A Framework of Microtectonic Studies

1.1 Introduction

1.2 Establishing and Interpreting Deformation Phases

1.3 Deformation Phases and Metamorphic Events

Basic concepts of microtectonics are introduced and discussed in this chapter. The study of thin sections of rocks, which was originally mainly petrographic, has evolved during the last century to include a number of structural characteristics, that constitute the microstructure or fabric of a rock. The study of this fabric can be used to reconstruct the structural and metamorphic history, but also to improve the understanding of deformation and metamorphic processes.

Successive stages in the deformational and metamorphic evolution of a rock are commonly preserved as part of a fabric and the recognition and correct interpretation of these fabrics is essential for the understanding of this evolution. Two concepts are important: deformation phases and metamorphic events.

The first relates to specific periods during which a rock is deformed under the influence of a deviatoric stress field, leaving visible records such as folds, cleavages or lineations. Successive deformation phases may be superposed on each other leaving overprinting structures such as folded foliations, refolded folds or folded lineations.

Metamorphic events correspond to the formation of a specific mineral assemblage, thought to reflect particular *P-T* conditions or the crossing of a reaction equilibrium curve in *P-T* space. These may also be superposed on each other, leaving only a recognizable record if the equilibrium during the last event(s) was incomplete.

The main objective of a microstructural analysis is therefore to unravel the sequence of deformation phases in a specific area and to link this sequence to metamorphic events, in order to establish a *P-T-t* path.

1.1 Introduction

From their first use in the 19th century, thin sections of rocks have been an important source of information for geologists. Many of the older textbooks on structural geology, however, did not treat microscopic aspects of structures, while petrologists would describe microscopic structures as, for example, lepidoblastic or nematoblastic without paying much attention to kinematic and dynamic implications. During the last decades, however, structural geologists learned to profit from the wealth of data that can be obtained from the geometry of structures studied in thin section, and metamorphic petrologists have appreciated the relation of structural evolution on the thin section scale and metamorphic processes.

Deformed rocks are one of the few direct sources of information available for the reconstruction of tectonic evolution. Nevertheless, observations on the geometry of structures in deformed rocks should be used with care; they are the end product of an often complex evolution and we can only hope to reconstruct this evolution if we correctly interpret the end stage. Simple geometries such as folds can be formed in many ways and it may seem hopeless to try and reconstruct a complex evolutionary sequence from geometrical information only. However, despite the simple geometry of our face, we can individually recognise most of the six billion people on our planet. It is likely that structures in rocks also contain a large amount of detail, which we cannot (yet) recognise and interpret because we are not trained to do so, and partly because we do not know what to look for. It is interesting to page through old publications on microstructures, e.g. on inclusions in garnet or on porphyroclasts, to see how drawings evolved from simple to complex while understanding of the processes related to the development of these structures increased. At any time, some degree of misinterpretation of structural evolution is unavoidable and part of the normal process of increasing our understanding of the subject. This book is therefore a-state-of-the-art description of microstructures and their interpretation.

Observations on the microstructure or *fabric* of a rock (Box 1.1), specifically in thin section, can be used in two major fields. They can be applied to thematic studies, to understand mechanisms of rock deformation and metamorphism; or they can be used to reconstruct the structural and metamorphic history of a volume of rock. Thin section studies are mostly in the latter field. Because such thin section studies can serve to reconstruct tectonic evolution, we use the term *microtectonics*.

This chapter is not only meant as a general introduction to the subject of microtectonics, but also serves as a definition of the framework within which we see studies in microtectonics. As such, it contains terminology that is explained only later in the text and in the glossary. This chapter can be read before, but also in conjunction with the other chapters.

Box 1.1 Fabric, texture, microstructure

In this book we mainly deal with *fabrics*. A fabric "includes the complete spatial and geometrical configuration of all those components that make up a rock. It covers concepts such as *texture, structure* and crystallographic preferred orientation" (Hobbs et al. 1976). The parts that make up a fabric, also known as *fabric elements*, should be penetratively and repeatedly developed throughout a volume of rock; a single fault in a volume of rock is not considered to be part of the fabric, but a large number of parallel foliation planes are. Fabric elements are therefore dependent on scale (cf. Fig. 2.4). A volume of rock may have a *random fabric*, i.e. a random distribution and orientation of its elements or, more commonly, a non-random fabric, including foliations and lineations.

In this book, we mainly deal with fabrics on microscopic scale, or *microfabrics*. Microfabric elements may include grain shape, grain boundaries, deformation lamellae, aggregates of grains with similar shape, and lattice preferred orientation.

In the non-geological literature about metals and ceramics, the term *texture* is generally used for lattice-preferred orientation. On the other hand, most of the older textbooks on metamorphic petrology (e.g. Turner 1968; Miyashiro 1973; Best 1982; Williams et al. 1982; Bucher and Frey 1994) make a distinction between the *texture* and the *structure* of a metamorphic rock. In these texts, *texture* refers to the geometrical aspects of the component particles of a rock including size, shape and arrangement, whereas *structure* usually refers to the presence of compositional layering, folds, foliation, lineation, etc. In fact there is no clear difference between the two concepts and the subcommission on the systematics of metamorphic rocks of the IUGS recommends substituting the term texture by *microstructure*. In this book, we use the terms microstructure and microfabric (see also Sect. 1.1) as synonyms.

In theory, one could expect that a sedimentary rock, which is buried, deformed, metamorphosed and brought back to the surface, should have the same mineral composition as the original sediment if perfect equilibrium conditions were to be attained at each stage. A simple fabric should be developed in such a case in response to gradual changes in the stress field and in metamorphic conditions. Fortunately for the geologist, who relies on structures and mineral assemblages in deformed rocks as a source of information, this is almost never the case. In most deformed rocks, structures with different style and orientation and minerals, which represent different metamorphic grades, *overprint* each other. This means that equilibrium is generally not attained at each stage: mineral assemblages representative of different metamorphic conditions may be 'frozen in' at different stages during burial and uplift. With overprint we mean that structures or mineral assemblages are superposed on each other and must therefore differ in age; this may be visible through crosscutting relations, overgrowth, or even differences in deformation intensity. In practice, however, *overprinting relations* can be difficult to establish. This book mainly serves to illustrate the

possibilities of recognising overprinting relations in thin section and to determine the conditions at which they formed. The aim is then to translate overprinting relations in terms of *deformation phases* and *metamorphic events*.

Deformation phases are thought to be distinct periods of active deformation of rocks on a scale exceeding that of a single outcrop, possibly separated by time intervals with little or no deformation during which metamorphic conditions and orientation of the stress field may have changed (Sects. 1.2, 2.11). The concept was originally created in relation to groups of structures that can be separated in the field by overprinting criteria (Sect. 1.2). Metamorphic events are episodes of metamorphism characterised by changes in mineral assemblage in a volume of rock. Such changes are thought to reflect changes in metamorphic conditions.

Once deformation phases and metamorphic events are defined, it is necessary to determine to what extent they correspond to *tectonic events* or *metamorphic cycles*, i.e. events on a larger scale such as those associated with plate motion or collision. Finally, *orogenies* (e.g. the Alpine orogeny) may encompass several tectonic events with associated metamorphic cycles. The following example illustrates this concept. In thin sections from several outcrops, a horizontal biotite foliation is overprinted by a steeply dipping chlorite foliation, and both are cut by brittle faults (Fig. 1.1). Based on these overprinting relations we could argue that a first 'deformation phase' with a component of vertical shortening formed a foliation under conditions suitable for growth of biotite; later, a second 'deformation phase' of oblique shortening was accompanied by chlorite growth under lower-grade metamorphic conditions. A third deformation phase affected both earlier structures at very low-grade or non-metamorphic conditions or at high strain rate, to cause brittle faulting.

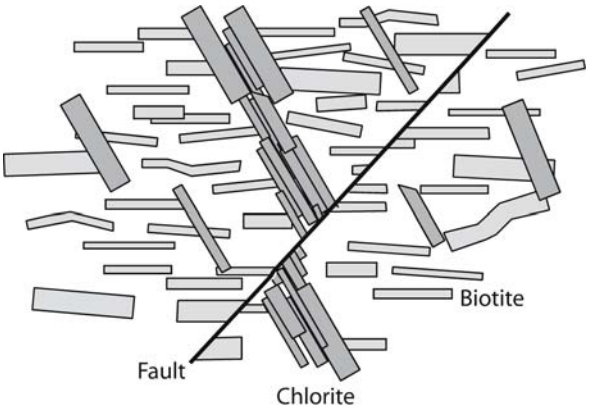


Fig. 1.1. Schematic diagram of a biotite foliation (*horizontal*), a chlorite foliation (*inclined*) and a brittle fault. The sequence of overprinting relations is: biotite foliation-chlorite foliation-fault. The three structures may represent different deformation phases since they overprint each other, have different orientation and represent probably different metamorphic conditions

Time intervals of no-deformation activity are postulated between the deformation phases during which metamorphic conditions changed significantly while the volume of rock under consideration was 'passively' transported to another position in the crust (e.g. by erosion and uplift). The deformation phases are accompanied by metamorphic events, which may lie on the retrograde leg of a single metamorphic cycle (Sect. 1.3). The size of the area over which these deformation phases can be recognised should now be investigated and gradients in style and orientation monitored. Finally, the synchronous or diachronous nature of a deformation phase can in some cases be established by absolute dating of minerals associated with structures visible in thin section, or by dating cross-cutting intrusions. Comparison with similar data on a larger scale, either from the literature or by carrying out further field and thin section research, can establish the regional significance of deformation phases with relation to tectonic events. Because such large-scale analysis is not part of the subjects covered in this book, we restrict ourselves to the establishment of overprinting relations, deformation phases and metamorphic events from data obtained in thin section. The following section gives an outline of some of the problems involved in establishing overprinting relations and deformation phases.

1.2 Establishing and Interpreting Deformation Phases

The concept of deformation phases has been used extensively in the geological literature in reconstruction of the structural evolution of rock units with complex deformation patterns (e.g. Ramsay 1967; Hobbs et al. 1976; Ramsay and Huber 1987; Marshak and Mitra 1988). The underlying idea is that permanent deformation in a volume of rock occurs when differential stresses (Sect. 2.11) are relatively high and that the orientation of the stress field may change between such periods of permanent deformation without visible effects on the rock fabric. The older fabric is not always smoothly erased or modified to a new fabric, since deformation in rocks is commonly partitioned (that is: concentrated in certain domains and less concentrated or absent in others); relicts of older fabric elements may be locally preserved. A foliation that is shortened parallel to the foliation plane may develop folds, commonly with a new crenulation cleavage developing along the axial surface. The older foliation will be completely erased only at high strain or by recrystallisation and grain growth under favourable metamorphic circumstances (Box 4.9). Boudins and tight or isoclinal folds may be refolded but remain recognisable up to very high strain. Lattice-preferred orientation may be preserved in less deformed lenses up to high strain and porphyroblasts may preserve relicts of older structures as long as the porphyroblast phase remains intact (Sects. 7.3–7.7).

Although the concept of deformation phases seems fairly simple and straightforward, there are some problems with its general application, as outlined below.

1. Overprinting relations may be produced by a single deformation phase

Non-coaxial progressive deformation (Sect. 2.5.2) may produce overprinting relations between structures without a major change in the large-scale orientation and magnitude of the stress field. Especially in mylonitic rocks developed in shear zones, it is common to find folds (often sheath folds) that deform the mylonitic foliation and which are clearly the result of the same deformation phase that produced the mylonitic foliation in the first place (Sect. 5.3.2); such folds can be formed at any time during progressive deformation (Fig. 1.2, ⊘Video 1.2).

2. Subsequent deformation phases do not necessarily produce overprinting relations

Two subsequent deformation phases with a similar orientation of the stress field and a similar metamorphic grade may be indistinguishable in the final fabric (Fig. 1.3). For example, a 2 400 Ma-old hornblende foliation, formed under amphibolite facies conditions, could be overprinted by a 1 600 Ma phase of amphibolite facies deformation in a stress field with approximately the same orientation. The result would be strengthening of the earlier foliation. In such cases, only detailed microprobe work or mineral dating may reveal the correct sequence of events.

3. Only the relative age of deformation phases can be established

Identical overprinting relations may develop where a Paleoproterozoic foliation is overprinted by a crenulation cleavage of Phanerozoic age, or in a thrust nappe within an interval of several hundred thousand years only (Fig. 1.4). If metamorphic conditions are significantly different for two deformation phases, a minimum time separation can be established but otherwise absolute age dating is required.

4. The significance of deformation phases depends on the scale of observation

During development of a fold the axial planar foliation may be rotated to such an extent that a crenulation cleavage is locally formed, overprinting the earlier formed foliation (Williams 1972a). Such overprinting relations form during a single phase of deformation. The same effect may occur on a larger scale; consider a volume of rock in a thrust sheet that is transported over a ramp; the sudden changes in orientation of the rock volume when it moves up and over the ramp can induce overprinting relations. In this case, the final fabric will show separable deformation phases on thin section and outcrop scale, but these will be part of a single deformation phase on a regional scale.

5. Deformation phases may be diachronous

Deformation may affect volumes of rock in a progressive way, starting from one side and reaching the other end much later (Hobbs et al. 1976). As a consequence, an overprinting structure labelled D_2 may be older in a certain area than a D_1 fabric in another. A common setting for such an evolution may be in accretionary wedges, where undeformed rocks arrive at a subduction zone, and subsequently become incorporated in the wedge (Figs. 1.5, B.7.1, ⊘Video B.7.1).

Because of the problems mentioned above and also because of the subjective nature of subdivision in sets of structures (e.g. Hobbs et al. 1976), some geologists have become reluctant to use the deformation phase concept

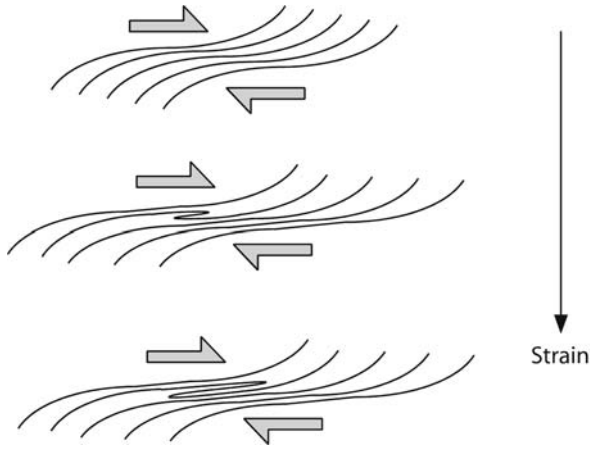


Fig. 1.2. Sequence of events in a shear zone to show how overprinting relations may form during a single phase of progressive deformation if some heterogeneity is present to cause folding

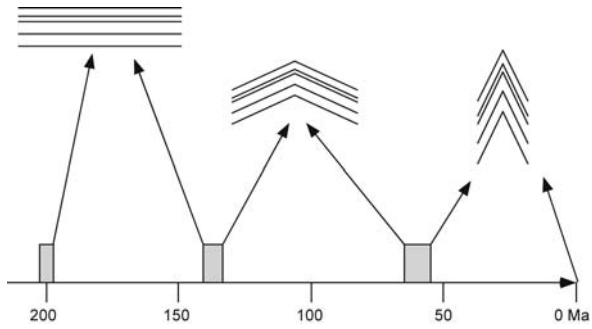


Fig. 1.3. Subsequent deformation phases, represented as *grey blocks* on the *time bar*, do not necessarily produce overprinting relations. If metamorphic conditions and stress orientation are similar, structures like folds may just be further tightened

any longer. However, we feel that the concept continues to be useful to classify structures in a sequential order, if used with care. Deformation phases refer only to the relative age of structures in a limited volume of rock, (commonly in the order of a few hundred km^3) and are generally not equivalent to tectono-metamorphic events of regional significance. It is therefore necessary to determine the tectonic significance of local deformation phases. To establish deformation phases it is important to define sets of structures based on reliable overprinting criteria, such as a foliation (S_n) that has been folded (D_{n+1} folds), and not just on style, orientation, tightness of folds etc., which are criteria that may change from one outcrop to the next in structures of the same age. It is also important to take metamorphic conditions during deformation into consideration, since these are not subject to rapid change (Fig. 1.1). A final warning must be given for the extrapolation of phases from one area to another, or even from one outcrop to the next. The criteria for subdivision remain subjective in the sense that different workers may define a sequence of deformation phases in a different way, resulting in a variable number of phases for the same area. This, however, does not necessarily mean that one of these workers is right, and the others in error; it may just be a matter of different criteria for definition.

For all overprinting relations it is necessary to determine whether they could have formed during a single phase of deformation under similar metamorphic conditions. The following criteria may help to determine whether overprinting relations correspond to separate deformation phases:

a Two overprinting structures composed of different mineral assemblages that represent a gap in metamorphic grade must belong to different deformation phases.
b Foliations that overprint each other commonly represent deformation phases on thin section scale (Sect. 4.2.10.2), but exceptions such as oblique fabrics (Sect. 5.6.2) and shear band cleavages (Sect. 5.6.3) exist.
c Overprinting folds with oblique axial surfaces represent different deformation phases. Care should be taken with refolded folds with parallel axes (Type III of Ramsay 1967), especially in the case of isoclinal folds since these may form during a single deformation phase (Fig. 1.2).
d Shortened boudins are commonly formed by overprinting of two deformation phases (Passchier 1990a; Sect. 5.6.13).
e Some structures preserved in porphyroblasts represent separate deformation phases (Sects. 7.3–7.5).
f Intrusive veins or dykes can be important to separate phases of deformation and their associated foliations.

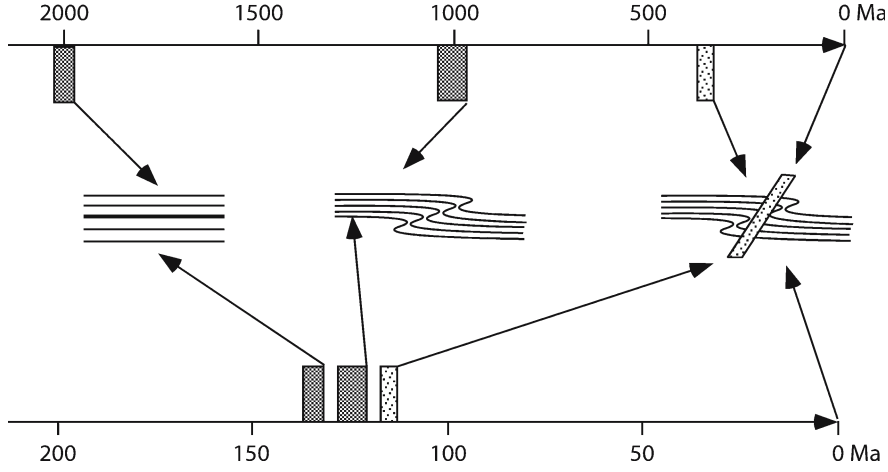


Fig. 1.4.
Only relative ages of deformation can be established by overprinting criteria; overprinting structures shown at *centre right* could form over any time interval, e.g. over 2000 Ma (*upper bar*) or over 30 Ma (*lower bar*)

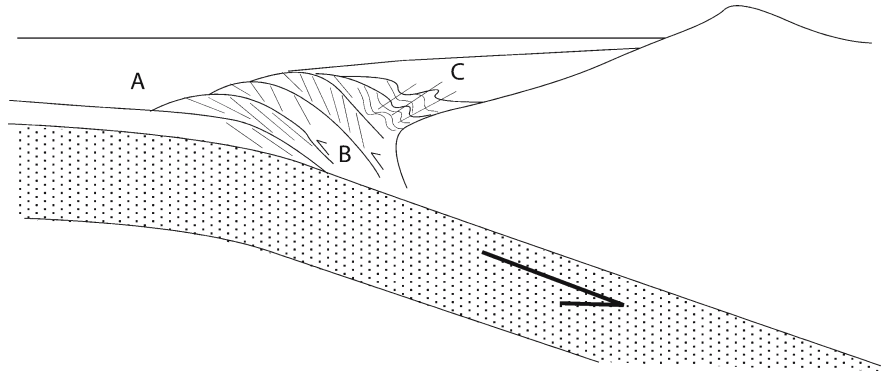


Fig. 1.5.
Schematic representation of an active accretionary prism. At *A* no deformation is occurring whereas at *B* a first deformation phase D_1 is responsible for oceanward thrusting, probably accompanied by the development of foliations and folds in deep levels. While such D_1 structures develop at *B*, a second phase of deformation D_2 related to back thrusting is already overprinting D_1 structures at *C* (see also ⊘Video B.7.1)

1.3 Deformation Phases and Metamorphic Events

A metamorphic evolution can be subdivided into *metamorphic events* defined by the growth of particular metamorphic minerals, in a way similar to the concept of deformation phases. Certain fabrics are indicative of growth sequences in metamorphic rocks (e.g. inclusions in porphyroblasts and reaction rims; Sects. 7.6.5, 7.8) and relations between porphyroblasts and foliations commonly reveal the relative time sequence of their generation (Sects. 7.3–7.5). However, one must keep in mind that a metamorphic event is of an essentially different nature than a deformation phase. Whereas the latter is thought to reflect a period of deformation in between intervals of little or no deformation, the former normally reflects only the passing of critical *P-T* values necessary for a chemical reaction to start and to produce one or more new minerals in the rock. Since deformation often has a catalysing effect on mineral reactions, many such metamorphic events are found to coincide approximately with deformation phases. In other words, many metamorphic minerals are found to have grown during specific deformation phases.

The metamorphic history of a volume of rock can be presented schematically in a *P-T diagram* as a curve, the *P-T-t path* (pressure-temperature-time) (Fig. 1.6a; Daly et al. 1989). *P-T-t* paths as shown in Fig. 1.6 have been theoretically predicted (e.g. England and Richardson 1977; England and Thompson 1984; Thompson and England 1984) and have been reconstructed in tectonic studies from data points that give *P-T* conditions at a certain time. Such data points can be obtained from metamorphic events (reactions between minerals reconstructed from geometric relations in thin section; Sect. 7.8) as compared with theoretically determined petrogenetic grids. They can also be calculated from the chemical composition of mineral pairs or associations in equilibrium, the so-called *geothermometers* and *geobarometers* (e.g. Spear and Selverstone 1983; Essene 1989; Spear et al. 1990). For example, in Fig. 1.6a, the deformation phases are separated in time and the metamorphic events related with them are interpreted as points on a *P-T-t* path associated with a single *metamorphic cycle* (M_1) with peak pressure attained during D_1 and peak temperature during D_2. Data points are more common on the retrograde leg of *P-T-t* paths than on the prograde leg, since the latter are usually destroyed by ongoing metamorphic reactions and deformation.

P-T-t paths are usually clockwise but anticlockwise paths have also been reported (Harley 1989; Clarke et al. 1990). However, one should be aware that most published *P-T-t* paths are based on few data points (usually less than five). Though metamorphic reactions may indicate in which direction a *P-T-t* path was going (e.g. increasing temperature or decreasing pressure), many are based on the passage of a single reaction line and therefore the direction may vary by 180° (Fig. 1.6a). Although *P-T-t* paths are usually presented as a single smooth curve representing a single metamorphic cycle, possible complex details in the shape of the *P-T-t* path can rarely be resolved. Real *P-T-t* paths may have complex shapes with several minor metamorphic cycles and subcycles which can only be reconstructed in rare cases, and then only through detailed combined structural and petrological studies (Fig. 1.6b; Kriegsman 1993; Zhang et al. 1994).

The *P-T-t* path will generally be valid for only a relatively small volume of rock (at most a few km^3), and different paths can often be reconstructed for different crustal units. The way in which these differ gives important information on the regional tectonic evolution. Where paths merge and continue together, rock volumes have been fixed with respect to each other (Figs. B.7.1 and B.7.2,

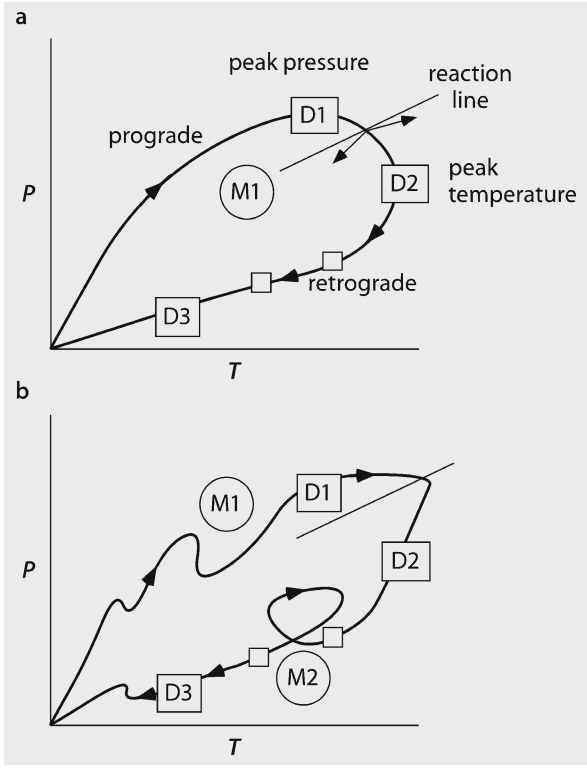


Fig. 1.6. a Data points in *P-T* space (*squares*) some of which are associated with deformation phases D_1 to D_3. A simple clockwise *P-T-t* path is postulated based on these data points, representing a single metamorphic cycle of prograde, peak and retrograde metamorphic conditions. The direction of the *P-T-t* path at peak metamorphic conditions is based on passage of a reaction line; however, other directions are also possible (*arrows*). **b** In reality, the *P-T-t* path may be more complex than the reconstruction based on the available data points; e.g. during retrogression two metamorphic cycles (*M1* and *M2*) may have been superposed. Such complex paths can sometimes be recognised with detailed structural and petrological work

Video B.7.1). This can be the case if major sections of crustal material such as nappes or terranes are juxtaposed along shear zones. Even within major nappes and terranes the *P-T-t* evolution may reveal considerable differences when analysed by detailed thermobarometric and microstructural analyses. Especially in complex tectonic domains like the Pennine nappe stack in the Alps, this technique showed to be capable to identify distinct tectono-metamorphic units within an apparently homogeneous basement nappe (Spalla et al. 1999, 2000; Paola and Spalla 2000).