

Chapter 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 don’t want to give the impression that every microstructure you see can be easily and unambiguously interpreted in terms of processes that produced the rock. Many can, 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 also 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 about 1830 showed how to make a slice of crystalline material thin enough to transmit light (0.03 mm is the standard thickness), stuck to a glass microscope slide (Shand, 1950, p. 6; Loewinson-Lessing, 1954), it wasn’t 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, 1880, 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). He 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, 1851, 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). So not only is he the founder of petrography (the description of rocks), but the founder of metallography as well (Smith, 1960). He also 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 (Sorby, 1858; Folk, 1965).

Sorby was followed soon after by many others, as discussed by Johannsen (1939) and Loewinson-Lessing (1954). Among them were Dawson (1859), Zirkel (1863, 1866, 1876), Vogelsang (1867), Fouqué & Michel-Lévy (1879), Allport (1874), Rosenbusch (1873, 1877) and Teall (1885, 1886). Since those days, the light microscope has become the main tool for identifying minerals and examining their microstructures, although 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 may 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 don't understand the relationships of these minerals to other minerals in the rock makes little sense. It's a waste of expensive resources, at 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 photographs 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 Bastin (1950), Edwards (1947, 1952), Cameron (1961), Ramdohr (1969), Stanton (1972), Craig & Vaughan (1994) and Craig (1990a,b).

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; Nesse, 1991; 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 (see, for example, 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* (see, for example, Byron *et al.*, 1994, 1995, 1996; Johnson & Moore, 1996), coupled with *image analysis* by computer, 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 (Carlson & Denison, 1992; 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 microstructures visible in the optical (light) microscope, in standard thin or polished sections, with the use of polarized light. However, some newer techniques are very useful for revealing features not apparent or less clearly shown in polarized light, as outlined below. Several examples of photographs taken with these techniques will be presented in the book. The new techniques underline the fact that the study of rock microstructure is a dynamic, progressive field of research.

(1) **Cathodoluminescence (CL)** is a technique that can reveal internal microstructures of grains of some minerals, for example, compositional zoning, overgrowths, microcracking and replacement veining in quartz, calcite, dolomite, magnesite, zircon, plagioclase, K-feldspar, diamond, fluorite, sphalerite, kyanite, pyrope garnet, corundum, cassiterite, anhydrite and apatite (Sippel & Glover, 1965; Smith & Stenstrom, 1965; Zinkernagel, 1978; Matter & Ramseyer, 1985; Owen & Carozzi, 1986; Sprunt, 1978, 1981; Sprunt & Nur, 1979; Field, 1979; Reeder & Prosky, 1986; Padovani *et al.*, 1982; Hanchar & Miller, 1993; Marshall, 1988; Ramseyer *et al.*, 1988; Morrison & Valley, 1988; Mora & Valley, 1991; Yardley & Lloyd, 1989; Hopson & Ramseyer, 1990; Barker & Kopp, 1991; Shimamoto *et al.*, 1991; Williams *et al.*, 1996; Mora & Ramseyer, 1992; D'Lemos *et al.*, 1997; Watt *et al.*, 1997, 2002; Hayward, 1998; Müller *et al.*, 2000; Pagel *et al.*, 2000; Janousek *et al.*, 2000; Ahn & Cho, 2000; Götze, 2000; Rubatto & Gebauer, 2000; Penniston-Dorland, 2001; Rubatto *et al.*, 2001; Hermann *et al.*, 2001; Barbarand & Pagel, 2001; Peppard *et al.*, 2001; Rusk & Reed, 2002; Viljoen, 2002; Rougvie & Sorensen, 2002). CL is especially useful for revealing microstructural details in minerals that are colourless in the light microscope, for example calcite, quartz and feldspar. For example, quartz, untwinned K-feldspar and untwinned plagioclase may be distinguished by their CL colours in fine-grained aggregates, and CL can assist in provenance and diagenetic studies in sedimentary rocks. The technique is not suitable for iron-rich minerals. Some applications of CL are discussed in Sections 3.11.7, 3.11.9 and 5.9.3.

It can be used with the light microscope (producing true CL colours with a spatial resolution of 1–2 μm), or the scanning electron microscope (producing grey-scale variations with a spatial resolution of less than 1 μm), and may be combined with CL spectroscopy to enable spectral spot analysis of revealed features. CL is combined with X-ray tomography to reveal the internal structure of diamonds (see, for example, Field, 1979).

CL is caused by defect structures in the crystal lattice, such as impurity atoms (transition metals, rare earth elements, lead, titanium, actinides), 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. This bombardment produces light from substitutional atoms in an excited state.

(2) **Laser-interference microscopy** 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,b; Pearce *et al.*, 1987a,b).

(3) **Scanning electron microscopy** (see, for example, Lloyd, 1987) is capable of revealing sharp microstructural details in shades of grey, although arbitrary colours may also be assigned to form a false-colour image. It involves

backscattered and foreshattered imaging in the scanning electron microscope (SEM). This is particularly useful for (a) revealing the detailed microstructure of small grains and fine-grained aggregates and intergrowths (see, for example, 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; Lloyd & Prior, 1999; Drüppel *et al.*, 2001; Blundy & Cashman, 2001; Rickers *et al.*, 2001; de Haas *et al.*, 2002; Schieber, 2002), (b) identifying very fine-grained minerals (see, for example, Prior *et al.*, 1999), (c) revealing fine-scale compositional zoning in minerals (see, for example, Yardley *et al.*, 1991; Müller *et al.*, 2000; Piccoli *et al.*, 2000; Kuritani, 2001; Alexandrov, 2001; Rubatto *et al.*, 2001; Hermann *et al.*, 2001; Ginibre *et al.*, 2002a,b; Lentz, 2002), (d) measuring orientation differences between grains and subgrains as small as 1 μm across (Prior *et al.*, 1996, 1999; Lloyd *et al.*, 1997; Trimby *et al.*, 1998; Wheeler *et al.*, 2001; Bestmann & Prior, 2003), and (e) revealing domains of different orientation in optically isotropic minerals, such as garnet (Spiess *et al.*, 2001; Prior *et al.*, 2000, 2002) and pyrite (Boyle *et al.*, 1998).

(4) **Transmission electron microscopy** (TEM) assists in the interpretation of some microstructures that can be optically ambiguous, such as some recovery features in deformed quartz (Section 5.4) and fine exsolution lamellae (Section 4.11). The principles and some applications have been reviewed by Champness (1977), Putnis & McConnell (1980), McLaren (1991) and Putnis (1992). TEM resolves very small objects, such as very fine to submicroscopic intergrowths, exsolution features, inclusions and twins 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 (see, for example, McLaren *et al.*, 1967; McLaren, 1974, 1991; McLaren & Retchford, 1969; Phakey *et al.*, 1972; Green & Radcliffe, 1972; McLaren & Hobbs, 1972; Champness & Lorimer, 1976; Champness, 1977; McLaren & Etheridge, 1976; 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; Vogelée *et al.*, 1998).

(5) **X-ray tomography** (in full: high-resolution computed X-ray tomography) is a more recent development in the study of rock microstructure (see, for example, Mees *et al.*, 2003). 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 (see below), which gives a clearer picture of spatial relationships and crystal size distributions (see, for example, Carlson & Denison, 1992; Carlson *et al.*, 1995, 1999; Denison *et al.*, 1997; Brown *et al.*, 1999; Philpotts *et al.*, 1999).

(6) **Computer-aided construction of three-dimensional images** is a technique whereby 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; Castro *et al.*, 2003). This approach is used in confocal laser scanning microscopy (CLSM), which enables objects (such as inclusions in minerals) to be viewed in focus through a thickness of sample in a single image (Petford & Miller, 1992; Petford *et al.*, 1995; Sheppard & Shotton, 1997; Bozhilov *et al.*, 2003), as described in Section 4.4.5. Readily available computer software can also be used to animate images, producing a more complete visualization of features such as grain shapes, grain distributions and vein networks (see, for example, Johnson & Moore, 1996; Carlson *et al.*, 1999; Pugliese & Petford 2001).

(7) **X-ray compositional mapping** produces maps of compositional zoning in crystals (see Sections 3.11, 4.12). Such maps 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 (see, for example, Lang & Gilotti, 2001; Williams *et al.*, 2001; Clarke *et al.*, 2001; Daczko *et al.*, 2002a,b). Raw X-ray intensity maps may be converted to maps of oxide mass percent by appropriate matrix corrections (Clarke *et al.*, 2001).

1.7 Quantitative approaches

Although 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 2.2.3). Grain size is also used in the classification of igneous rocks, though less precisely, and crystal size distributions (CSD) are being increasingly investigated in igneous and metamorphic rocks (Sections 3.4, 4.3.1). Various statistical techniques are used to determine spatial distribution patterns (SDP) of grains and crystals in rocks (see, for example, Flinn, 1969; Kretz, 1966b, 1969; Jerram *et al.*, 1996; Denison & Carlson, 1997; Daniel & Spear, 1999; Jerram & Cheadle, 2000). 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, 2000; Peterson, 1996). Moreover, computer software is readily available to do this and to make animated images, as mentioned in the previous section. 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,b; Jessell *et al.*, 2001).

1.8 Some terms

Although 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 equate 'fabric' with 'preferred orientation', as recommended by the IUGS Subcommission on the Systematics of Metamorphic Rocks (Brodie *et al.*, 2002).

It would be good to make 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 an increasing number of structural geologists, it would be best not to use it instead of 'microstructure' as many petrologists do. However, although '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' (see, for example, Sorby, 1851, 1858; Dawson, 1859; 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 a tautology, because 'texture' refers to the microscopic scale.

Of course, every gradation in scale exists between the microscopic and macroscopic (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 isn't 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 isn't 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 don't have to go to the bother of describing what they saw and evaluating the evidence.

Of course, recognizing evidence takes practice. As noted by Chalmers (1999):

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 shouldn't 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.

Carl Sagan (1996) 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 aren't 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 doesn't 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 don't 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 below (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 re-emphasized that the 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. Finally, it is as well to keep in mind the wise words of John Spong (*Sydney Morning Herald*, June 9, 2001): 'Explanations are always compromised by the levels of knowledge available to the explainer.' That applies to me just as much as to any other explainer!

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 firm 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, although strong differences of interpretation are common. 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 (see, for example, 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). 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 microstructure development during deformation (see, for example, Wilson, 1984, 1986; Wilson *et al.*, 1986). Moreover, a new experimental technique based on transparent and translucent organic compounds that behave somewhat similarly to minerals has been developed, and is being applied with great effect to the interpretation of microstructures, especially deformation features (see, for example, Means, 1977, 1981, 1983, 1989; Means & Jessell, 1986; Means & Park, 1994; Means & Ree, 1988; Park & Means, 1996;