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Rock Engineering

Second edition

Arild Palmström and Håkan Stille

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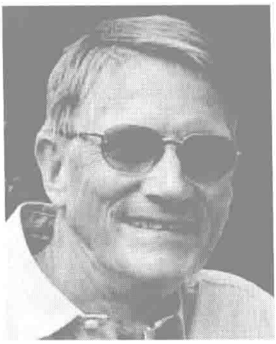
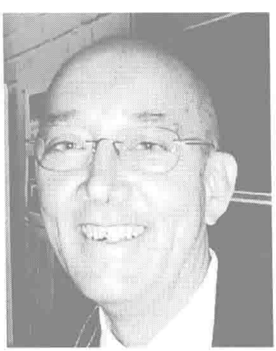


Arild Palmström

Dr Arild Palmström is a senior adviser with 40 years of experience in the fields of rock engineering and engineering geology. He has an MSc from the Norwegian Technical University of Norway, and gained his PhD from Oslo University. He has been involved with numerous hydropower projects and subsea tunnel projects in Europe, Asia and South America, and has written more than 50 journal articles, conference papers and book chapters and, in addition, two handbooks on rock engineering and excavation works.

Dr Palmström is a member of the Norwegian National Group of the ITA (International Tunnelling Association), the Norwegian National Group of the ISRM (International Society of Rock Mechanics), the Norwegian National Group of the IAEG (International Association of Engineering Geologists) and the Norwegian National Group of the ISSMFE (International Society for Soil Mechanics and Foundation Engineering), and has participated in the Norwegian group for geotechnical design (CEN/TC 250/SC 7) of the European Committee for Standardisation 1998–2010.

Dr Palmström's professional activities include the presidency of the Norwegian National Rock Mechanics Group of the ISRM (1995–1997) and the secretaryship of the Norwegian national committee for definitions and terminology of rock mechanic terms, from which came the books *Handbook in Rock Engineering* (in Norwegian) and *Handbook in Engineering Geology and Rock Engineering*.



Håkan P. Stille

Professor Dr Håkan P. Stille has been involved with geotechnical engineering works for more than 40 years in Europe, Africa, Asia and South America. He has published more than 50 special reports, book chapters and journal articles, and has authored/co-authored over 100 papers and publications for professional journals, conferences and seminars. Professor Dr Stille is a professor emeritus of soil and rock mechanics at the Royal Institute of Technology (KTH) in Stockholm, and has worked extensively in both industry and academia.

Professor Dr Stille is a member of the Swedish National Group of the ISRM (International Society of Rock Mechanics) and the Swedish National Group of the ISSMFE (International Society for Soil Mechanics and Foundation Engineering). His professional activities include the vice-presidency of Skanska technique and a professorship in soil and rock mechanics at the Royal Institute of technology in Stockholm. He has been involved in the Swedish group for geotechnical design (CEN/TC 250/SC 7) and Evaluation Group 13 (rock mechanics) of the European Committee for Standardisation, and is the chairman of ISRM's commission on rock grouting.

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Chapter 1
Introduction

The basis and goal of this book were formulated many years ago by John (1969):

> Rock mechanics has to provide methods of analysis which are realistic compromises between the best representation of the actual ground conditions and pragmatic engineering. The rock mechanics practitioner has to face the fact that many geological engineering and rock mechanics problems may be too complex to allow rigorous analysis, but at the same time are deemed satisfactory for the construction of major structures. Qualitative evaluations, quantitative descriptions of geologic features as such, and comparisons of specific test results are always of interest but may not suffice as basis for engineering decisions and designs.

Neither a purely geological nor a completely technical classification of rockmasses will answer its intended purpose but suitable parameters of rockmasses should be defined and quantified in rock engineering terms.

The material(s) surrounding an underground opening forms a complex structure. For example, it is seldom possible to make an accurate measurement of either the mechanical properties of the rockmass or the forces acting on it. Bieniawski (1984) wrote that 'Provision of reliable input data for engineering design of structures in rock is one of the most difficult tasks facing engineering geologists and design engineers.'

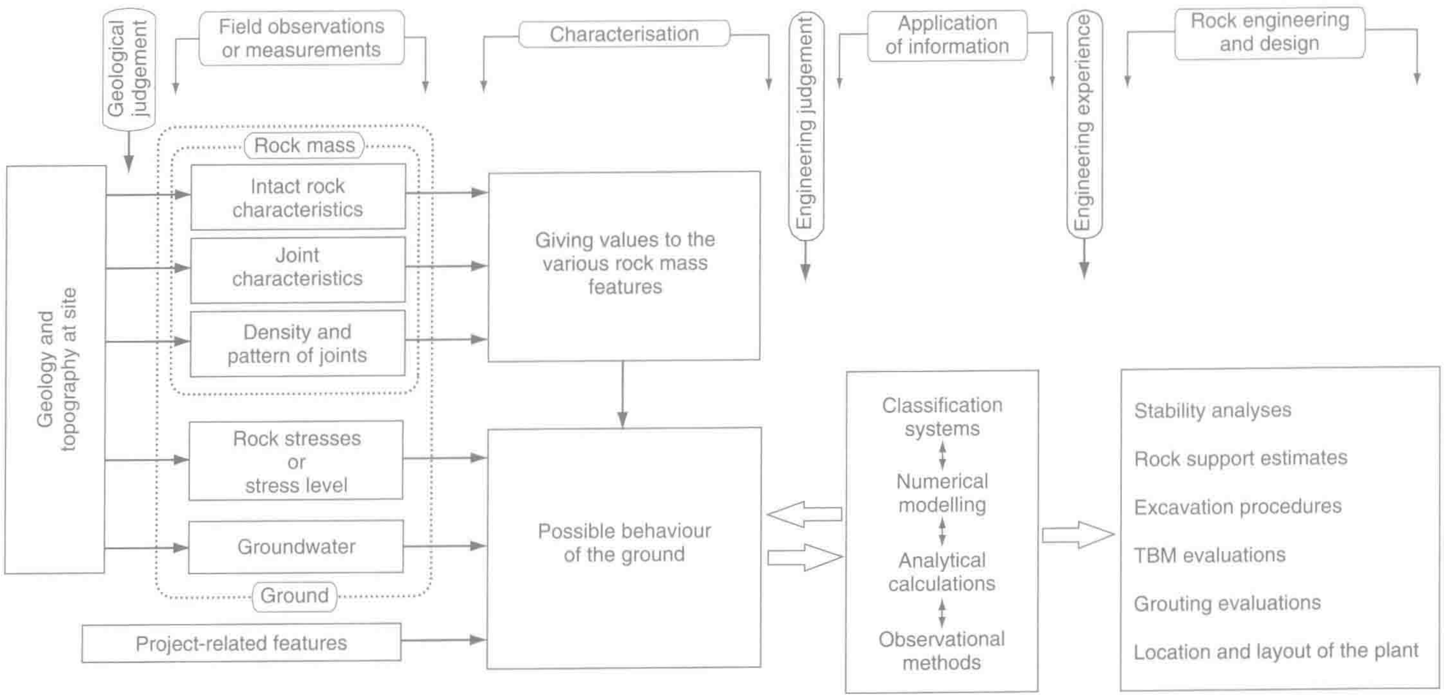
Frequently in this situation, the design of tunnels and caverns is based on observations, experience and personal judgement, where rock engineering classification systems (or, better expressed, empirical design methods) play an important role.

Figure 1.1 shows the main geological and topographical features influencing ground behaviour and the application of rock engineering tools used for design. The choice of suitable tools for engineering and design is essentially an outcome of the actual ground behaviour. In this context, ground behaviour is the way that the ground acts in response to the rockmass conditions, the forces acting and the project-related features.

An important requirement for all engineering and design tools is that the method or tool used adequately covers the behaviour of the ground around the opening.

In the authors' opinion, practical experience combined with knowledge and understanding of the complexity of the ground, including geology, is essential for the good design of

Figure 1.1 The principal relationships between ground behaviour and rock engineering and design. (Reproduced, with permission, from Stille and Palmström, 2003. © Elsevier)



underground openings. By presenting descriptions of rockmasses, with illustrations, the intention of this book is to strengthen the link between engineering geology (used for collecting characteristics of the site conditions) and rock mechanics; that is, to collect relevant and sufficient information on the ground and to use appropriate rock engineering tools in the design. The book will not cover all aspects and details of the subject: its focus is more on the interaction between engineering geology and rock design than on rock excavation methods. For further and more in-depth studies, references are made to the literature. Another prerequisite of a successful project is good cooperation between engineering geologists and rock engineers; also, the people involved should have long and relevant experience.

Thus, the sound engineering and design of an underground excavation in rock require:

- practical experience in rock excavation and rock-supporting works
- understanding of the geology and its impact on underground excavations
- knowledge of ground properties and parameters, and how they influence excavation and stability
- how to find representative input parameters to use in evaluations and calculations
- correct use of rock engineering methods and systems, including documentation on how the values and ratings used are selected.

This book is aimed primarily at experienced readers (engineering geologists, rock engineers, practitioners of rock excavation, post-graduate students) working within the field of underground rock excavations.

A central issue has been to present information on the various topics involved in design and engineering and how they are related to each other (Figure 1.2). A primary goal has been to link together various fields in geology with rock planning and construction, presenting principles in ground investigation with derivation of the results. Here, geological understanding, including evaluation of uncertainties in the geological and ground conditions, plays an important role. Further, it is shown how the information collected and the derivation performed can be applied in selecting appropriate engineering tools for the design of an underground opening.

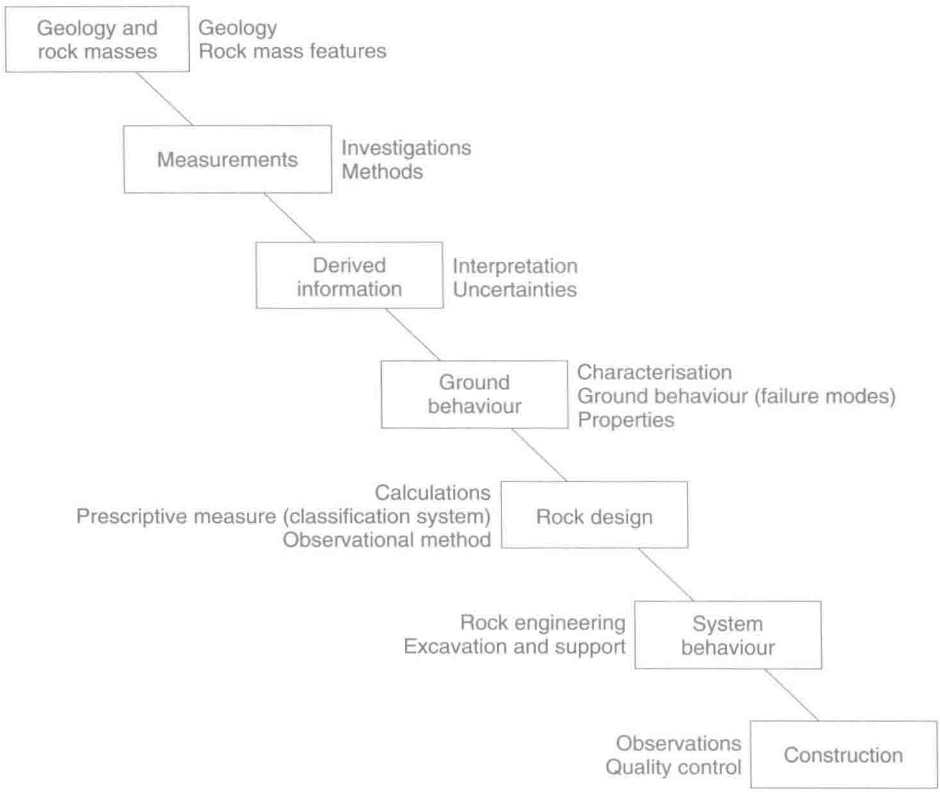
The various methods, calculations and systems used in rock engineering are not described in detail, but the principles, applications and limitations of the various tools and methods are given. An important issue has been to present how information on the ground properties can be collected and used in derivation, as well as in rock engineering and design.

The process is shown in Figure 1.3, where the main chapters in this book are listed, together with the main sections within each chapter.

The book covers a wide range of subjects. The following definitions are used:

- *Engineering geology*: the application of geological knowledge in engineering analysis, planning, design and construction. Within this field, geology is the focus.

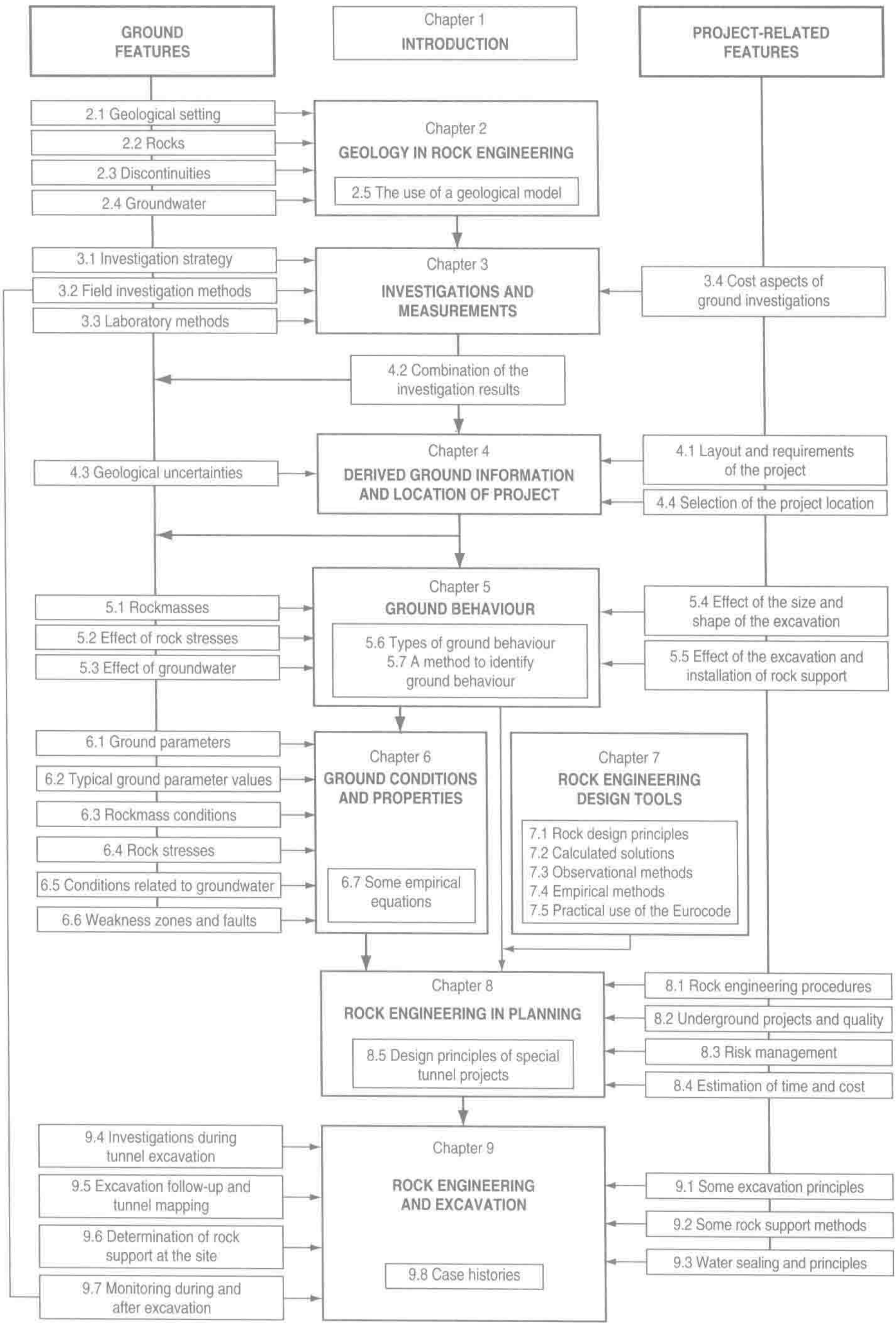
Figure 1.2 The main steps in rock engineering for an underground project. (Modified from Eurocode 7, Part 1. Permission to reproduce extracts from BS EN 1997-1 is granted by BSI)



- *Geological engineering*: has much the same meaning as engineering geology, but, as indicated by the order of the words, engineering is more in focus here.
- *Rock mechanics*: covers field measurements, laboratory testing and analytical methods. Calculation and numerical analyses are much in focus.
- *Rock engineering*: includes engineering geology/geological engineering and rock mechanics as well as elements of civil engineering/construction engineering.
- *Soil mechanics*: the experimental and theoretical study of soil behaviour, a parallel to rock mechanics.
- *Geotechnics*: used internationally, it encompasses the theoretical and practical aspects of all planning, design and construction related to soil and rock. (In some countries, including Scandinavia, the term is often used synonymously with soil mechanics.)

This new second edition is a revision of the original book content. Additionally, tables have been made more user-friendly and some figures have been amended.

Figure 1.3 The principal process in identifying ground behaviour and appropriate rock engineering tools to be applied in rock design. The main relevant chapters in this book are indicated



More detailed descriptions of slaking and swelling have been added. The last three chapters dealing with different aspects of rock engineering has been revised and updated with new findings. The section on Eurocode 7 has been completely changed, explaining the application of the Eurocode in a more user-friendly way.

The sections on underground projects and on quality and risk management have been reworked to include the latest developments in this field. Production capacity for tunnel excavations is now included. And new aspects of rock bolting, shotcreting and rock grouting are discussed.

In addition, the new edition contains descriptions of:

- the design principles of three special project types
- the case histories of three different underground projects
- the collection of engineering geological data and how to document predictions of ground conditions in an underground site from observations made at the terrain surface.

Rock Engineering is now a more comprehensive book, covering most areas in the planning and follow-up of rock construction, from field investigations through to rock design and the determination of rock support. The authors hope that the book will be helpful in the daily work of engineering geologists, rock engineers and those with an interest in rock mechanics, as well as for students.

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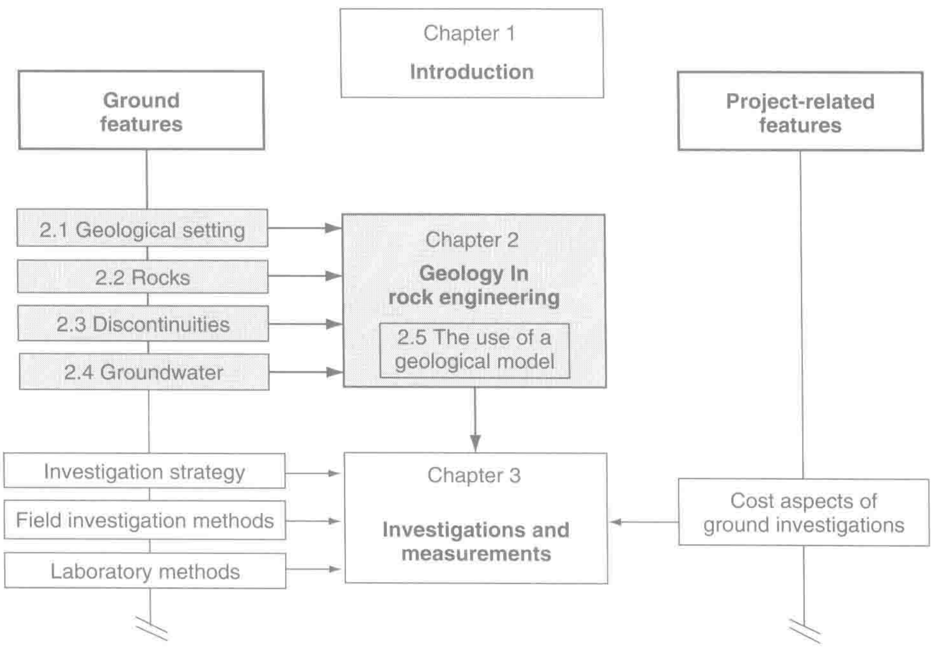
Chapter 2
Geology in rock engineering

Layout of Chapter 2



2.1. Geological setting
2.1.1 Introduction
The geological setting at the actual site is a crucial issue for an excavation in rock. It is a result of the geological history and geomorphological development, and is of particular importance where challenging or difficult ground conditions occur. On the project site, geological structures can result from:

- tectonic forces related to plate movement
- metamorphic action (heat and/or pressure)
- unloading by erosion
- loading by deposition
- cooling of igneous rocks
- drying out of sediments.

Table 2.1 Studies of world and regional geological settings as proposed by Stapledon (1982)

Objectives	Activities
Understand the geology of the region surrounding the project site, in particular: ■ Geological history – past processes and the resulting model ■ Active (or potentially active) processes ■ Locate the main geological features, especially faults. Such features may pass through or near the site, but may not be exposed or evident in the site area	■ Review published and other existing geological data ■ Interpretation of satellite imagery and air photographs ■ Ground geological surveys to fill relevant gaps in the geological picture ■ Prepare plans and sections on scales usually ranging from 1 : 50 000 to 1 : 250 000; these must show the layout of the proposed works

The structures can occur at different scales at different times, depending on the circumstances. As shown in Table 2.1, the geological studies for an excavation in rock should commence with consideration of the site location with respect to global tectonics, and include studies of the geology of a broad region surrounding the site. This should then be followed by studies at intermediate and detailed scales, a principal purpose of which is to ensure that the site geology 'fits' into the regional geological picture.

Much has been written on acquiring geological knowledge of the site. Most publications concerned with site investigations recommend the practice of first making regional and local desk studies, followed by specific investigations of the local geology.

A frequent mistake in rock engineering is to start an investigation with a detailed examination of drill cores. While these cores provide essential information, it is necessary to see this information in the context of the overall geological environment (Hoek and Bray, 1977).

Conventional approaches to a geological desk study for the feasibility and early phases of site evaluation typically use the local maps and literature that commonly exist in many developed areas around the world. In locations where much may be known already – for example, geological maps exist or there are good air photographs or other imagery – the initial local geology can be quite well anticipated by site-specific models prior to any preliminary inspection. The site inspection and preliminary and full ground studies can then be progressed quite quickly at such a location, to give as detailed a picture of the geology as is considered sufficient or necessary.

2.1.2 Tectonics

Tectonics is the scientific study of the deformation of the rocks that make up the Earth's crust and the forces that produce such deformation. It deals with the folding and faulting associated with mountain building; the large-scale, gradual upward and downward movements of the crust; and sudden displacements along faults. Other phenomena studied include igneous processes and metamorphism. Tectonics embraces as its chief working principle the concept of plate tectonics.

2.1.2.1 Plate tectonics

Plate tectonics is the theory dealing with the dynamics of the Earth's outer shell, the lithosphere. It is a unifying theory that explains the deformation and structure of the Earth's near surface. According to the theory, the lithosphere consists of about a dozen large plates and several small ones. These plates move relative to each other and interact at their boundaries, where they diverge, converge or slip past one another. Such interactions are thought to be responsible for most of the seismic and volcanic activity of the Earth, although earthquakes and volcanoes are not wholly absent in plate interiors. While moving about, the plates cause mountains to rise where they push together, and continents to fracture and oceans to form where they pull apart. The continents, sitting passively on the backs of plates, drift with them, and thereby bring about continual changes in the Earth's geography.

Deformation of the continental crust has occurred throughout most of geological time. The large massifs or plates are delineated by the Earth's major earthquake zones. The movements of the plates are thought to be driven by thermal convection in the upper mantle as well as by the gravitational pull of the cold, dense parts of plates descending into the mantle. Plates move apart at ocean ridges, or divergent plate margins, and towards one another along magmatic (island) arcs or orogenic belts at convergent plate margins. An important role in plate tectonic theory is played by ocean ridges, which are approximately linear zones of extensional faulting or rifting, characterised by basaltic volcanism.

Plate collisions are the main cause of orogenic episodes. Collisions may involve either two lithosphere plates, or varying combinations of continents or micro-continents. Orogenic belts appear to be made up of collages of diverse terranes (groups of rocks with similar history) jammed together by successive collisions. The collision of two or more continents forms a supercontinent. Plate margins can exhibit the following features:

- *Subduction*: the process of underthrusting one lithosphere plate beneath another at a convergent margin. Much ocean floor is lost by subduction.
- *Magmatic arcs*: dominated by andesite eruptions that form at the surface above subduction zones. Once a plate breaks down and begins to subduct, gravity helps to pull it downwards into the mantle, where it is slowly heated and assimilated.
- *Obduction*: the process of the overthrusting of one plate over another at a convergent margin.
- *Passive continental margins*: where the edge of a continent is not on a tectonically active convergent margin but moves with the adjacent oceanic crust, to which it is welded.
- *Subsidence associated with plates*: important, as it provides room for the accumulation of thick strata in sedimentary basins of various types during periods of tens to hundreds of millions of years.

A typical orogenic episode is preceded by the subsidence of marginal troughs in which sediments accumulate; plate convergence then initiates deformation in a belt that extends hundreds of kilometres from the original troughs. The converging plates causes deformation of marginal sediments by folding or faulting; thrust sheets 10–20 km thick slide over one another, often for distances of tens to hundreds of kilometres. Intrusions of large volumes of igneous rocks (batholiths) and metamorphism typically occur with the orogeny. Mountains are raised in a deformed belt, and erode after the orogeny ends. Renewed stages of uplift, or block faulting, that again raise the region account for many of the large-scale topographic features we see today (Figure 2.1).

The continuous formation of new crust produces an excess that must be disposed of elsewhere. This is accomplished at convergent plate boundaries where one plate descends (i.e. is subducted) beneath the other (Figure 2.2). At depths between 300 and 700 km, the subducted plate melts and is recycled into the mantle, which rises to the surface and gives birth to a line of volcanoes.

2.1.2.2 Faulting and folding

Faults are typically larger structures commonly formed by shear, where significant movements have taken place in the plane of the fault. Fault movement ranges from up to a few centimetres on shallow faults to tens or hundreds of kilometres on faults extending to the base of the lithosphere.

Faults may be vertical, horizontal or inclined at any angle. Although the angle of inclination of a specific fault plane tends to be relatively uniform, it may differ considerably along its length from place to place. When rocks slip past each other in faulting, the upper or overlying block along the fault plane is called the hanging wall, or headwall; the block below is called the footwall.

Faults are classified according to their angle of dip and to the direction of slip of the adjacent blocks: for example, a dip–slip fault or a strike–slip fault (Figure 2.3). Normal dip–slip faults are produced as the Earth's crust lengthens. The hanging wall slides down relative to the footwall. Normal faults are common: they bound many of the mountain ranges of the world and many of the rift valleys found along spreading margins of tectonic plates. Rift valleys are formed by the sliding of the hanging walls downward hundreds to thousands of metres, where they then become the valley floors.

A block that has dropped downwards between two normal faults dipping towards each other is called a *graben*. A block that has been uplifted between two normal faults that dip away from each other is called a *horst*.

Reverse dip–slip faults result from horizontal compression forces caused by a shortening, or contraction, of the Earth's crust. The hanging wall moves up and over the footwall. Thrust faults are reverse faults that dip less than 45°. Thrust faults with a very low angle of dip and a very large total displacement are called overthrusts or detachments; these are often found in intensely deformed mountain belts. Large thrust faults are characteristic of compressive tectonic plate boundaries, such as those that have created the Himalayas and the subduction zones along the west coast of South America (see Figures 2.1 and 2.2).

Strike–slip faults are similarly caused by horizontal compression, but they release their energy by rock displacement in a horizontal direction almost parallel to the compression

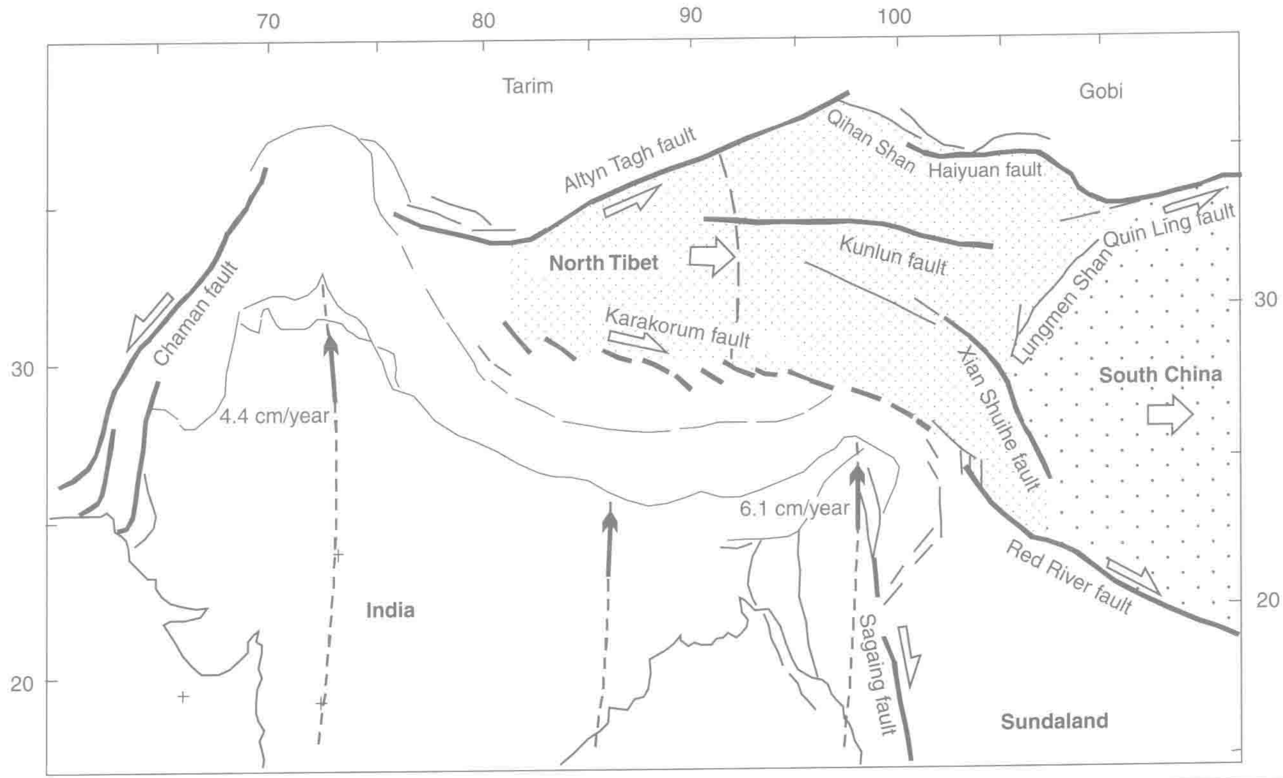


Figure 2.1 Map showing the kinematics of the India–Asia collision. Northern Tibet is extruded eastwards along the Karakorum and Altyn Tagh faults (open arrow). South China is also extruded eastwards along the Qin Ling and Red River faults (open arrow). Black arrows directed north indicate the present motion of India relative to a stable Asia. (Reproduced, with permission, from Armijo *et al.*, 1989. © American Geophysical Union)