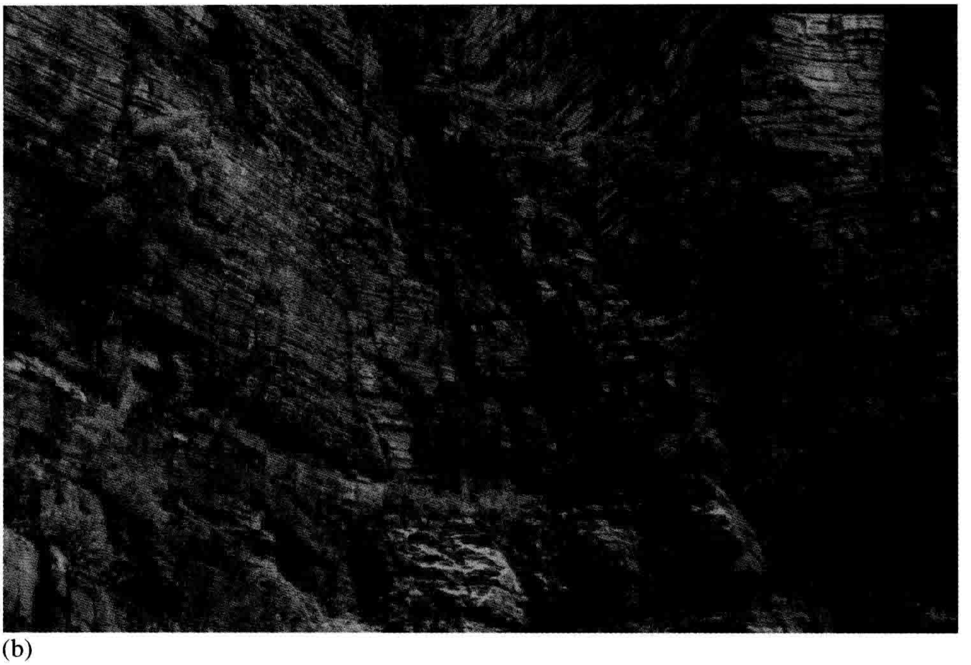
(2) Shear joints.

Tension joints may develop either during the formation of rocks or after their formation, which can be attributed to the tensile forces acting on the rock mass. Columnar, sheeting and mutually perpendicular joints are some common types of tension joints. Columnar joints generally occur in hexagonal shape and are often found in basalt rocks, whereas sheet joints may develop in granite. Figure 1.6a and b show columnar joints in basalt and sheeted joints in granite rocks. The mechanism of formation of columnar joints in basalt is associated with the stress caused by the cooling of magma. Theoretical aspects of the development of joints and faults have been discussed by Price (1966). He proposed that the joints in horizontally bedded rocks were mainly due to uplifting forces developed on the earth's crust. It can sometimes create both shear and tension joints on either side of the limbs of the fold, as shown in Fig. 1.7. Apart from geological processes, fracturing may occur on the surface rocks due to human activities, and the natural weathering accelerated by temperature changes and the action of surface water. According to the definition given by Pettijohn et al. (1972), cross joints are defined as a structure confined to a single sedimentation unit, and characterised by internal discontinuities inclined to the principal bedding plane.

The most common feature of sedimentary rocks is the occurrence of bedding planes, in which each bed is fairly homogeneous and differs in properties from the other beds, in relation to the texture and composition. In some circumstances, significant variations of material properties within a layer may occur because of the varied lithological conditions due to random, uniform or systematic deposition. When the sediments are deposited uniformly, homogenous layers are formed. Between each stratum, a new discontinuity is developed, and the properties of this discontinuity depend upon the properties of the adjacent layers. Typical bedding planes in a sedimentary rock are shown in Fig. 1.8.



(a)



(b)

Figure 1.6. (a) Columnar joints at a basalt quarry in Kiama, NSW, Australia. (b) Closely packed sheet joints, National Park, Western Australia.

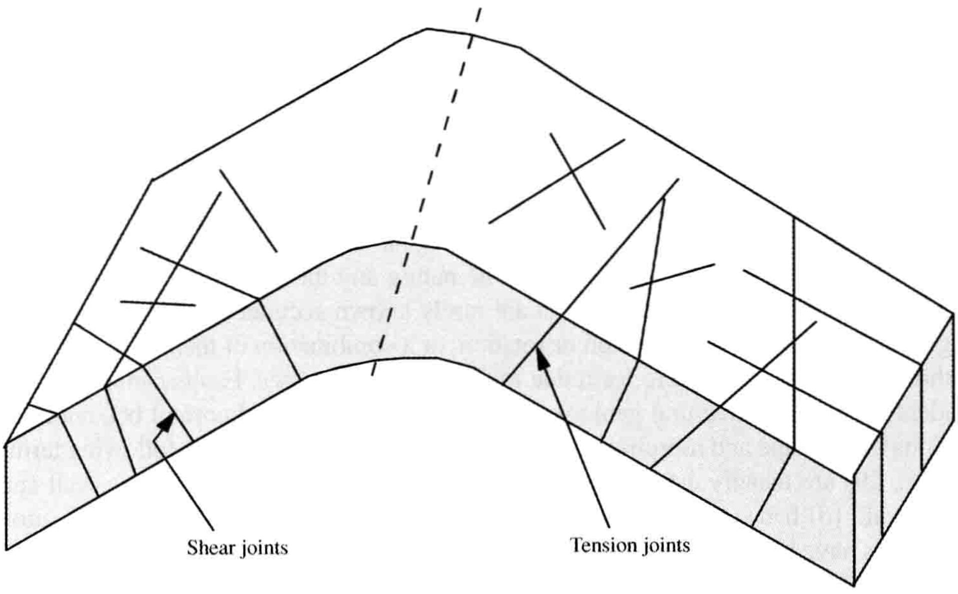


Figure 1.7. Development of shear and tension joints on the limbs of fold (modified after Price, 1966).

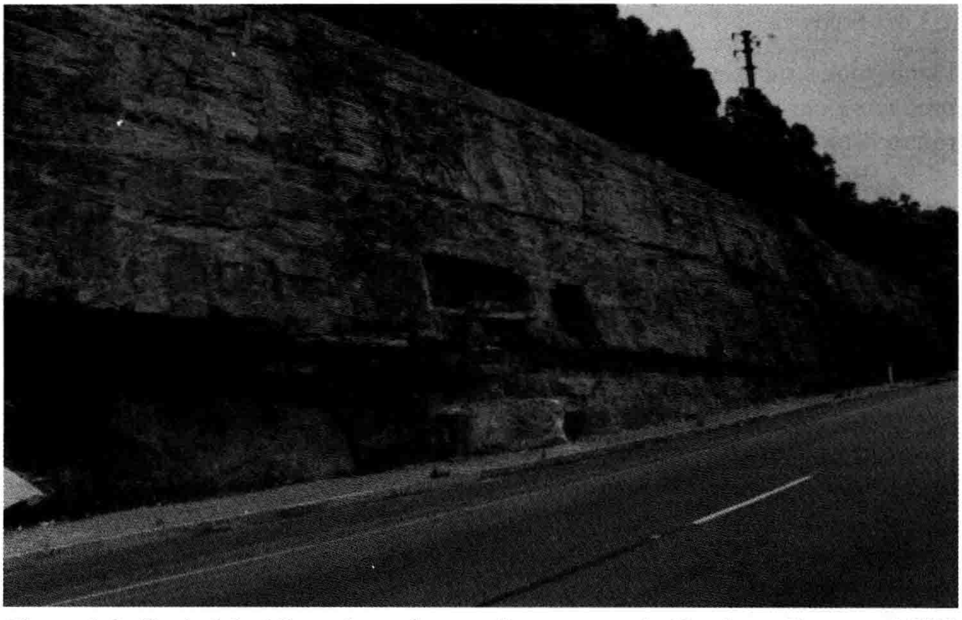


Figure 1.8. Typical bedding planes in a sedimentary rock (Southern Freeway, NSW, Australia).

1.3.2 Faults

When the shearing stress exceeds the shearing resistance of rocks, fractured rock blocks undergo considerable displacement along a favourable shear plane resulting in the formation of a new discontinuity, which is referred to as a fault. Depending on the internal stresses, and the rock properties, these relative displacements may vary from few centimetres to several kilometres. Priest (1993) reported the extent of some major faults, such as the San Andreas Fault in California, the Great Glen Fault in Scotland and the Alpine Fault in New Zealand. The nature and the magnitude of the internal forces developed on the earth's crust are rarely known accurately. These forces may give rise to tension, compression or rotation, or a combination of them. For example, thrust faults are believed to form due to compressive stresses. Faults can be broadly identified by the structural geology (e.g., shear zone, gouge, abnormal behaviour of strata), landscape and morphology. To describe a fault geometrically, following terms (Fig. 1.9) are usually used: (a) strike and dip, (b) fault plane, (c) hanging wall and footwall, (d) hade, (e) heave and (f) throw. In the literature, different classification systems have been employed to identify various faults based on the following:

(1) The type of fault (e.g., thrust fault, normal fault, vertical fault), for example see Fig. 1.10;
(2) The dip angle of the fault (e.g., low-angle fault, high-angle fault); and
(3) The direction of slip (e.g., strike fault, oblique fault).

1.3.3 Folds

Planar rock structures on the earth's crust have been subjected to deformation and producing curved or non-planar structures. These new geological structures are referred to as folds, and usually these rocks behave as a ductile material. The

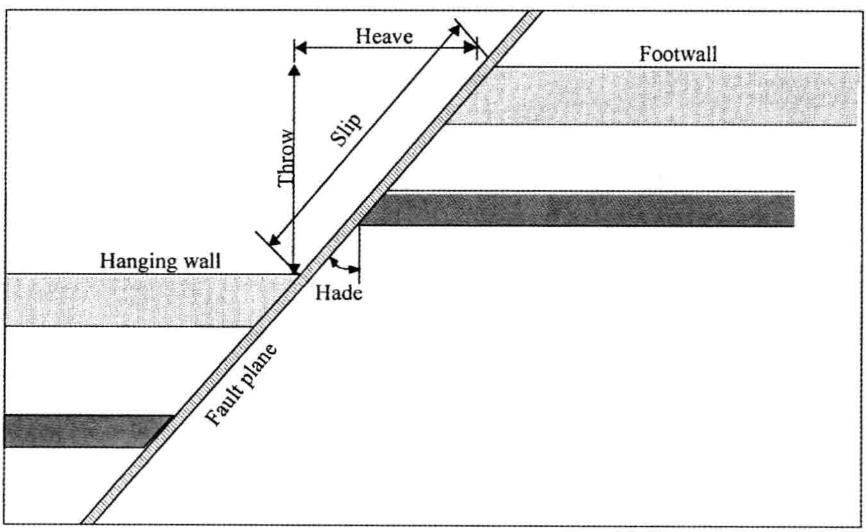


Figure 1.9. Simplified schematic diagram of a typical fault.