1 Background

1.1 Introduction

I wrote this book to help you to interpret what you see when you look at thin and polished sections of rocks with the microscope. I say 'help', rather than 'teach', because I do not want to give the impression that every microstructure can be easily and unambiguously interpreted in terms of processes that produced the rock. Many can be, but in many other instances, conventional interpretations are ambiguous or poorly understood. So I intend the book to be only a guide, and I present alternative ideas where appropriate. A healthy scepticism should be maintained when interpreting rock microstructures yourself and when reading the interpretations of others.

1.2 History of the Examination of Rocks with the Microscope

Rocks in natural outcrops, in samples knocked off these outcrops and in drill cores, are beautiful and instructive. We can see different minerals, and identify many of them with the aid of a hand lens. We can also see some of the more obvious structures in the rocks. However, cutting a slice (section) through a rock with a diamond-impregnated circular saw and polishing the sawn surface shows us the various minerals alongside each other, rather than piled confusingly all around each other. This reveals the structure even more clearly, as can be seen in the polished facing slabs on many buildings and bench tops.

But we always want to see more. So, when D. Brewster, in 1817, and William Nicol, in about 1830, showed how to make a slice of crystalline material thin enough to transmit light (0.03 mm is the standard thickness) and stuck it to a glass microscope slide (Shand, 1950, p. 6; Loewinson-Lessing, 1954), it was not surprising that a curious person, such as Henry Sorby, should start looking at these *thin sections* of rocks (Sorby, 1851, 1853, 1856, 1858, 1870, 1877, 1879, 1908). Sorby learnt the technique of making thin sections from W. C. Williamson in 1848 (Judd, 1908; Folk, 1965) and made the first rock thin section in 1849 (Judd, 1908). Sorby was the first to look seriously at rock sections with the microscope, beginning with a study of chert, a siliceous sedimentary rock that was a very appropriate choice for microscopic investigation in view of its very fine grain size. He described and suggested a mechanical origin for slaty cleavage (Sorby, 1853, 1856); noticed many of the basic features of igneous and metamorphic rocks; made many important observations on sedimentary rocks, including carbonate rocks (Sorby, 1879); investigated pressure solution (using fossil crinoids); described meteorites; and published the first papers on the examination of polished sections of metals with the microscope (Sorby, 1864, 1887). Thus, Sorby is not only the founder of petrography (the description of rocks), but also the founder of metallography as well (Smith, 1960). In 1858 he investigated fluid inclusions in minerals, heating crystals to watch the gas bubbles disappear, in order to get an estimate of the temperature of crystallization of the mineral (Folk, 1965).

Sorby was followed soon after by many others, as discussed by Johannsen (1939) and Loewinson-Lessing (1954). Prominent among them were Zirkel (1863, 1866, 1876), who learnt the technique of making thin sections from Sorby, Vogelsang (1867), Fouqué & Michel-Lévy (1879), Rosenbusch (1873, 1877), Allport (1874) and Teall (1885, 1886, 1888). Since those days, the light microscope has become the main tool for identifying minerals and examining their microstructures, though it has been augmented by many modern techniques (Section 1.6).

1.3 How Relevant Is the Microscope Today?

Many petrologists concentrate on the mineralogical and chemical aspects of rocks, without spending much time looking at rocks with the microscope. In fact, in these days of marvellous techniques for the chemical and isotopic analysis of minerals, some people feel that simply looking at and measuring the shapes and arrangements of crystals in rocks with the microscope is a little out of date. However, carrying out detailed chemical and isotopic analyses of minerals when you do not understand the relationships of these minerals to other minerals in the rock is a waste of expensive resources, at the very least.

On the other hand, many structural geologists look at the physical or structural aspects of minerals and rocks, especially from the viewpoint of deformation processes and preferred orientations of grains, without being concerned

about the chemical aspects of these processes. Both approaches are valuable, of course, but their interrelationships can be particularly illuminating. Fortunately, many researchers are attempting to integrate the chemical and physical approaches, and the study of rocks with the microscope provides a link between them. In fact, the detailed study of processes in rocks at the microscopic scale is now a major area of research, especially among younger people, in many universities and other research institutions. Moreover, new observational techniques are being developed and used, as discussed in Section 1.6.

Research microscopes commonly have both transmitted and reflected light facilities. An excellent example of the simultaneous use of transmitted and reflected light microscopy is the study of Columbia River basalts by Long & Wood (1986), in which reflected and transmitted light photos are arranged side by side, clearly revealing the dendritic shapes of the opaque Fe–Ti oxide minerals and their relationships to the transparent and translucent silicate minerals. Some leading books and review articles on minerals in reflected light, with emphasis on microstructures, are those of Edwards (1947, 1952), Bastin (1950), Cameron (1961), Ramdohr (1969), Stanton (1972), Craig (1990a, 1990b), and Craig & Vaughan (1994).

1.4 Mineral Identification

Learning to identify minerals takes time and practice, and is outside the scope of this book. Close teaching in a laboratory situation is the best way to learn about the optical properties of minerals, using textbooks specifically written for the purpose (e.g., Fleischer et al., 1984; Shelley, 1985a; Gribble & Hall, 1992; Deer et al., 1992). Ideally, this should go hand-in-hand with learning about microstructures.

1.5 The Concept of a Section

Thin and polished sections are two-dimensional sections through three-dimensional objects, and this must always be kept in mind, as explained in some detail by Hibbard (1995). Mineral grains can have unexpectedly complex three-dimensional shapes (e.g., Rigsby, 1968; Byron et al., 1994, 1995, 1996). Two or even three orthogonal sections may be necessary to reveal the structure of structurally anisotropic rocks, and some recent detailed microstructural studies have used (1) *serial sectioning* (e.g., Byron et al., 1994, 1995, 1996; Johnson & Moore, 1996), coupled with *image analysis* by computer, in order to construct a three-dimensional image of the microstructure and (2) *computed X-ray tomography* (Section 1.6), to reveal the three-dimensional distribution of

large crystals (porphyroblasts) in metamorphic rocks (Denison & Carlson, 1997), plagioclase chains in basalts (Philpotts et al., 1999) and former melted rock (leucosome) in migmatites (Brown et al., 2002).

1.6 Newer Techniques

This book deals mainly with microfabrics visible in the optical (light) microscope, either in thin or polished section, using polarized light. However, some newer techniques are also very useful for revealing features not apparent or less clearly shown in polarized light as outlined. Several examples of photos taken using these techniques will be presented in the book. The new techniques underline the fact that the microscopic study of rocks is a dynamic, progressive field of research.

1.6.1 Cathodoluminescence

Cathodoluminescence (CL) is a technique that can reveal internal microfabrics of grains of some minerals, for example, compositional zoning, microcracking and replacement veining in quartz, calcite, dolomite, zircon, plagioclase, K-feldspar, diamond and apatite (Sippel & Glover, 1965; Smith & Stenstrom, 1965; Sprunt, 1978, 1981; Zinkerngel, 1978; Field, 1979; Sprunt & Nur, 1979; Hanchar & Miller, 1984; Matter & Ramseyer, 1985; Owen & Carozzi, 1986; Reeder & Prosky, 1986; Marshall, 1988; Morrison & Valley, 1988; Ramseyer et al., 1988; Yardley & Lloyd, 1989; Hopson & Ramseyer, 1990; Barker & Kopp, 1991; Shimamoto et al., 1991; Mora & Ramseyer, 1992; Williams et al., 1996; D'Lemos et al., 1997; Watt et al., 1997, 2002; Hayward, 1998; Ahn & Cho, 2000; Janousek et al., 2000; Müller et al., 2000; Pagel et al., 2000; Rubatto & Gebauer, 2000; Barbarand & Pagel, 2001; Hermann et al., 2001; Penniston-Dorland, 2001; Peppard et al., 2001; Rubatto et al., 2001; Rougvie & Sorensen, 2002; Rusk & Reed, 2002; Viljoen, 2002). CL is especially useful for revealing microstructural details in minerals that are colourless in the light microscope, for example, calcite, quartz and feldspar. It can be used with the light microscope or the scanning electron microscope, and some applications are discussed in Sections 3.12.7, 3.12.9 and 5.9.3. CL is combined with X-ray topography to reveal the internal structure of diamonds (e.g., Field, 1979).

CL is caused by defect structures in the crystal lattice, such as impurity atoms, vacancies and dislocations produced during formation and/or deformation of the mineral, which therefore reflect conditions of crystallization, deformation and alteration. The technique involves coating a polished

thin section with carbon and bombarding it with electrons in a vacuum, which produces light from substitutional atoms in an excited state.

1.6.2 Laser-Interference Microscopy

This is a relatively new optical technique that detects small differences in refractive index, and so can reveal in great detail subtle compositional differences (on which refractive index depends), for example, in zoned plagioclase (Chao, 1976; Pearce, 1984a, 1984b; Pearce et al., 1987a, 1987b).

1.6.3 Scanning Electron Microscopy

Scanning electron microscopy (e.g., Lloyd, 1987) is capable of revealing sharp microstructural details in shades of grey, though arbitrary colours may also be assigned, to form a false-colour image. It involves backscattered and forescattered imaging in the *scanning electron microscope* (SEM). This is particularly useful for (1) revealing the detailed microstructure of small grains and fine-grained aggregates and intergrowths (e.g., Vernon & Pooley, 1981; Wirth & Voll, 1987; Cashman, 1988; Simpson & Wintsch, 1989; Swanson et al., 1989; Johnson & Carlson, 1990; van der Voo et al., 1993; Brodie, 1995; Harlov & Wirth, 2000; Blundy & Cashman, 2001; Drüppel et al., 2001; Rickers et al., 2001; de Haas et al., 2002; Schieber, 2002), (2) identifying very fine-grained minerals (e.g., Prior et al., 1999), (3) revealing fine-scale compositional zoning in minerals (e.g., Yardley et al., 1991; Müller et al., 2000; Piccoli et al., 2000; Alexandrov, 2001; Hermann et al., 2001; Kuritani, 2001; Rubatto et al., 2001; Ginibre et al., 2002a, 2002b; Lentz, 2002), (4) measuring orientation differences between grains and subgrains as small as 1 μm across (Prior et al., 1996; Lloyd et al., 1997; Trimby et al., 1998;Prior et al., 1999; Wheeler et al., 2001) and (5) revealing domains of different orientation in optically isotropic minerals, such as garnet (Prior et al., 2000, 2002; Spiess et al., 2001) and pyrite (Boyle et al., 1998).

1.6.4 Transmission Electron Microscopy

The interpretation of some optical microstructures can be ambiguous, for example, some recovery features in deformed quartz (Section 5.4) and fine exsolution lamellae (Section 4.9). In such instances the *transmission electron microscope* (TEM) can provide more reliable information. The principles and some applications have been reviewed by Champness (1977), Putnis and McConnell (1980), McLaren (1991) and Putnis (1992). Transmission electron microscope resolves much smaller objects, such as very fine to submicroscopic intergrowths, and can reveal the arrangement of defects (including dislocations, discussed in Section 5.3.2) in the atomic structure of individual grains of both optically transparent and opaque minerals (e.g., McLaren et al., 1967; McLaren & Retchford, 1969; Green, 1972; Phakey et al., 1972; McLaren & Hobbs, 1972; McLaren, 1974, 1991; Champness & Lorimer, 1976; McLaren & Etheridge, 1976; Champness, 1977; Zeuch & Green, 1984; Doukhan et al., 1985; Allen et al., 1987; Cox, 1987a; Couderc & Hennig-Michaeli, 1989; Hennig-Michaeli & Couderc, 1989; Green, 1992; Ando et al., 1993; Doukhan et al., 1994; Vogelé et al., 1998).

1.6.5 X-ray Tomography

A more recent development in the study of rock microstructure is the use of *high-resolution computed X-ray tomography*. This technique maps the variation of X-ray attenuation within solid objects, the attenuation varying with each mineral present. A source of X-rays and a set of detectors revolve around the rock sample, producing images in layers or cross-sections. The series of two-dimensional images can be computed into a three-dimensional representation of the grains and aggregates in the rock, which gives a clearer picture of spatial relationships and crystal size distributions (e.g., Carlson & Denison, 1992; Carlson et al., 1995, 1999; Carlson & Denison, 1997; Denison et al., 1997; Brown et al., 1999; Philpotts et al., 1999).

1.6.6 Computer-Aided Construction of Three-Dimensional Images

Serial two-dimensional optical or X-ray tomographic images can be scanned and imported into suitable computer graphics programs to provide three-dimensional constructions (Johnson & Moore, 1993, 1996; Carlson et al., 1995, 1999; Pugliese & Petford, 2001). Readily available computer software can also be used to animate the images, producing a more complete visualization of features, such as grain shapes, grain distributions and vein networks (e.g., Johnson & Moore, 1996; Carlson et al., 1999; Pugliese & Petford, 2001).

1.6.7 X-ray Compositional Mapping

Maps of compositional zoning in crystals (Sections 3.12 and 4.12) are produced by multiple stage-scan chemical analyses made with wavelength-dispersive spectrometers on an electron microprobe, different colours being assigned to different concentrations of the analysed element. Examples are shown

in Section 4.12. The technique can also be used for more clearly revealing mineral or compositional domains in fine-grained aggregates (e.g., Clarke et al., 2001; Lang & Gilotti, 2001; Williams et al., 2001; Daczko et al., 2002a, 2002b). Raw X-ray intensity maps can be converted to maps of oxide weight per cent by appropriate matrix corrections (Clarke et al., 2001).

1.7 Quantitative Approaches

Though most work on rock microstructures is qualitative, involving description and interpretation, quantitative methods are also used. For example, grain measurement is important in the classification and interpretation of clastic sedimentary rocks in terms of transport and depositional environments (Section 2.2.2). Grain size is also used in the classification of igneous rocks, though less precisely, and crystal size distributions are being increasingly investigated in igneous and metamorphic rocks (Sections 3.5 and 4.3.1). Numerical modelling has been used to convert two-dimensional measurements of grain shapes and sizes in thin section to three-dimensional grain shapes and true crystal size distributions (Higgins, 1994; Peterson, 1996). Moreover, computer software is readily available to do this and to make animated images, as mentioned in Section 1.6. Interfacial angles have been measured in many metamorphic rocks, sulphide rocks and igneous cumulates, as indicators of mutual solid-state growth of minerals (Section 4.2). In addition, the orientations of inclusion trails in porphyroblasts have been used as indicators of tectonic processes (Section 5.10). Numerical simulation of the development of metamorphic and deformation microstructures is also well under way (Jessell, 1988a, 1988b; Jessell et al., 2001).

1.8 Some Terms

Though no hard and fast rule exists, it is probably best to use *crystal* for a volume of crystalline mineral with well-formed, planar faces (called crystal faces or facets), and *grain* for any other volume of crystalline mineral. For me, the shapes, arrangements and orientation of the minerals constitute a rock's *fabric*. At the microscope scale, the fabric (*microfabric*) consists of the grain shapes and arrangement (the *microstructure*) and the spatial orientation of the minerals (the *preferred orientation*). However, many people use 'fabric' for 'preferred orientation', which is the usage recommended by the International Union of Geological Sciences (IUGS) Subcommission on the Systematics of Metamorphic Rocks (Brodie et al., 2002).

It would be good to get materials scientists more interested in rocks, as they are the great class of natural solid materials. Therefore, because 'texture' means 'preferred orientation' to most materials scientists and some structural geologists, it would be best not to use it instead of 'microstructure' as many petrologists do. However, though 'microstructure' is gaining in popular usage, 'texture' is common, and no ambiguity is caused among petrologists by using it. Actually, 'microstructure' appears to have priority, because the first publications on the microscopic examination of rocks referred to 'microscopical structure' or 'microscopic structure' (e.g., Sorby, 1851, 1858; Allport, 1874). Moreover, the IUGS Subcommission on the Systematics of Metamorphic Rocks has recommended that the term 'texture' be replaced by 'microstructure', which is defined as 'structure on the thin section or smaller scale' (Brodie et al., 2002). The term 'microtexture', which unfortunately is starting to enter the literature, is unnecessary because 'texture' mainly refers to the microscopic scale.

Of course, every gradation in scale exists between the microscopic and mesoscopic (outcrop) scales, and so I have not been able to confine the discussion to the microscopic, although this is by far the main scale discussed.

1.9 Traditional Rock Groupings

Many rock-forming processes apply to more than one of the traditional igneous, sedimentary and metamorphic rock groups. For instance, similar basic principles governing the nucleation and growth of crystals apply to all rocks, and grain growth in the solid state occurs not only in metamorphic rocks (in which it is a universal process) but also in the late stages of formation of some rocks conventionally regarded as igneous. In addition, growth of new minerals in the solid state (*neocrystallization*) occurs not only in metamorphic rocks but also in the late-stage alteration (*deuteric alteration*) of igneous rocks, and in the low-temperature alteration (*diagenesis* or *burial metamorphism*) of rocks that many people would consider to be still sedimentary. Moreover, metamorphic rocks begin to melt at high temperatures, producing rocks with both igneous and metamorphic features. In addition, radiating crystal aggregates ('spherulites') commonly grow in glass, which, though technically solid, is liquid-like with regard to its atomic structure. Furthermore, exsolution, which is a solid-state process, occurs in both igneous and metamorphic minerals. As if that is not enough, fragmental material thrown out of explosive volcanoes produces rocks that are technically sedimentary, but consist entirely of igneous material, and may also show evidence of solid-state flow of glass. The result of this cross-linking of

processes is that, though this book adheres roughly to the traditional sedimentary-igneous-metamorphic subdivision, processes discussed under one of these headings may also be relevant to another of these groups. These instances are cross-referenced.

1.10 Importance of Evidence

Science relies on *evidence*. An assertion made without evidence is not worth very much. Yet I often read statements such as: 'the microstructural (textural) evidence indicates . . .' This implies that the writers are asserting that their interpretations are so obviously right that they do not have to go to the bother of describing what they saw and evaluating the evidence.

Of course, recognizing evidence takes practice. As noted by A. F. Chalmers in *What Is This Thing Called Science?* 'It is necessary to learn how to see expertly through a telescope or microscope, and the unstructured array of bright and dark patches that the beginner observes is different from the detailed specimen or scene that the skilled viewer can discern.'

Whenever you make interpretations based on microscopic examination of rocks, you should (1) *describe* clearly what you see and (2) *evaluate* the possible interpretations. If one or more interpretations are valid, you should not arbitrarily favour one of them, unless other evidence (e.g., field or chemical evidence) clearly points in that direction. This is the 'method of multiple working hypotheses' advocated by Chamberlain (1890). In many instances, the microstructural evidence may not be at all clear, in which case, you should not use it to support a hypothesis. Maybe you will have to suggest equally valid alternative interpretations and leave it at that.

The paramount importance of evidence in making scientific inferences is emphasized in the following quotation.

> On so important a question, the evidence must be airtight. The more we want it to be true, the more careful we have to be. No witness's say-so is good enough. People make mistakes. People play practical jokes. People stretch the truth for money or attention or fame. People occasionally misunderstand what they're seeing. People even sometimes see things that aren't there. (Sagan, 1997)

Carl Sagan (*The Demon-Haunted World*) was referring to UFOs, but at least some of these statements could refer to petrologists interpreting rock microstructures. People do make mistakes and even see things that are not there, and though practical jokes may be uncommon in such a serious pursuit as petrology (!), people certainly do occasionally misunderstand what they're seeing. We all do, in fact. Most important, we often want something to be true so much that we may be tempted to gloss over the evidence, whereas we should be doubly careful, in order to save ourselves falling into the trap of a woefully wrong interpretation, no matter how attractive it may seem.

It does not matter how many times an assertion is repeated or how loudly it is trumpeted in conversation, in the scientific literature, in textbooks or even on the Internet; it is only as good as the evidence for it. Another point to remember is that an interpretation presented by a great authority on the subject, though worthy of respect perhaps, is also only as good as the evidence for it. Such 'arguments by authority' can subdue interpretations based on careful accumulation of evidence (Vernon, 1996b).

Too often we see examples of interpretations based on inadequate evidence used to support a preferred model. Even some well-accepted interpretations may be wrong. A good example is the common belief that an 'order of crystallization' in igneous rocks can be inferred by looking at the microstructure. Generally this is impossible, as explained in Section 3.6. If the microstructure cannot give you the evidence, please do not try to extract it anyway!

In fact, the more I examine and read about rock microstructures, the more cautious I become about interpreting them, and that will be a constant theme in this book. As mentioned in Section 1.11, recent work on the direct microscopic observation of developing microstructures in organic compounds used as mineral analogues has revealed many unexpected processes, and has shown that similar microstructures may have very different histories. They remind us of the necessity for caution in the interpretation of natural rocks.

So I will try to give explanations that are sufficiently general to be regarded by most people as 'reasonable' on the available information and that students can infer largely from the optical microstructure. Where alternatives need to be discussed, the relevant publications will be mentioned. Moreover, where pitfalls exist, they will be pointed out, and it must be reemphasized that this book is only the most general of guides. It indicates what to look for and how to start (not stop) thinking about what is observed.

1.11 Kinds of Evidence Used

What evidence is useful in interpreting rock structures? Imagine you had never seen a rock section, either a thin section or a slab cut through a hand sample. How could you begin to interpret the crystal shapes and arrangements you see? You must have some guides. These are *field relationships* and *experimental evidence* on rocks and minerals, assisted by some general inferences from experiments on

other materials, such as metals, ceramics, organic polymers and synthetic ice. For example, when Sorby first looked at thin sections of slates with the microscope, he would have already known that slates are formed by strong deformation and that the deformation is in some way responsible for their characteristic strong foliation (*slaty cleavage*). Furthermore, once Sorby had observed and described the features shown by the microstructure of the slate, others were in a position to recognize similar cleavages in thin sections of rocks from other areas. In this way, general guides to the interpretation of rock microstructures have been established.

If we can observe rocks forming, as with sedimentary and volcanic rocks, we are on strong ground for making inferences about how the microstructures were formed. We are on much shakier ground when it comes to intrusive igneous and metamorphic rocks. However, we can learn much from careful interpretation of field relationships, though strong differences of interpretation often occur. In addition, experiments on the cooling of melted rocks and the melting of solid rocks are valuable guides to the interpretation of rocks involving melts, and many recent experimental advances have been made in the interpretation of igneous microstructures (e.g., Lofgren, 1971b, 1973, 1974, 1976, 1980; Lofgren et al., 1974; Fenn, 1974, 1977, 1986; Donaldson, 1976, 1977, 1979; Swanson, 1977; Swanson & Fenn, 1986; London, 1992; Hammer & Rutherford, 2002; Hammer, 2004, 2009; Brugger & Hammer, 2010a, 2010b). However, we should keep in mind possible problems caused by the short duration of experiments.

Experimentally determined stability fields of mineral assemblages in different bulk chemical compositions reveal the conditions of pressure, temperature and fluid composition that occur during metamorphism. However, it is not as easy to conduct successful experiments on the development of microstructures in metamorphic rocks because of the high temperatures and pressures involved in the experiments and the generally small size of the samples used.

Many important experiments on mineral and rock deformation have been carried out (Chapter 5), but again we can only observe the finished product, not the stages along the way. Fortunately, experiments on ice deformation have helped our understanding of progressive microfabric development during deformation (e.g., Wilson, 1984, 1986; Wilson et al., 1986). Moreover, a new experimental technique using transparent and translucent organic compounds that behave somewhat similarly to minerals has been developed (Sections 3.3.5 and 5.2) and is being applied with great effect to the interpretation of microfabrics, especially deformation features (e.g., Means, 1977; Urai et al., 1980, 1986; Means, 1981; Urai & Humphreys, 1981; Means, 1983; Urai, 1983a, 1983b, 1987; Means & Jessell, 1986; Means & Ree, 1988; Means, W. D. 1989; Ree, 1991; Means & Park, 1994; Park &

Means, 1996; Ree & Park, 1997). Because these compounds deform, melt and crystallize rapidly at room temperatures, the processes can be observed and photographed in progress in the microscope ('see-through' experiments). Of course, these materials are generally not minerals, but nevertheless, they have provided some startling and surprising insights into possible grain-scale processes that may occur in natural rocks.

Another technique developed recently is direct transmitted light observation of crystallization of minerals during cooling from realistically high temperatures, using the 'moissanite cell' (Hammer, 2009; Schiavi et al., 2009; Ni et al., 2014), as described in Section 3.3.5.

In the absence of reliable experimental evidence, it is necessary to fall back on 'commonsense' interpretations based on accumulated experience of the type outlined previously. This applies especially to metamorphic rocks. Unfortunately, commonsense isn't so common, and what makes perfectly good sense to one person may make no sense at all to somebody else. The most important thing is to be as honest and logical as possible, and to evaluate (and if necessary retain as possibilities) every interpretation that can reasonably explain the observations. If the end result is the unsatisfying conclusion that you cannot make an unequivocal interpretation on the available evidence, leave it at that. No harm will be done. On the contrary, many a doubtful interpretation, presented as being reliable, has been accepted at face value and used in later work, thereby misleading subsequent researchers.

1.12 Complexity

A rock's microstructure is the product of a complicated sequence of events and processes. So is a rock's chemical analysis. Both may tell us something about the rock's history, but neither can fully reveal all the historical complexities. This is a problem that petrologists have to accept. We do our best with the evidence available, without taking it too far, and we must acknowledge that our interpretations are often incomplete.

Another point to add to the complexity is that superficially similar microstructures may be formed in different ways, as with exsolution and epitaxial replacement producing similar intergrowths (e.g., Craig, 1990a, 1990b). For example, hematite lamellae in magnetite, usually inferred to be of replacement origin, can be due to exsolution in some rocks (Edwards, 1949). Another complication is the optical similarity between subgrains formed by recovery and similar features formed by fracture, as discussed in Section 5.4. Other complexities of rock microstructure will become apparent in the following chapters.

2 Microstructures of Sedimentary Rocks

2.1 Introduction

Though this book is mainly concerned with igneous, metamorphic and deformation processes, in this chapter I briefly review the main sedimentary microstructures, because they need to be understood in order to interpret residual sedimentary microstructures in some metamorphic rocks.

Though the basic sedimentary microstructures are relatively straightforward, variations (reflecting variable sedimentary environments) can be very complex, and many complicated classification schemes to deal with this complexity have been suggested. Detailed classification schemes, microstructural details and discussions of sedimentary environments can be found in many excellent books (e.g., Pettijohn, 1949; Williams et al., 1954; Carozzi, 1960; Milner, 1962; Folk, 1968; Selley, 1970; Blatt et al., 1972; Bathurst, 1975; Friedman & Sanders, 1978; Adams et al., 1984; Greensmith, 1989; Boggs, 1992; McPhie et al., 1993; McLane, 1995).

Sediments are loose, unconsolidated fragments, and sedimentary rocks are the consolidated or lithified equivalents. *Residual (pedogenic)* sediments are essentially in situ deposits of the products of rock weathering, for example weathering crusts, soils and regoliths. *Epiclastic (terrigenous)* sediments are accumulations of solid fragments formed by erosion of existing rocks. *Pyroclastic* sediments are deposits of fragmented igneous material (e.g., volcanic glass and crystal fragments) ejected from volcanoes in explosive eruptions and deposited directly onto Earth's surface. *Bioclastic* sediments are accumulations of organic skeleton or shell fossils that have been at least slightly transported. *Chemical* sediments are precipitated directly from aqueous solution or by replacement of existing sediment. *Polygenetic* sediments consist of mixtures of the foregoing types, and are named according to the dominant kind of sediment present (e.g., 'fossiliferous limestone', 'tuffaceous sandstone'). Moreover, epiclastic rocks commonly contain chemical components in the form of a *cement* (Section 2.2.5).

2.2 Epiclastic ('Terrigenous') Sedimentary Rocks

2.2.1 Detrital (Clastic, Fragmental) Minerals

Quartz and the clay minerals constitute up to about 70–80 per cent of the epiclastic sedimentary rocks, with less abundant feldspar, mica and carbonate. The clay minerals belong to a group of very fine-grained, water-rich, complex aluminosilicates with various other elements, especially potassium, magnesium and iron. Generally they are too fine-grained to be identified with the microscope, and so other techniques (especially X-ray diffraction) are used for their accurate determination. Other chemically and physically resistant minerals, such as zircon, tourmaline, ilmenite, magnetite, monazite, tourmaline, rutile, topaz and garnet, are also commonly present in very small quantities – generally no more than 1 per cent, except in local 'black sand' concentrations.

The detrital (clastic, fragmental) minerals in epiclastic sediments depend on (1) their presence in the source rocks, (3) their resistance to mechanical abrasion and (3) their chemical stability in the surface environment. Common fragmental minerals are those that are most stable in Earth's atmosphere, especially quartz and the clay minerals. Quartz is the most common mineral stable in Earth's atmosphere, and is simply released from rocks undergoing weathering as individual grains or fragments. In contrast, clay minerals are formed by the chemical breakdown of minerals that are not as stable in the atmosphere, especially feldspars and the ferromagnesian minerals (pyroxene, olivine, biotite and amphibole). However, these less stable minerals can occur as fragments in sediment that has been transported relatively short distances and/or deposited rapidly.

2.2.2 Fragment Size and Sorting

Transport at normal conditions in water tends to sort the detritus into different sizes, namely, pebbles (> 2 mm in diameter), sand ($2 - 1/16$ mm in diameter), silt ($1/16 - 1/256$ mm in diameter) and clay ($< 1/256$ mm in diameter). Prolonged washing of sediment, for example in waves in relatively shallow water (involving traction currents), leads to a well-sorted sedimentary rock with a relatively even grain size (Figs. 2.1, 2.2), whereas if the sediment is deposited rapidly (for example, in turbidity currents produced by submarine slumps on continental slopes), the fragments tend to have very different sizes (said to be poorly sorted or unsorted), as shown in Figs. 2.3 to 2.7.
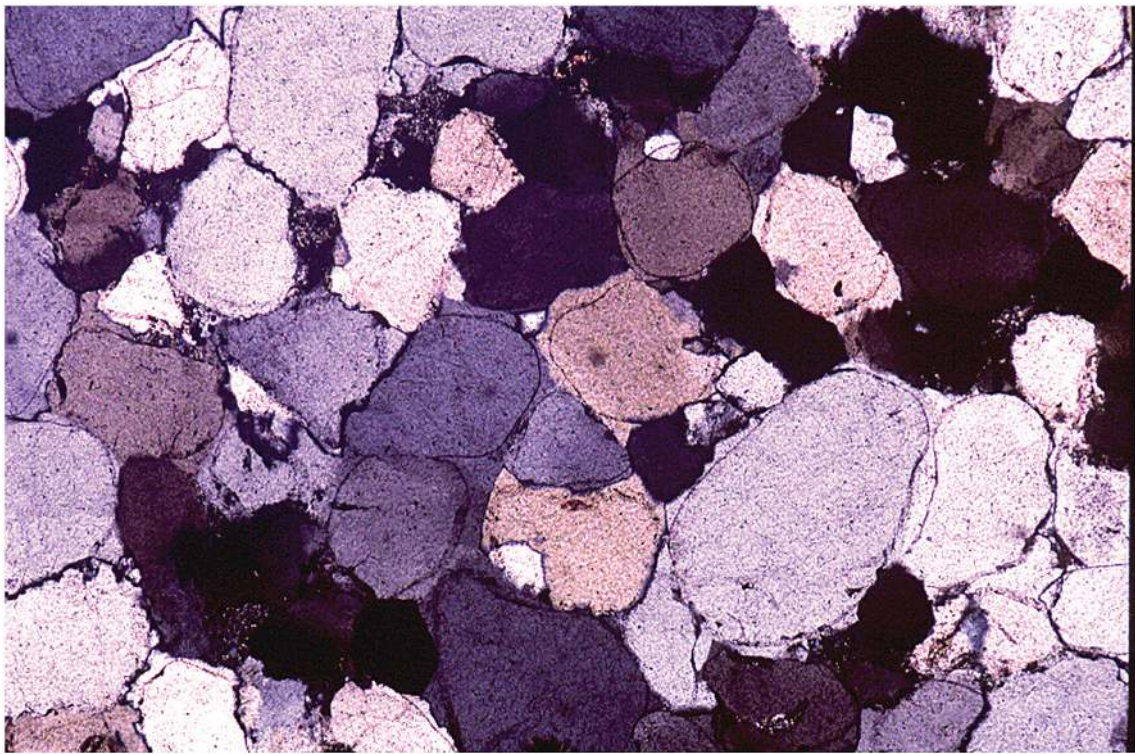
Fig. 2.1: Orthoquartzite, consisting of well-sorted, rounded clastic quartz grains (outlined by minute, dusty-looking inclusions) with secondary overgrowths (forming a quartz cement) in optical continuity with the clasts. The resulting new grains (clasts plus their overgrowths) form a roughly polygonal aggregate (compare with Fig. 2.13). Some of the grain contacts are irregular to sutured (*stylolitic surfaces*; Section 5.9.2), owing to 'pressure-solution' in response to local stress increases as the grains were pressed together, during either compaction or weak tectonic activity (Chapter 5). Crossed polars; base of photo 2.8 mm.
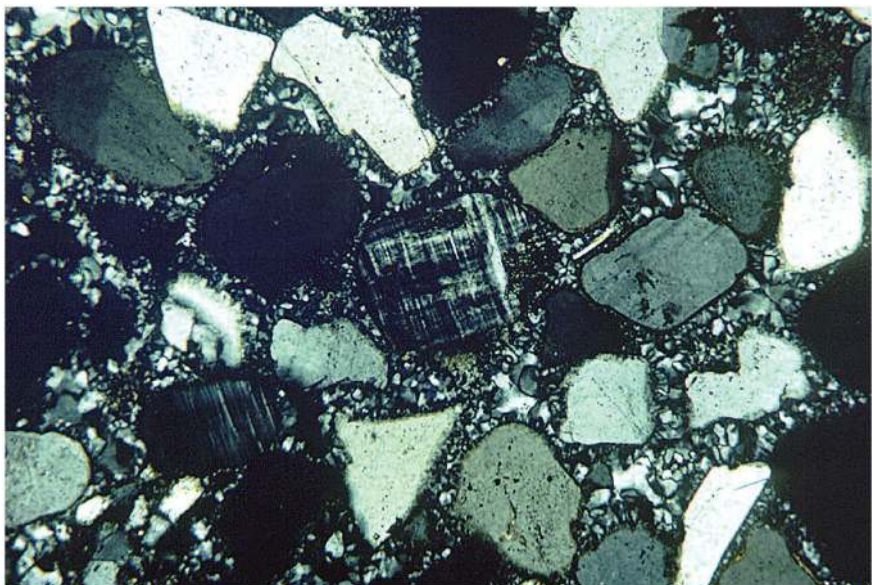
Fig. 2.2: Relatively well-sorted sandstone consisting of fragments of quartz and feldspar (mainly microcline, showing tartan twinning; Section 4.8) that are mainly well rounded, though some are subrounded to angular. The fragments have been cemented by fine-grained aggregates of quartz precipitated from hydrous solutions percolating between the clasts; the quartz cement grains nucleated on the clasts, forming 'micro-vughs'. Crossed polars; base of photo 1.3 mm. From Vernon (2000b, fig. 103).
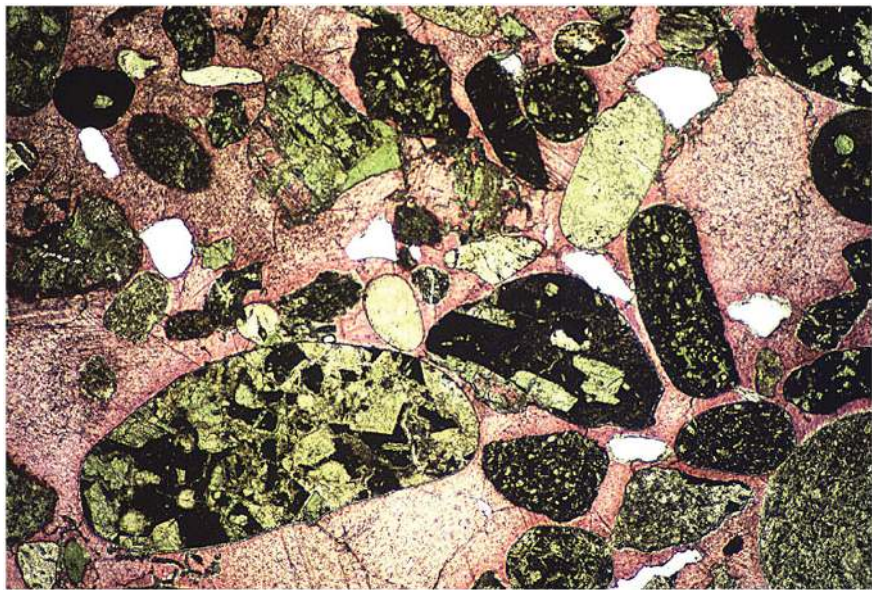
Fig. 2.3: Moderately poorly sorted volcanic sandstone composed of clasts of volcanic rock fragments with igneous microstructures, including phenocrysts (Chapter 3). The feldspar of the rock fragments has been replaced by fine-grained, green chlorite. The clasts have been cemented by calcite in grains that are much larger than the clasts ('lustre mottling' structure). The calcite (which is normally colourless in thin section) has been stained with an organic dye (alizarin red S), to distinguish it from other carbonate minerals. Plane-polarized light; base of photo 4.4 mm. From Vernon (2000b, fig. 104).
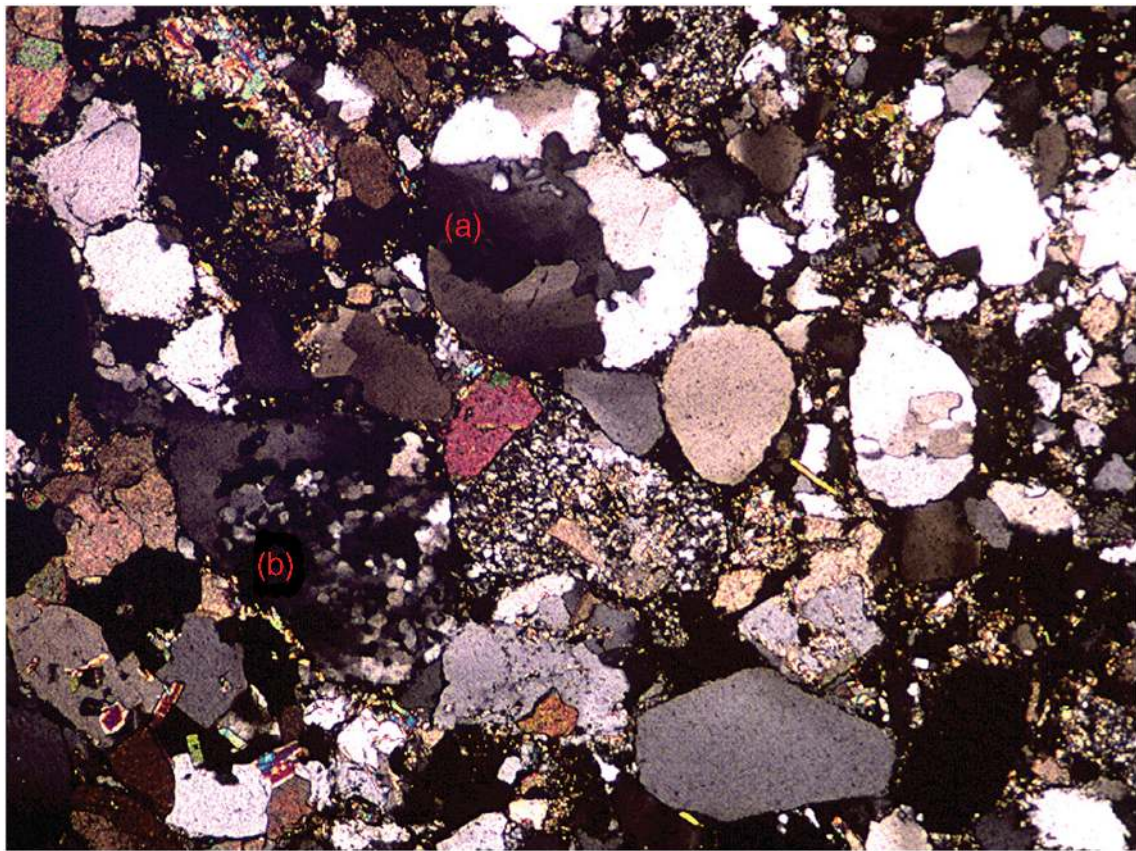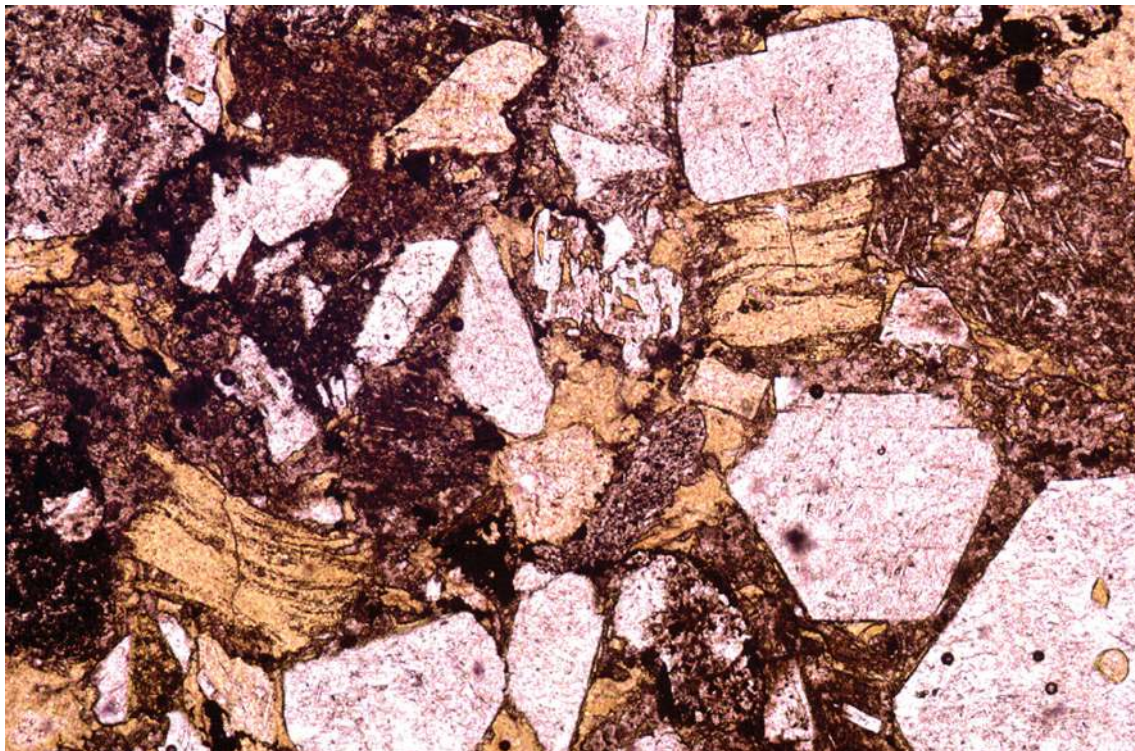

Fig. 2.4: Poorly sorted sandstone, consisting mainly of angular to rounded quartz fragments – with some altered feldspar, carbonate and fine-grained rock fragments – all cemented by opaque iron oxide. Some of the quartz clasts show evidence of recovery (a) and/or recrystallization (b), as discussed in Section 5.4, owing to deformation in the source area; such microstructures assist in determining the source (provenance) of the sediment. Crossed polars: base of photo 4 mm.
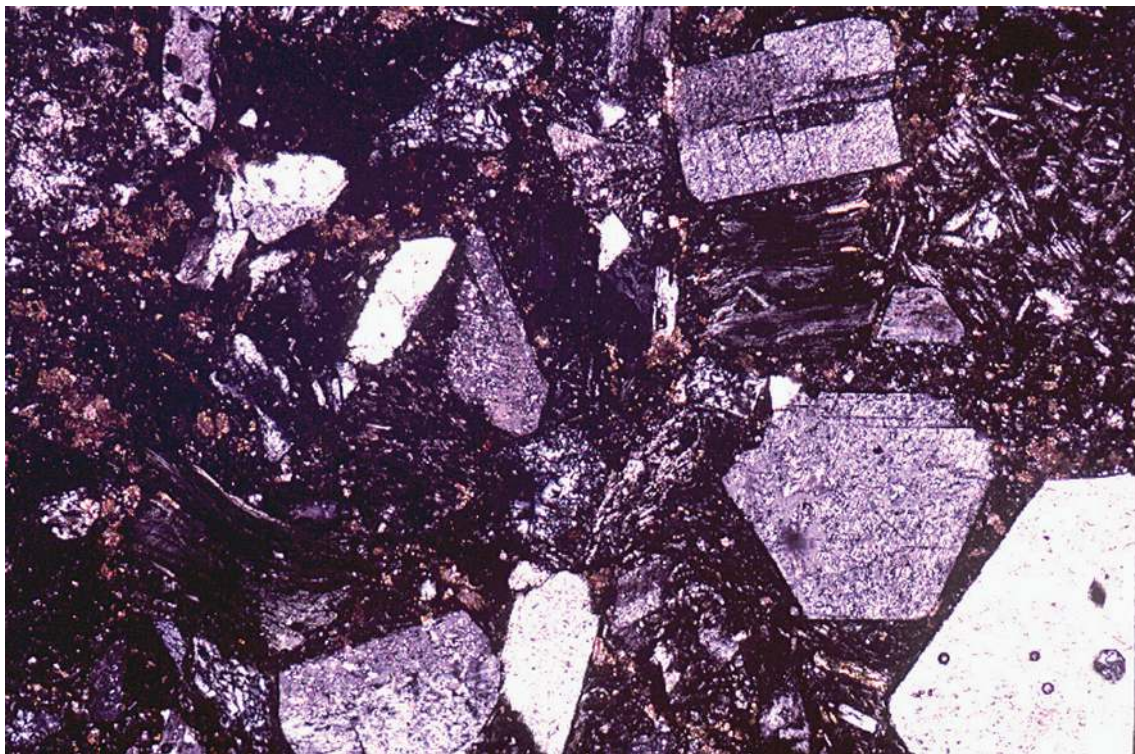
(a)

(b)

Fig. 2.5: (a) Poorly sorted volcanic sandstone ('greywacke') consisting of angular fragments of quartz and plagioclase (some with remnants of crystal faces) and volcanic rock fragments, some with feldspar laths aligned in a magmatic flow structure (right), as discussed in Section 3.10, with a fine-grained chlorite-rich matrix (pale yellowish green). The presence of former glassy volcanic rock fragments with