PETROLOGY OF THE METAMORPHIC ROCKS

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Foreword

With the appearance of *Petrology of the metamorphic rocks* a long-standing wish of mine has been satisfied, namely the publication of a book on metamorphic rocks designed primarily for non-specialist students interested in the Earth sciences, and which would in this way form a companion to the existing books concerned with igneous and sedimentary rocks.

Individual authors necessarily approach their subjects differently not only because of their varied interests but also because of major differences in subject matter. Igneous rocks of a volcanic nature can actually be observed in the making, albeit from a respectful distance, so it has been natural that in studying igneous rocks attention has been directed very much to laboratory investigations into the crystallisation of minerals from silicate melts. Similarly, with sedimentary rocks it is generally possible to gain critical insight into their origins by observing present conditions of sedimentation and by exploration of the oceans. Metamorphic processes, however, can never be observed directly. They are largely, therefore, matters of inference from evidence provided by the rocks themselves, backed by the accumulated evidence of field studies which may be regarded as case histories relating to given sets of geological conditions and events. Since both the nature of the rocks prior to metamorphism, and the conditions to which they are subjected, vary very widely, it is impossible to do justice to all in one book, and certainly in one of an introductory nature. This is perhaps the main justification for emphasis in the present case on selected topics which have proved of special interest to the Author in his teaching and research experience.

Certainly from my own experience there are few pursuits more exciting and rewarding than studying crystalline rocks, ideally in the field in the first instance, and then petrographically, in order to determine their nature and to interpret their histories. Fortunately this is an experience in which anyone can share who is prepared to gain acquaintance with the minerals concerned and to learn the basic rules of petrographic interpretation.

Although a mainly petrographic approach has thus been adopted for this book – as for its igneous and sedimentary companions – other considerations vital to an understanding of metamorphic rocks are not neglected. Improvements in experimental techniques have allowed minerals stable in metamorphic rocks to be investigated with an intensity and degree of precision previously reserved for those of volcanic rocks. Great strides have also been made in mineral analysis with instruments like the electron microprobe, to which the reader is introduced. Finally, the study of trace-element distribution, particularly of radiogenic isotopes, has provided students of crystalline rocks with tools which no modern Earth scientist can afford to neglect: they can reveal evidence of ultimate origins of rock materials from the crust or mantle, and of the timing and rates of geological processes.

We are finding increasingly that rocks can retain remarkably complete memories of the conditions and events which have affected them. The starting point in releasing these memories is careful examination of the rocks in the field, with a lens or a microscope. It is here that the reader will hopefully find this book of value.

M. K. Wells

Preface

The writing of this book has been urged upon me by teaching colleagues in universities and polytechnics, by the publishers and not least by my students. There is no textbook more recent than A. Harker's classic work (which is nearly half a century old) which treats metamorphic rocks on their own from a petrographic rather than a petrogenetic viewpoint. There is also a need for a book above the introductory level, but comprehensible by geology students who are not petrology specialists. Such students are often alarmed by the physical chemistry involved in the theory of metamorphic petrogenesis, and come to regard metamorphic rocks as peculiarly complex and difficult to understand. I hope I can help to enlighten them.

This book has evolved from a course of lectures given to second-year students in a three-year honours B.Sc. course in geology. The method adopted is to illustrate general principles from the evidence presented by selected suites of metamorphic rocks, particularly when studied under the petrological microscope. This inevitably means that some subjects are treated in greater depth than others, and some have probably received too little attention. It also means that general principles are expounded in a rather haphazard order throughout the text. Therefore to help the reader a glossary of definitions of the terms used in the book is provided. Terms in the glossary are indicated in **bold type** when they first appear and also subsequently where the context suggests that the reader might wish to refresh his memory of the definition.

My theme throughout is the recognition of assemblages of minerals coexisting in equilibrium during metamorphism. The substance of the book is in Part II where I try to illustrate the criteria for recognising such assemblages in a series of examples. I also discuss briefly the way in which estimates of temperature, pressure and activity of volatile phases during metamorphism may be derived from the study of mineral assemblages. I have given less prominence than some textbooks to the definition of a scheme of metamorphic facies as a way of interpreting mineral assemblages, believing that in doing so I am following the tendency among metamorphic petrologists today. I have been more concerned to show how ideas on metamorphic petrogenesis are founded in the study of the rocks themselves than to give a comprehensive account of those ideas. I hope I have thereby provided the reader with a sound basis for further exploration of this fascinating and rapidly advancing branch of the Earth sciences.

A large number of people have helped me during the preparation and writing of this book. I must especially thank the following, who supplied me with rocks to describe, and improved my understanding of branches of the subject of which I was ignorant: Dr S. O. Agrell, Dr R. Hall, Dr B. Harte, Professor R. A. Howie, Dr R. M. F. Preston, Dr S. M. F. Sheppard, Dr J. D. Smewing, Dr C. Taylor, Dr J. H. Milledge and Dr M. K. Wells. If I have misinterpreted what they told me, the fault is mine, not theirs. My views on metamorphism have been strongly influenced by my having read Professor A. Miyashiro's book on metamorphism before its publication, and corresponded with him about it. Dr S. W. Richardson, Professor Janet Watson and Dr R. Vernon have read the manuscript, correcting numerous errors and suggesting many improvements. I would like to thank Dr P. W. Edmondson for help in preparing the index, and my wife Joy for her help and support throughout the writing of this book. Finally, I must thank Roger Jones of George Allen & Unwin, without whose tactful and patient persuasion I would never have completed this work.

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September 1977

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Part I

Metamorphic rocks in the field

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Metamorphism and metamorphic rocks

DEFINITION

Metamorphic rocks are those whose character has been changed since their original formation by processes operating within the Earth (or other planetary bodies). The change may include a change in the minerals making up the rock, or a change in the relationship between those minerals, the **texture** of the rock, or both. 'Metamorphism' is a general name given to the processes of change. All metamorphic rocks were once igneous or sedimentary, although the processes of metamorphism may have changed them so much that their original nature is unrecognisable.

Metamorphism almost always involves the partial or complete recrystallisation of the original rock minerals. The original crystals of the rock have been broken down and new crystals have grown. The recrystallisation has taken place at temperatures below those a which the rock melts. Thus metamorphism involves processes of *solid-state* recrystallisation. Geological observation and laboratory experiments in solid-state recrystallisation (see Ch. 13) indicate that recrystallisation occurs much more rapidly as temperature increases. The temperature and pressure during metamorphism, and the composition of the pore-fluid (if any) in the rock, influence the minerals present in the metamorphosed rock.

It is not sufficient to define metamorphic rocks as those which have recrystallised since their original sedimentary deposition or igneous crystallisation. Many sedimentary rocks have undergone recrystallisation after their primary deposition, a process which geologists call **diagenesis**. This process falls outside the generally accepted scope of metamorphism, because it may affect sediment which is buried only a few metres below the surface, and may occur very soon after deposition. The distinction between diagenesis (which is therefore regarded as a sedimentary process) and metamorphism is conventionally drawn by saying that diagenesis takes place under conditions of temperature, pressure and ground water composition comparable with those found at the surface of the Earth's crust; whereas metamorphism involves higher temperatures or pressures, or different pore-fluid compositions, or combinations of these. This is a genetic distinction, difficult to apply in practice to rocks on the borderline between the two processes.

Igneous rocks may undergo solid-state recrystallisation after they have crystallised from molten magma but before they have cooled to the temperature at the surface of the Earth's crust. For example, glassy lavas may partially devitrify, or granitic rocks recrystallise locally with hydrous minerals such as muscovite, kaolinite and epidote replacing feldspars. Rocks formed by such **deuteric alteration** are usually not regarded as metamorphic rocks. In some cases, for example where deuterically altered igneous rocks have been intruded while their **country rocks** were being metamorphosed, metamorphism and deuteric alteration are indistinguishable. However, for the great majority of metamorphic rocks, a brief examination of a hand-specimen is sufficient to show compositional and textural features which differ from those of sedimentary or igneous rocks.

The definition of metamorphic rocks may be summarised as follows. Metamorphic rocks have undergone partial or complete recrystallisation under conditions of temperature and pressure significantly higher than those found at the surface of the Earth's crust, but below the temperature at which they melt. Note that in this definition the phrase 'at the surface of the Earth's crust' includes the range of conditions found on the surface of the land and also on the beds of the seas and oceans.

THE THREE FIELD CATEGORIES OF METAMORPHIC ROCKS

Metamorphic rocks are divided into three categories on the basis of their field occurrence: **contact** metamorphic rocks, **dynamic** metamorphic rocks and **regional** metamorphic rocks. The first two categories include rocks which outcrop over small areas in particular geological settings. Rocks in the third category outcrop over large areas and in a variety of settings.

Contact metamorphic rocks occur at or near the contacts of igneous intrusions. In some cases the degree of metamorphic recrystallisation can be seen to increase as the surface of contact between the country rocks and the igneous intrusion is approached (Ch. 2 and Ch. 5). This relationship suggests that the most important agent causing metamorphic recrystallisation in these rocks is the heat supplied to the country rock by the cooling intrusion. Therefore the process of metamorphism in contact metamorphic rocks is often called **thermal metamorphism**.

Dynamic metamorphic rocks are found in narrow zones such as major faults and thrusts, where particularly strong deformation has occurred. They also occur near the impact sites of large meteorites.

Regional metamorphic rocks occur over large tracts of the Earth's surface. They are not necessarily associated with either igneous intrusions or fault or thrust belts, although these are often present. The regional metamorphic rocks extend beyond the immediate vicinity of the intrusions, faults or thrusts, and the process of metamorphism is not obviously related to them (Ch. 9). Regional metamorphic rocks characteristically have distinctive textures, such as **schistosity and lineation** (Ch. 2). It is often possible to demonstrate that regional metamorphic rocks underwent metamorphism at about the time they were intensely deformed and that this deformation played a major part in their textural evolution.

AIMS OF STUDY OF METAMORPHIC ROCKS

One important aim of the study of metamorphic rocks is to attempt to discover from their present mineralogical compositions and textures the history of heating, deformation and other processes involved in the metamorphism of rocks of different areas. In attempting this, the geologist studying metamorphic rocks is at a severe disadvantage compared with his colleagues who study sedimentary and igneous rocks. They have the chance to study directly the processes of formation, of some rocks at least, in operation on the Earth at the present day, and to apply the **principle of uniformitarianism** to the formation of comparable rocks in earlier geological periods. The geologist studying metamorphic rocks has to rely almost entirely upon indirect methods to understand metamorphic processes. These include reconstruction based upon interpretation of present field relationships, minerals and textures, and laboratory investigations relating to the stability of metamorphic minerals.

For this reason the **petrogenesis**, or mode of origin of metamorphic rocks, is a matter of more uncertainty and differences of opinion than for sedimentary or igneous rocks. There is not only argument about the petrogenesis of individual suites of metamorphic rocks, but also disagreement about which features of the rocks are most relevant in the discussion of their metamorphism. Some geologists emphasise the mineral assemblages of the rocks, which may be used in conjunction with laboratory studies of mineral stability to make generalisations about the temperatures and pressures of recrystallisation. Others emphasise the study of the textures and structures of metamorphic rocks, which may be compared with structural geological data to determine the deformation and recrystallisation history of a particular area of metamorphic rocks. Although there is no fundamental contradiction between these two approaches, their proponents quite often disagree about the metamorphic processes operating in a particular area.

In recent years, there has been an upsurge of interest in metamorphic rocks. This has been stimulated by the achievement of some reliability in determining the temperatures of metamorphism, linked with at least roughly accurate estimates of pressures. Thus the study of metamorphic rocks can now reveal the distribution of temperature with depth in the geological past in parts of the Earth's crust and even upper mantle. This approach was first demonstrated by Miyashiro (1961) who discussed the evolution of island arcs of the Japanese islands, and has become incorporated into the body of evidence used to support the plate tectonic theory. More recently studies of the metamorphism of ancient oceanic rocks (Gass & Smewing 1973) and of older orogenic belts such as the Caledonides of Scotland (Dewey & Pankhurst 1970, Winchester 1974) have also been used to argue in support of modern tectonic theory. The most ancient rocks so far discovered are metamorphic and igneous, and study of metamorphic rocks is crucial to discussion of the early evolution of the Earth's crust (Read & Watson 1975a).

Metamorphic rocks are not only of academic interest. Many of the Earth's economically exploited resources of metals are found among metamorphic rocks and many are metamorphic rocks themselves (e.g. Davies 1969). Exploration for such metal deposits, and extraction once the deposits are discovered, demand a knowledge of metamorphic processes.

Thus while the study of metamorphic rocks used to be the speciality of a small group of petrologists, most students of Earth science are now aware at least of some of the conclusions derived from the study of metamorphism.

THE AIMS OF THIS BOOK

It is the aim of this book to give some indication of the observations, experiments and theoretical discussions upon which conclusions of wider value to Earth science may be founded. In the first two Parts, the emphasis will be upon observations of the type students can make for themselves. The observations of Part I are those which can be made in the field or by examining hand-specimens. Those in Part II include as well as field observations, descriptions of thin sections of rocks, studied by means of the petrological microscope. Part III discusses laboratory techniques and their results which are important in the study of metamorphic rocks.

Part II describes only a small selection of metamorphic rocks. They are mainly of two compositional types: **pelitic** sediments and basic igneous rocks (Ch. 3). The important case of progressive contact metamorphism of siliceous carbonate rocks is also briefly discussed. The two compositional types most frequently discussed are common in most types of progressive metamorphic sequence. Pelitic rocks show an unusually wide variety of changes in their minerals with varying metamorphic grade. The particular areas of metamorphic rocks selected for detailed description have been chosen because of their regional tectonic settings, as described in Chapter 2. Also, in as many cases as possible, the author has chosen rocks of which