Ground Engineer's Reference Book

F G Bell

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Preface

The idea of a reference book for ground engineers was suggested to me by Don Goodsell, a former commissioning editor for Butterworth Scientific Ltd. He also suggested that such a book should have a very wide appeal and that this, no doubt, could be achieved by recruiting authors from around the world. At that time this concept captured my imagination; in fact I was rather displeased that I had not thought of this myself. However, like many good ideas, implementation of the project proved to be a very different matter. It must be recorded that the production of this tome has caused me both headaches and heartaches, anguish and despair, and has consumed an extraordinary amount of time and effort these past four years. Indeed it has been a major cause of my premature ageing. Yet, with typical magnanimity, I still regard Don as a good friend. Nor can I complain, since I was warned on several occasions by a friend and colleague (T.H.H.) of the difficulties that would be involved (and the friend grossly underestimated!). And so it was with typical British spirit (i.e. complete ignorance and total unpreparedness) that I embarked upon my task.

Now to more serious matters! The book itself sets out to provide a concise general coverage of those aspects of engineering which are involved with the ground. As such, it is obviously aimed at those practising engineers who seek their living by toiling on or in the ground. The book is divided into five parts. The first part considers the properties and behaviour of ground materials. The second outlines the various means by which the ground is investigated. Some ground has to be improved before it can be developed, hence this represents the subject matter of the third part. Then part four deals with construction on or in the ground. Finally, the last part covers numerical methods and modelling as related to ground engineering. Like every subject, ground engineering has made great advances in recent years. It is hoped that most of these, if not all, have been incorporated somewhere in this text.

As with all reference books, this volume does not pretend to be a complete and exhaustive compilation of the subject matter it deals with. It is not meant to act as a replacement for other sources of material. Hence it does not seek to supplant tried and trusty textbooks, codes and standards of practice, or papers in learned journals. Nonetheless it is hoped that, first, it will become one of the first books that the engineer will take from his shelves when he needs guidance with a particular problem in ground engineering and, secondly, that it will represent a quick and useful means of refreshing his memory. The book provides a general source of basic knowledge, although the individual chapters have been written by specialists in the particular subject concerned. Accordingly a comprehensive number of references are provided for the reader to gain further detail regarding the particular topic of interest. The original aim was that the book should have a practical bias so as to appeal to practising engineers, but that at the same time the fundamental theory should not be neglected. The readers, of course, will be the judges of whether or not this aim has been achieved.

In producing this reference book, I have received much help and advice. In particular, a great debt is owed to the late Professor W. F. Cassie, C.B.E. Bill was one of those men who always gave of his time willingly, whose advice was always constructive and therefore much valued and appreciated, and who always encouraged and praised one's efforts. It was he who gave this book its structure, among other things. He is sorely missed! Others who deserve mention include Professor D. Brunsden, Professor S. Budavari, Professor I. W. Farmer, Dr J. R. Hall, Professor T. H. Hanna, Professor B. O. Hardin, Professor H. L. Jessberger, Professor W. R. Judd, Professor G. S. Littlejohn, Dr E. J. Klohn, Professor R. Mark, Dr A. C. Meigh, O.B.E., Professor A. Myslivec, Dr J. W. Norman, Professor D. G. Price, Dr F. J. Sanger and Professor Christian Veder.

Thanks also must be accorded to those authors who have taken part in this enterprise. At this point special mention must be made of the late Professor Arpád Kézdi. His chapter was the last written contribution which that giant in geotechnical engineering made. We are truly honoured. Indeed it has been my privilege to work with so many notables in the field of ground engineering.

Fred G. Bell
Blyth, Notts.
1986.

Obituary: Professor Dr Arpád Kézdi

While this book was being prepared, an outstanding author died on 20 October 1983: Professor Dr Arpád Kézdi, an internationally respected representative of Hungarian technical science, and a highly regarded European, in the true sense of the word.

Professor Kézdi was born in Komarom, Hungary, on 19 November 1919 and studied civil engineering at the Technical University of Budapest. His teacher of soil mechanics, Professor Jaky, aroused his interest in this relatively new technical science. In 1942 he obtained his diploma and in 1958 his doctorate. When Professor Jaky died in 1950, A. Kézdi became a university teacher at the Institute for Soil Mechanics and Foundation Engineering, together with Professor Dr K. Szechy. In 1961 he was appointed full Professor for soil mechanics.

His international reputation was secured with the book *Erddrucktheorien* (Earth-pressure theories), published in Germany in 1962. His predominent research interests were soil physics, bearing capacity of foundations, settlements, stress distribution, piles, etc. Besides these specialized topics he was not only well-versed in the whole field of soil mechanics, but was also experienced in practical foundation engineering due to his activities as a consultant in Hungary and abroad.

His tireless activity and creativity resulted in 44 books and more than 150 other scientific publications – his major work being the four-volume *Handbook of Soil Mechanics*, which has been translated into German, English, Spanish and Russian. In addition he presented lectures in many cities of the world. In appreciation of his scientific activity, honorary doctorates were bestowed upon him by the Technical University of Dresden and the Polytechnic of Agriculture in Vienna.

Professor Kézdi played an important role in the international soil mechanics community. He was one of the main initiators of the Danube-European Conferences and was Vice-President for Europe of ISSMFE during the period 1973–1977. Having been fluent in several languages and coming from a central European country, he always emphasized the community of European history and culture, bringing together east and west.

As a lover of the fine arts, he found relaxation in literature and music. Participants of (Danube-) European Conferences would certainly remember him reciting poems and singing several *lieder*. His Hungarian and Austrian colleagues and his numerous friends in the International Society of Soil Mechanics and Foundation Engineering will long benefit from his life work and will retain his memory with reverence.

H. Brandl, N. Rohla
Vienna

List of Contributors

N N Ambraseys
Department of Civil Engineering, Imperial College, London, UK

O B Andersland
Department of Civil Engineering, Michigan State University, East Lansing, Michigan, USA

D Atherton
Golder Associates, Maidenhead, UK

J H Atkinson
Department of Civil Engineering, The City University, London, UK

N Barton
Norwegian Geotechnical Institute, Oslo, Norway

M Bastick
Research Department, Terre Armée Internationale, Paris, France

T E Beaumont
Scott Wilson Kirkpatrick & Partners, Basingstoke, UK

E E De Beer
Formerly of the Belgian Geotechnical Institute and the University of Ghent, Belgium

H J van den Berg
Delft Geotechnics, Delft, The Netherlands

H Brandl
Institute for Soil Mechanics and Foundation Engineering, Geology and Rock Mechanics, Technical University of Vienna, Austria

V Brown
Department of Civil Engineering, University of Surrey, Guildford, UK

H Cambefort
L'Ecole des Travaux Publics, Paris, France

H R Cedergren
Consultant Civil Engineer, Sacramento, California, USA

J Charrua Graça
Laboratorio Nacional de Engenharia Civil, Lisbon, Portugal

R N Chowdhury
Department of Civil and Mining Engineering, University of Wollongong, New South Wales, Australia

J T Christian
Stone & Webster Engineering Corp., Boston, Massachusetts, USA

D R Coates
Department of Geological Sciences, State University of New York, Binghampton, New York, USA

B O Corbett
Department of Civil Engineering, Brighton Polytechnic, Brighton, UK

D E Daniel
Department of Civil Engineering, University of Texas, Austin, Texas, USA

W R Dearman
Department of Geotechnical Engineering, University of Newcastle upon Tyne, Newcastle upon Tyne, UK

A Drescher
Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis, Minnesota, USA

M J Dumbleton
Formerly of Transport and Road Research Laboratory, Crowthorne, Berkshire, UK

C Fairhurst
Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis, Minnesota, USA

M P Gambin
Soletanche-Entreprise, Nanterre, France

R E Goodman
Department of Civil Engineering, University of California, Berkeley, California, USA

D H Griffiths
Department of Geological Sciences, University of Birmingham, UK

S C Haley
Woodward-Clyde Consultants, San Diego, California, USA

A M Hanna
Department of Civil Engineering, Concordia University, Montreal, Quebec, Canada

T H Hanna
Department of Civil and Structural Engineering, University of Sheffield, UK

W L van Heerden
Council for Scientific and Industrial Research, Pretoria, Republic of South Africa

D Hoare
Department of Civil Engineering, University of Birmingham, UK

K Höeg
Norwegian Geotechnical Institute, Tasen, Oslo, Norway

O G Ingles
School of Civil Engineering, University of New South Wales, Sydney, Australia

H L Jessberger
Department of Civil Engineering, Ruhr University, Bochum, Federal Republic of Germany

T J M Kennie
Department of Civil Engineering, University of Surrey, Guildford, UK

Arpad Kézdi
Formerly of Department of Civil Engineering, University of Budapest, Budapest, Hungary

J Kerisel
Formerly of L'Ecole Nationale des Ponts et Chaussées, Paris, France

R F King
Department of Geological Sciences, University of Birmingham, UK

C J Kirkland
Sir William Halcrow & Partners, London, UK

F H Kulhawy
Department of Civil Engineering, Cornell University, Ithaca, New York, USA

H G Locher
Losinger Ltd, Berne, Switzerland

Shashi Mathur
Department of Engineering, The University of Delaware, USA

P Matt
VSL International Ltd, Berne, Switzerland

A C Meigh
Woodward-Clyde Consultants, West Woodhay, Berkshire, UK

V F B de Mello
Consultant, São Paulo, Brazil

C W Mitchell
Consultant, Bracknell, UK

Sir Alan Muir Wood
Sir William Halcrow & Partners, London, UK

R Oliveira
Laboratoria Nacional de Engenharia Civil, Lisbon, Portugal

A W Parsons
Transport and Road Research Laboratory, Crowthorne, Berkshire, UK

H G Poulos
Department of Civil Engineering, University of Sydney, Sydney, Australia

L R Richards
Principal, Golder Associates, Maidenhead, UK

R Richards Jr
Department of Civil Engineering, State University of New York, Buffalo, New York, USA

F E Richart Jr
Department of Civil Engineering, The University of Michigan, Ann Arbor, Michigan, USA

F Schlosser
Ecole Nationale des Ponts et Chaussées, Paris, France

W L Schroeder
Department of Civil Engineering, Oregon State University, Corvallis, Oregon, USA

A P S Selvadurai
Department of Civil Engineering, Carleton University, Ottawa, Ontario, Canada

P D Shelton
British Coal, Mining Research & Development Establishment, Bretby, Staffordshire, UK

N E Simons
Department of Civil Engineering, University of Surrey, Guildford, UK

B O Skipp
Soil Mechanics Ltd, Bracknell, UK

U Smoltczyk
Department of Soil Mechanics and Foundation Engineering, Stuttgart University, Federal Republic of Germany

T R Stacey
Steffen, Robertson and Kirsten, Johannesburg, Republic of South Africa

R N Taylor
Department of Civil Engineering, City University, London, UK

U V Vogler
Council for Scientific and Industrial Research, Pretoria, Republic of South Africa

R J M De Wiest
The Florida A & M University and The Florida State University, Florida, USA

R D Woods
Department of Civil Engineering, The University of Michigan, Ann Arbor, Michigan, USA

Q Zaruba
Formerly of the Department of Geology, Technical University of Prague, Prague, Czechoslovakia

L Zeevaert
Graduate School of Engineering, Faculty of Engineering, UNAM, Mexico City, Mexico

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1 Geological Considerations

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1.1 Igneous rocks

Rocks are divided according to their origin into three groups, namely, igneous rock, metamorphic rock and sedimentary rock. Igneous rocks are formed when hot molten rock material, called magma, solidifies. Magmas are developed either within or beneath the Earth's crust, that is, in the uppermost region of the mantle. They comprise hot solutions of several liquid phases, the most conspicuous of which is a complex silicate phase. Hence silicate minerals are quantitatively the most important constituents of igneous rocks (*Figure 1.1*). Because silica is the most important constituent in igneous rock it has been used to distinguish the following groups

(1) Acid igneous rocks, over 65%;
(2) Intermediate igneous rocks, 55–65%;
(3) Basic igneous rocks, 45–55%;
(4) Ultrabasic igneous rocks, less than 45%.

The terms tend to be associated with various groups of igneous rock, acid with granitic-rhyolitic rock; intermediate with dioritic-andesitic rock; basic with gabbroic-basaltic rock; and ultrabasic with rocks such as peridotite.

However, it would appear that most granitic igneous rocks are developed by either granitization or anatexis. Granitization has been defined as the process by which solid rocks are converted to rocks of granitic character without passing through a magmatic stage. Anatectic processes, which lead to the melting of rocks, are not included within granitization. Rocks formed from remelted material have a mixed or hybrid appearance and have been referred to as migmatites.

The most important rock-forming minerals are often referred to as felsic and mafic depending on whether they are light or dark in colour, respectively. Felsic minerals include quartz, muscovite mica, feldspars and feldspathoids, whilst olivines, pyroxenes, amphiboles and biotite mica are mafic minerals.

Usually, acidic igneous rocks are light in colour whereas basic igneous rocks are dark in colour.

An igneous rock may be composed of an aggregate of crystals, of natural glass, or of crystals and glass in varying proportions. Igneous rocks may be divided into intrusive and extrusive types according to their mode of occurrence. In the former the magma crystallizes within the Earth's crust, whereas in the latter it solidifies at the surface, having been erupted as lavas and/or pyroclasts from a volcano. The intrusions may be further subdivided by size into major and minor categories. The former are developed in a plutonic, the latter in a hypabyssal environment.

1.1.1 Intrusions

The most important major intrusion is the batholith. Batholiths are very large in size and are generally composed of granitic or granodioritic rock. They are associated with orogenic regions. Some batholiths would appear to have no visible base and have well-defined contacts which dip steeply outwards. Bosses and stocks probably represent upward extensions from deep seated batholiths. Their surface exposures are of limited size, frequently less than 100 km^2.

Dykes and sills are the commonest minor intrusions. The former are discordant, that is, they traverse the host rocks at an angle and are steeply dipping (*Figure 1.2*). As a consequence their surface outcrop is hardly affected by topography and commonly they strike in a straight line. Dykes range in width up to several tens of metres and their length of surface outcrop also varies; dykes have been traced at the surface for distances exceeding 200 km. Dykes often occur along faults, which provide a natural path of escape for the intruded magma. Most dykes are of basaltic composition. However, dykes may be multiple or composite. Multiple dykes are formed by two or more injections of the same material which occur at different times so that the different phases are distinctly discernible. A composite dyke involves two or more injections of magma of different composition.

Sills, like dykes, are comparatively thin, parallel-sided igneous intrusions which frequently occur over relatively extensive areas. Their thickness varies up to several hundred metres. However, unlike dykes, they are injected in an approximately horizontal direction, although their attitude may be subsequently altered by folding. When sills form in a series of sedimentary rocks the magma is intruded along bedding planes (*Figure 1.3*). Nevertheless, an individual sill may transgress upwards from one horizon to another. Because sills are intruded along bedding planes, they are described as concordant and their outcrop is similar to that of the country rocks. Sills may be fed from dykes and small dykes may arise from sills. Most sills are composed of basic igneous material. Like dykes, they may be multiple or composite in character.

1.1.2 Volcanic activity

Eruptions from volcanoes are spasmodic rather than continuous. Between eruptions activity may still be witnessed in the form of steam and vapours issuing from small vents named fumaroles or solfataras. But in some volcanoes even this form of surface manifestation ceases and such a dormant state may continue for centuries. To all intents and purposes these volcanoes appear extinct. In old age the activity of a volcano becomes limited to emissions of gases from fumaroles and hot water from geysers and hot springs.

Most material emitted by volcanoes is of basaltic composition. Lavas are extravasated from volcanoes at temperatures only slightly above their freezing point. During the course of their flow the temperature falls outwards from within until solidification occurs somewhere between 600 and 900°C, depending upon their chemical composition and gas content. Basic lavas solidify at a higher temperature than do acidic ones.

The rate of flow of a lava is determined by the gradient of the slope down which it moves and by its viscosity which, in turn, is governed by its composition, temperature and volatile content. The higher the silica content of a lava, the greater is its viscosity. Hence basic lavas tend to flow much faster and further than do

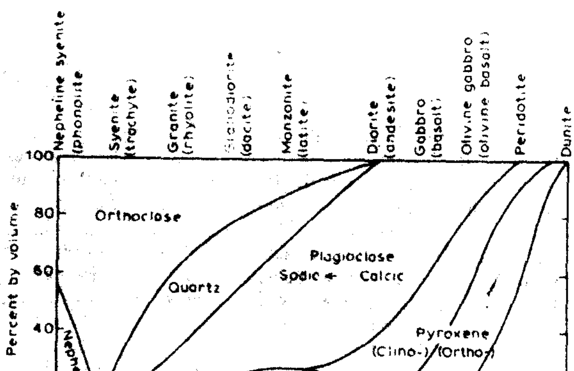

Figure 1.1 Approximate mineralogical composition of the commoner types of igneous rocks (plutonic types without brackets; volcanic equivalents in brackets)

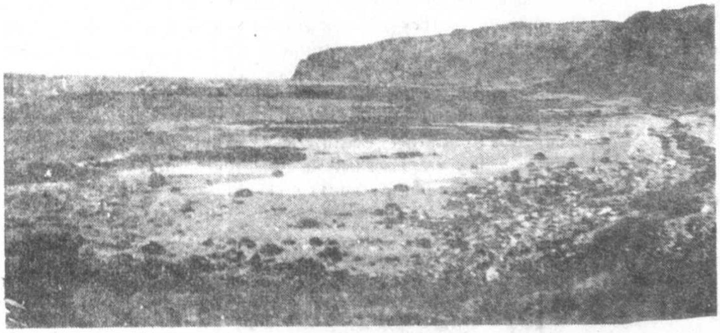

Figure 1.2 Basalt dykes on the south shore of the Isle of Arran

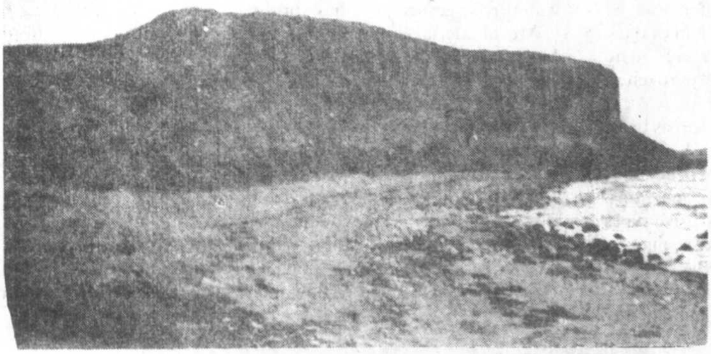

Figure 1.3 Composite sill (basalt and quartz porphyry) at Drumadoon Point, Isle of Arran

acidic lavas. Indeed the former have been known to travel at rates of up to 80 km/h.

The surface of a lava solidifies before the main body of the flow beneath. If this surface crust cracks before the lava has completely solidified, then the fluid lava below may ooze up through the crack to form a squeeze-up. Pressure ridges are built on the surface of lava flows where the solidified crustal zone is pushed into a linear fold. Tumuli are upheavals of dome-like shape whose formation may be aided by a localized increase in hydrostatic pressure in the fluid lava beneath the crust. Pipes, vesicle trains or spiracles may be developed in a lava flow depending on the amount of gas given off.

Thin lava flows are interrupted by joints which may either run at right angles or parallel to the direction of flow. Joints do occur with other orientations but they are much less common. Those joints which are normal to the surface usually display a polygonal arrangement but only rarely do they give rise to columnar jointing. The joints develop as the lava cools. First primary joints form, from which secondary joints arise and so it continues.

Typical columnar jointing is developed in thick flows of basalt (*Figure 1.4*). The columns in columnar jointing are interrupted by cross joints which may be either flat or saucer-shaped. The latter may be convex up or down. These are not to be confused with platey joints which are developed in lava flows as they become more viscous on cooling so that slight shearing occurs along flow planes.

When a magma is erupted it separates at low pressures into lava and a gaseous phase. If the magma is viscous, then separation is accompanied by explosive activity. On the other hand, volatiles escape quietly from very fluid magmas.

Steam may account for 90% or more of the gases emitted during a volcanic eruption. Other gases present include carbon dioxide, carbon monoxide, sulphur dioxide, sulphur trioxide, hydrogen sulphide, hydrogen chloride and hydrogen fluoride.

The amount of and rate at which gas escapes determine the explosiveness of an eruption, an explosive eruption occurring when, because of its high viscosity, magma cannot readily allow the escape of gas. The term pyroclast is collectively applied to material which has been fragmented by explosive volcanic

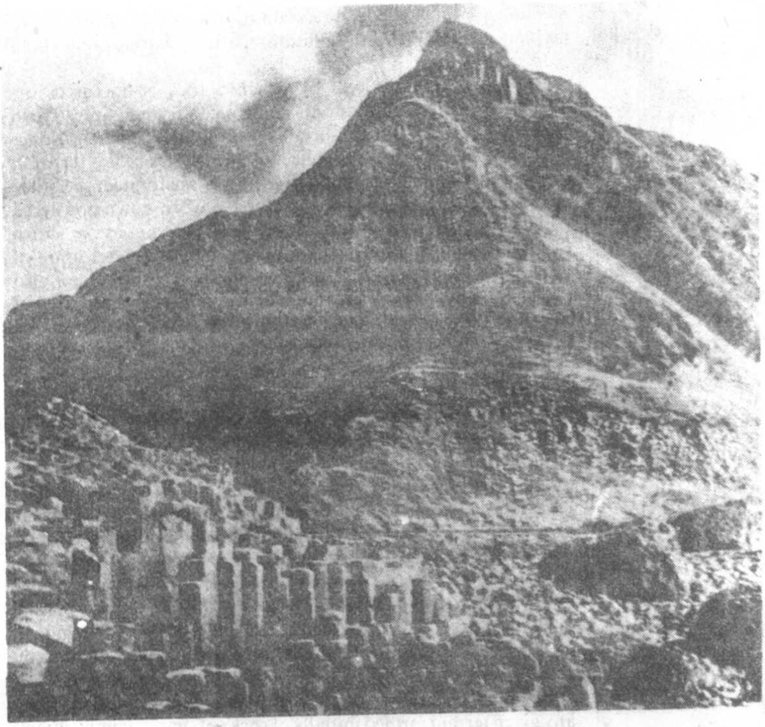

Figure 1.4 Columnar jointing in basalt lava flows of the Giants' Causeway, Northern Ireland (courtesy of the Northern Ireland Tourist Board)

action. Pyroclasts may consist of fragments of lava exploded on eruption, of fragments of pre-existing solidified lava or pyroclasts, or of fragments of country rock.

The size of pyroclasts varies enormously. It is dependent upon the viscosity of the magma, the violence of the explosive activity, the amount of gas coming out of solution during the flight of the pyroclast, and the height to which it is thrown. The largest blocks thrown into the air may weigh over 100 tonnes whereas the smallest consist of very fine ash which may take years to fall back to the Earth's surface. The largest pyroclasts are referred to as volcanic bombs. Lapilli is applied to pyroclastic material which has a diameter varying from about 10–50 mm. The finest pyroclastic material is called ash. Rocks which consist of fragments of volcanic ejectamenta set in a fine grained groundmass are termed agglomerate or volcanic breccia, depending upon whether their fragments are rounded or angular respectively.

After pyroclastic material has fallen back to the surface it eventually becomes indurated. It is then described as tuff. According to the material of which tuff is composed, distinction can be made between ash tuff, pumiceous tuff and tuff breccia. Tuffs are usually well-bedded and the deposits of individual eruptions may be separated by thin bands of fossil soil or old erosion surfaces. Mudflows are frequently interbedded with tuffs, having formed when downpours of rain, associated with eruption, mixed with ash.

When clouds of intensely heated incandescent lava spray fall to the ground, they weld together. Because the particles become intimately fused, they attain a largely pseudo-viscous state, especially in the deeper parts of the deposits. The term ignimbrite has been used to describe the resultant rock. If ignimbrites develop on a steep slope, then they begin to flow. Hence they frequently resemble lava flows.

1.2 Metamorphic rocks

Metamorphic rocks are derived from pre-existing rock types and have undergone mineralogical, textural and structural changes. The latter have been brought about by changes which have taken place in the physical and chemical environments in which the rocks existed. The processes responsible for change give rise to progressive transformation which occurs in the solid state. The changing conditions of temperature and/or pressure are the primary agents causing metamorphic reactions in rocks. Individual minerals are stable over limited temperature-pressure conditions which means that when these limits are exceeded mineralogical adjustment has to be made to establish equilibrium with the new environment. When metamorphism occurs there is usually little alteration in the bulk chemical composition of the rocks involved, that is, with the exception of water, volatile constituents and organic matter, little material is lost or gained.

1.2.1 Types of metamorphism

Thermal metamorphism occurs around igneous intrusions so that the principle factor controlling these reactions is temperature, shearing stress being of negligible importance. The rate at which chemical reactions take place during thermal metamorphism is exceedingly slow and depends upon the rock type and temperatures involved. It has been estimated that the reaction rate doubles for a rise of 10°C, whilst a rise of 100°C may increase the rate by a thousand-fold and 200°C by a million-fold. Equilibrium in metamorphic rocks, therefore, is attained more readily at a higher grade than at a lower grade because reaction proceeds more rapidly.

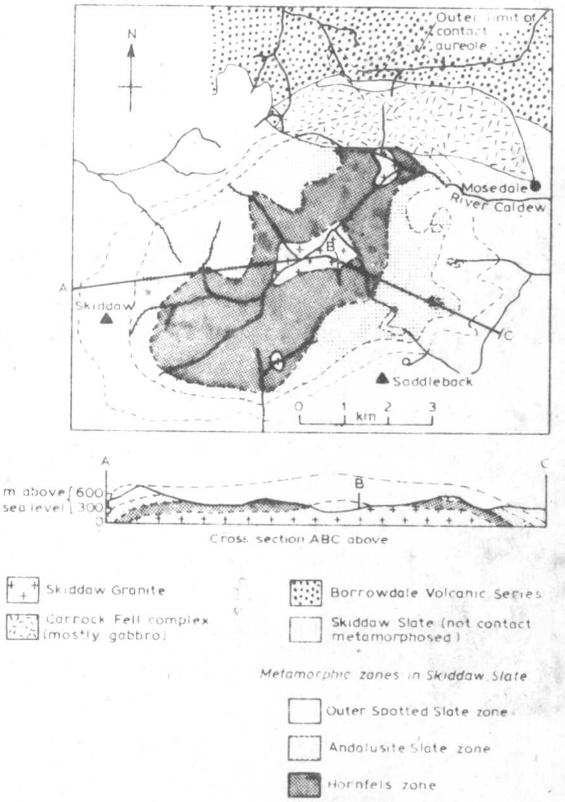

Figure 1.5 Geological sketch map of the Skiddaw granite and its contact aureole (after Eastwood, T., Hollingworth, S. E., Rose, W. C. C. and Trotter, F. M., 'Geology of the country around Cockermouth and Caldbeck', *Mem. Inst. Geol. Sci.*, HMSO, London (1968))

As remarked above, thermal metamorphism is associated with igneous intrusions and the encircling zone of metamorphic rocks is referred to as the contact aureole (*Figure 1.5*). The size of the aureole depends upon the temperature and size of the intrusion, the quantity of volatiles which emanated from it and the types of country rocks involved. For example, aureoles developed in argillaceous sediments are more extensive than those found in arenaceous or calcareous rocks. Nevertheless, the capricious nature of thermal metamorphism must be emphasized, for even within one formation of the same rock type the width of the aureole may vary.

Within a contact aureole there is a sequence of mineralogical changes from the country rocks to the intrusion, which have been brought about by the effects of a decreasing thermal gradient whose source was in the hot magma. Indeed aureoles developed in argillaceous sediments may be concentrically zoned with respect to the intrusion. A frequently developed sequence varies from spotted slates to schists then hornfels.

Dynamic metamorphism, like contact metamorphism, is usually highly localized: for example, its effects may be found in association with large faults or thrusts. On a larger scale it is associated with folding, however, in such instances it is difficult to distinguish between the effects of dynamic metamorphism and those of low-grade regional metamorphism. What can be said is that at low temperatures recrystallization is at a minimum and the character of a rock is governed by the mechanical processes which have been operative. The processes of dynamic metamorphism include brecciation, cataclasis, granulation, mylonitization, pressure solution, partial melting and slight recrystallization.

Brecciation is a process by which a rock is fractured, the angular fragments produced being of varying size. Crush breccias commonly are associated with faulting and thrusting. The fragments of a crush breccia may themselves be fractured. If, during the process of fragmentation, pieces are rotated, then they are eventually rounded and embedded in worn-down powdered material. The resultant rock is referred to as a crush conglomerate. Mylonites are produced by the pulverization of rocks, which not only involves extreme shearing stress but also considerable confining pressure. In the most extreme cases of dynamic metamorphism the resultant crushed material may be fused to produce a vitrified rock referred to as a pseudotachylite.

Metamorphic rocks outcropping over hundreds or thousands of square kilometres are found in the pre-Cambrian shields and the eroded roots of fold mountains. As a consequence the term regional has been applied to this type of metamorphism. Regional metamorphism involves both the processes of changing temperature and stress. The principal factor is temperature, of which the maximum figure concerned in regional metamorphism is probably around 800°C. Regional metamorphism can be regarded as taking place when the confining pressures are in excess of three kilobars, whilst below that figure, certainly below two kilobars, falls within the field of contact metamorphism. What is more, temperatures and pressures conducive to regional metamorphism have probably been maintained over millions of years.

Regional metamorphism is a progressive process, that is, in any given terrain formed initially of rocks of similar composition, zones of increasing grade may be defined by different mineral assemblages. Slates are the product of low-grade regional metamorphism of argillaceous sediments. As the grade of metamorphism increases slates give way to phyllites which, in turn, are replaced by schists. Gneisses are characteristic of high-grade metamorphism. When sandstones are subjected to regional metamorphism quartzites, schists or granulite may form depending on the original composition of the sandstone and grade of metamorphism. Marbles, of various types, are produced when carbonate rocks are metamorphosed. Schists, gneisses and granulites may be developed from igneous rocks.

1.2.2 Metamorphic textures and structures

Most deformed metamorphic rocks possess some kind of preferred orientation. Preferred orientations are commonly exhibited as megascopic linear or planar structures which allow the rocks to split more easily in one direction than others. One of the most familiar examples is cleavage in slate and phyllites, a similar type of structure in metamorphic rocks of higher grade is schistosity. Cleavage is independent of any original bedding, which it normally intersects at high angles. Where cleavage is developed in a series of beds of different lithologies, its attitude changes as it passes from one bed to another. Cleavage planes do not intersect although they may meet or branch. They are always roughly parallel to each other. Frequently cleavage forms parallel to the axial planes of folds, having developed perpendicular to the direction of maximum principal stress. In other words, recrystallization of minerals of platey habit has occurred in the plane of least stress. Micro-shearing along individual cleavage planes or in narrow zones, together with elongation of parts of the rock mass in the direction of the cleavage, are often present in slates.

Schistosity has been assumed to be developed in a rock when it was subjected to increased temperature and stress which involved its reconstitution, which was brought about by localized solution of mineral material and recrystallization.