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12.8 Choosing the Orientation of Thin Sections

This final short chapter describes the background to microstructural studies, mainly the way samples should be collected and oriented, and where to find the most suitable sites to take samples for specific studies. Also treated are types of thin sections and problems caused by the fact that thin sections, and most other techniques to study microstructures, are two dimensional sections which have to be used to reconstruct three dimensional features.

12.1 Introduction

A sound analysis of microstructures relies on correct sampling and on the right choice of the direction in which thin sections are cut from samples. This chapter discusses the steps of sample collection, choice of sectioning plane, and problems involved in the interpretation of three-dimensional structures from two-dimensional sections.

12.2 Sampling

The choice of samples for thin sections depends on the topic of interest and methods that are going to be used. In any case, it is important that the main structure in the area is understood in broad lines before samples are taken; thin sections usually contain a lot of information, which is useless if no good field record exists. For example, if a foliation is found in thin section that has not been recognised in the field, it cannot be fitted in a tectonic model and is useless unless a new field trip can be made to identify it. Thin section studies usually give best results if they are undertaken to solve a specific problem that has been defined before the sections were cut (cf. Passchier et al. 1990b). Thin sections cut at random to 'see what it looks like' will be less useful than those prepared with a specific aim.

12.3 Orientation of Hand Specimens

Hand specimens for structural studies should be oriented in the field. This is best done by marking dip and strike of a planar surface of the specimen on that surface (Fig. 12.1). Notice, however, that this still leaves two possible orientations, since the mark could be made on the top surface or on the lower side of a sample. An extra mark is therefore needed; for example, a cross on the top surface or an arrow indicating top (Fig. 12.1b).

Mistakes can easily be made in orienting samples and for the most important samples (e.g. those needed to determine shear sense) it is therefore useful to make a photograph or simple sketch of the sample, its orientation in outcrop and of the marking. Also, samples should be wrapped in paper or plastic bags to avoid breakage and erosion of markings and numbers.

12.4 Where to Sample in Outcrop

If a *P-T-t* path is to be reconstructed for a specific area (Sect. 1.3, Box 7.5), the most informative lithologies to sample are pelites and metabasites. Pelitic rocks generally develop foliations, which are not easily destroyed by subsequent deformation phases. Metabasites have a weaker memory for a sequence of deformation phases but, as for pelites, their mineral content is sensitive to changes in *P-T* conditions. Psammites usually develop relatively coarse structures, which are difficult to study in thin section, and limestones have a weak memory for a sequence of deformation phases because calcite recrystallises readily, even at low temperature.

Samples should preferably be taken in association with major structures which are understood and of which the relative age is known. If three phases of deformation have been recognised, it is useful to have samples from foliations belonging to each of the phases. If porphyroblasts are visible, these should also be sampled in order to determine their relative age with respect to the foliation. Samples in which overprinting relations are visible are particularly important. Small fold closures or shear zones of each of the phases, if possible from several lithotypes, should also be sampled. The mineral assemblage in such structures may allow an estimation of metamorphic conditions during the deformation phase. If a sample is taken in a major fold, it is useful to know from which limb or part of the hinge it was taken. Shear zones should be sampled in the high strain core, in the low strain rim and in the wall rock; in many cases, it is useful to compare mineral assemblages in the undeformed wall rock with those in a shear zone, in or-

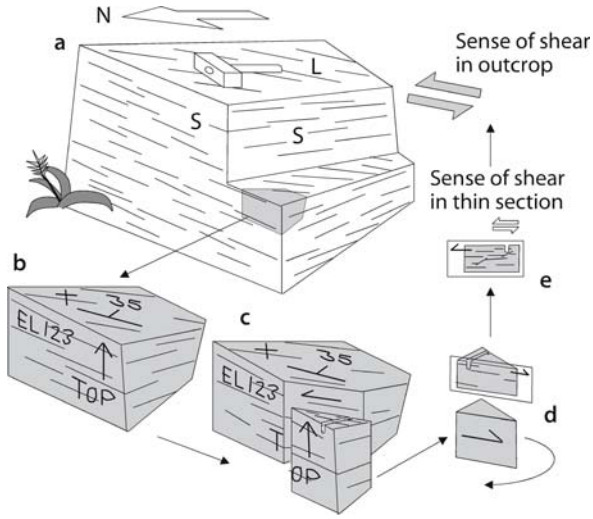


Fig. 12.1. Method to obtain an oriented sample from an outcrop and an oriented thin section from a sample. A sample for structural studies must be oriented, for example as shown in **a. b** A *strike-dip symbol* (here 160–35) on the planar top surface of the sample and a *cross* (marking the *top*) fix the orientation of the sample in space. When a thin section is to be cut parallel to the lineation (here 200/15), a chip is cut from the sample with a diamond saw. In order to orient the chip, an *arrow* with a single barb pointing in the direction of the top surface can be used and is drawn on both the sample and the chip. **c** Care should be taken that this *arrow* is copied correctly onto the thin section. **d** Alternatively, a small saw-cut scar can be made in the top surface of the chip, which can be found back in the thin section. **e** Shear sense determined in the thin section, e.g. by shear bands can now be directly related to the sample, and through the sample to the original outcrop. Here, the outcome is thrusting to the NE

der to determine which metamorphic conditions accompanied deformation in the zone, and which ones are older.

If shear sense in a shear zone is to be determined, care should be taken that samples are correctly oriented and that suitable small-scale structures such as porphyroclasts are present in the sample. In many ductile shear zones, fine-grained mylonites and samples representing highly strained parts of the shear zone give better results than samples of coarse-grained or low strain domains.

Different shear sense markers are preferentially found in different lithologies; C'-shear bands in strongly foliated mica-rich mylonite; C/S fabric mainly in granite mylonite; mantled porphyroclasts in deformed granites or pegmatites, and mica fish in quartzite-mylonites. Deformed quartzite should be sampled where possible to determine LPO of quartz; in many shear zones, this is the only suitable shear sense indicator.

If gradients in the style of a structure exist over an area it is useful to take a series of samples across this gradient in a single lithology. In all cases, it is useful to write down in the field for what purpose a sample was taken. Photographs of important sampling sites are also essential and should be taken before the sample is removed. GPS coordinates of sample sites should be obtained in all cases.

Structures like large folds and boudins are spectacular in the field and are consequently often sampled. However, they may be difficult to interpret on the scale of a thin section where only a small fragment of the structure is seen. In many cases it is more advantageous to sample also directly adjacent to such structures where the rock deformed more homogeneously. Care should also be taken to sample the more fine-grained parts of a structure; in coarse-grained rocks only a small (and possibly non-representative) part of the structure can be studied in thin section. For example, if a sample is taken of a mylonite with large feldspar porphyroclasts in a shear zone, and a thin section is made of the matrix between two large feldspar grains, this matrix may give a shear sense opposite to that of the main zone (cf. Bell and Johnson 1992).

One should also not forget to take samples of the 'ordinary matrix rock'; some geologists realise afterwards that they took samples only of the curious and exceptional. If a metamorphic gradient is present or suspected, it is useful to take samples at a regular distance across this gradient for possible later microprobe work.

Finally a remark about geological heritage. It is our opinion that sampling of beautiful prominent structures such as folds, boudins and shear zones destroys field evidence and potential teaching material, and should therefore be avoided; in most cases, it is possible to take similar samples from other less prominent parts of the same outcrop. The same applies to drill cores, which should preferably be taken in parts of the outcrop where they do not destroy the geometry of beautiful structures.

12.5 Cutting Samples

12.5

When oriented samples are cut to make thin sections, it is crucial to avoid loss of orientation data. Although several methods can be used, we suggest the following procedure. After a saw cut is made, the orientation of the sample should be copied on both sides of the saw cut in mirror image (Fig. 12.1); we propose a system in which an arrow with a single barb is drawn parallel to the lineation, with the barb indicating the top of the sample. The arrow should be copied from the rock chip that is used to make the thin section onto the glass as shown in Fig. 12.1. Be careful when preparing the rock chips for thin sections that the orientation is not lost or confused. Alternatively, a small saw-cut scar can be made in the top surface of the rock chip used to make the thin section. This scar can be found back in the thin section and reduces the chances of confusion in its orientation.

12.6 Types of Thin Sections

12.6

Standard thin sections consist of a basal glass plate of 0.8 to 1.9 mm thick, a slice of sample material, and a cover glass with a thickness of 0.2 mm. The parts of the thin section are assembled with glues with a fixed refractive index, usually between 1.5 and 1.6. The standard thickness of the sample material is 30 μm. The presence of a cover glass is important because the objective lenses of most microscopes have been constructed to give best results when a cover glass is present. Sections should therefore be studied with the cover glass towards the objective lens. Besides standard thin sections, a number of other sections are used for various purposes:

- *Large thin sections*, up to 20 cm long can be made for unusually coarse-grained rocks and large structures; they can be made in the same way as standard sections.
- *Polished sections* and thin sections without cover glass are used for microprobe work and for observation of opaque minerals in reflected light. They usually have a standard thickness of 30 μm and can also be used for normal microtectonic observations. If small scale, delicate structures are to be studied, it can be advantageous to use a polished rather than a standard thin section. Even better results are obtained with sections polished at both sides. Polished thin sections can also be used in other analytical equipment such as the microprobe and SEM, which has the advantage that the same feature can be observed by optical and other techniques (Chap. 10).
- *TEM sections* are prepared with a dissolvable resin such as lakeside, and without a cover glass. After a reconnaissance study of the structure by optical microscope, small rings are glued on the surface with araldite, and subsequently the thin section is emerged

in ethanol, which dissolves the lakeside and leaves the rock chip floating in the fluid; the metal rings remain attached to the chip since araldite does not dissolve in ethanol. The chip can now be broken into fragments to free the metal sample rings with the attached fragment of the rock chip. This fragment can be mounted with the metal ring in an ion-thinning device and subsequently be studied in the TEM (Sect. 10.2.5).

- *Ultrathin sections* with a thickness of 5 μm or even less are used to study minerals with a high birefringence such as calcite. Polishing of the surface is important in this case. Production of ultrathin sections is relatively difficult and requires some experience.
- *Ultrathick sections* are 100 μm thick and are polished on both sides. They are not mounted on a glass slide since they are thick enough to be handled without breaking. Because of their thickness, these sections show high order interference colours and are difficult to use for normal tectonic studies. However, they are suitable for microthermometry of fluid inclusions, since these remain intact in thick sections, but commonly fracture and leak in normal thin sections. Ultrathick sections are also useful to determine the orientation of planar and linear microstructures such as fluid inclusion walls, solid inclusions, grain and subgrain boundaries and axes of microfolds.
- *Thin sections of unconsolidated material* can be made in some cases. Samples can be taken using a small container that is pressed into the outcrop face, peeled of and closed with tape. The samples can even be oriented by measuring the orientation of the container. The sample should be impregnated with a raisin such as araldite before sectioning. Penetration of the impregnation fluid can be improved by applying a vacuum-technique (Stoffel 1976). If water-swelling clay minerals are present, samples can be cut with a diamond saw using isopropyl alcohol and should be impregnated with epoxy between cuts. Dehydrated kerosene can be used as a lubricant during polishing (Chester and Logan 1987).

12.7 Geometries in Thin Section – a Problem of Dimensions

Thin sections are cross-sections through complex three-dimensional structures and are therefore not always easily translated into their three-dimensional equivalents. There is a general tendency to simplify things in the sense that angles, sizes and shapes in thin section are directly assumed to be 'maximum values' in the three-dimensional shape, often with erroneous results. We therefore list some three-dimensional features and the limits within which the geometry of their two-dimensional sections will lie. Figure 12.2 demonstrates the importance of the preparation of several thin sections of different orientation in the case of complex or irregular geometries.

Grain diameter. The presence of grains of variable diameter in thin section does not mean that grains have variable diameter in three dimensions; even if small grains in an aggregate are equidimensional and have equal radius, the grain diameter in thin section will show both small and large grains, and all grain diameters are smaller than or equal to the true diameter (Fig. 12.2a). If the three-dimensional diameter is variable, the distribution of grain size in thin section will be even more irregular. If three-dimensional grain size has to be determined, e.g. the size of recrystallised grains in order to determine the differential stress (Sect. 9.6.2), a correction factor has to be used (Heilbronner and Bruhn 1998; Higgins 2000).

Grain shape. If grains are elliptical in thin section, the ellipticity will lie between the maximum and minimum elliptical ratios of the ellipsoidal shape in three dimensions. Even if all ellipses in the thin section have equal size and orientation, this does not necessarily mean that they represent the maximum ellipticity. An equidimensional shape of grains in thin section may occur if elongate grains are cut normal to their maximum elongation axis. The presence of a shape fabric in thin section may result from a planar or linear fabric in three dimensions. Planar structures are seen as lines in thin section and are therefore indistinguishable from linear structures. An interesting phenomenon that results from this relation may be observed in inclusions of porphyroblasts (Fig. 12.2b). If inclusions have a prolate ellipsoidal shape, as seems to be common in nature, some sections may show elongate aligned inclusions, and others equidimensional ones. The former porphyroblasts may be classified as inter- or syntectonic ones, and the latter erroneously as pretectonic (Fig. 7.9). This illustrates the need to investigate thin sections in at least two orthogonal sections if complex inclusion patterns are studied.

Ellipticity of tubes. Sections through elliptical tubes such as burrows or vermicular intergrowth in symplectites will have an ellipticity that is equal to or exceeding the ellipticity in a section normal to the tube (Fig. 12.2c). In sections parallel to the tube, the structure may resemble layering. Sheath folds (Sect. 5.3.2) can be considered as a special category of tubular structures (Fig. 12.2d); in sections parallel to the tube they resemble tight to isoclinal folds, while in other sections they appear as elliptical shapes.

Thickness of layering. Thickness of layering in thin section corresponds only to true thickness if the section is cut perpendicular to the layering (Fig. 12.2e); in other sections it exceeds true thickness.

Angle between planes and tightness of cylindrical folds. The angle between two planar elements in thin section can be greater or smaller than the true angle (Fig. 12.2f). This principle applies to the angle between a quartz grain

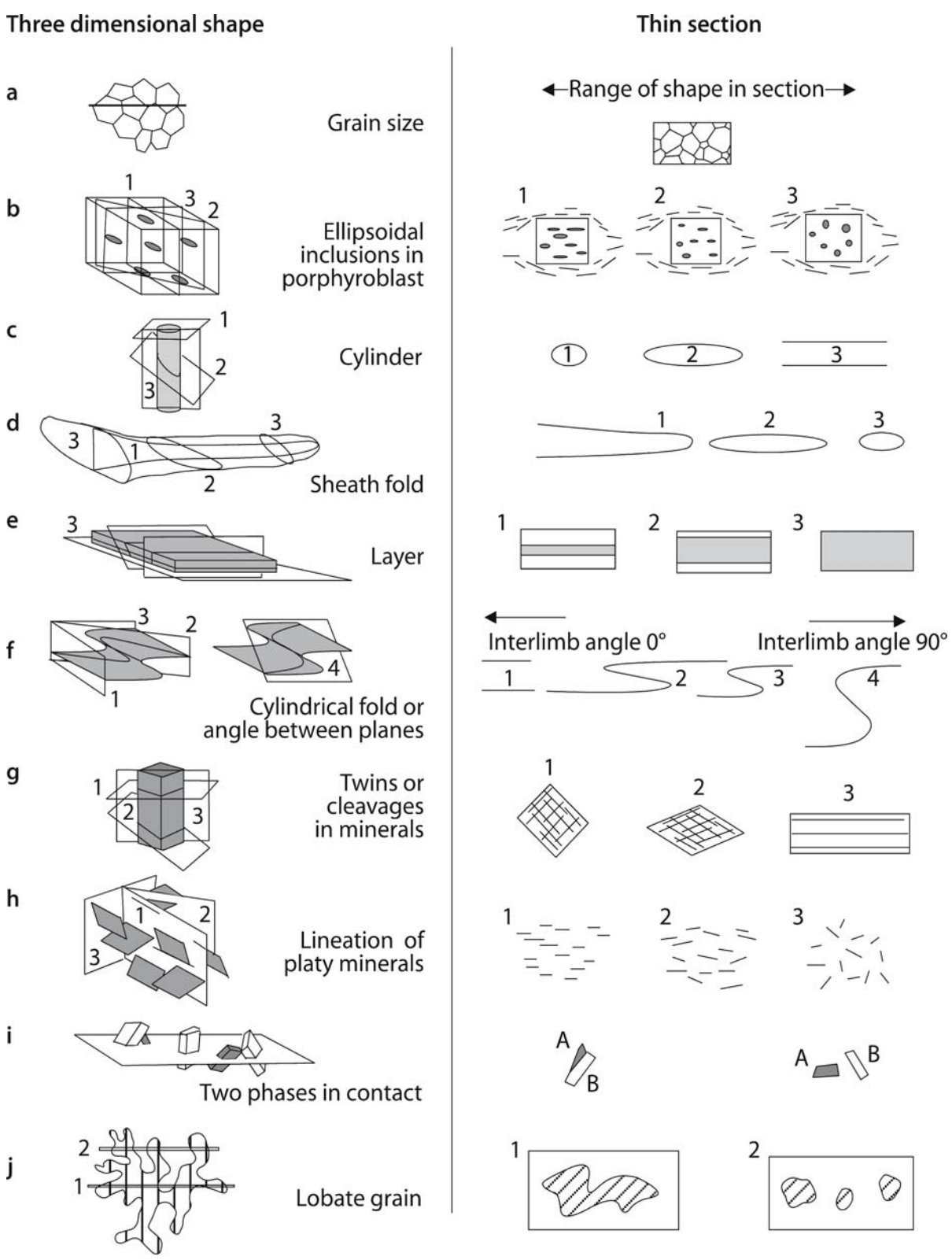


Fig. 12.2. Relationships of some three-dimensional geometries and the corresponding two-dimensional geometries visible in thin section. Two end-member geometries are shown in each case between which the geometries in thin section will lie. The *numbers* in the drawings refer to section planes. Further explanation in text

12.8

shape fabric and layering in a mylonite, but also to cleavage planes in minerals (Fig. 12.2g). By analogy, cylindrical folds in sections oblique to the fold axis may appear tighter, or less tight, than in sections perpendicular to the axis (Fig. 12.2f).

In sections parallel to an intersection lineation or fold axis, intersecting planes cannot be distinguished and seem to be parallel. Folds are not visible and the structure may resemble undisturbed layering. Polyphase deformation may be missed in this way; a crenulation cleavage may not be recognised if sections are cut parallel to the intersection lineation (the crenulation axis). Microkinks in large single crystals may be confused with undulose extinction or faults if cut parallel to the kink axis.

A special case exists where platy minerals or fractures are oriented in such a way that they share a common axis (Fig. 12.2h). In this situation, thin sections parallel to the joint axis may give the impression that a foliation is present, while those normal to the axis show no preferred orientation whatsoever.

Contact between minerals. In many cases it is critical to determine whether minerals are in contact or not. When minerals A and B are in contact in a thin section, they must be in contact in three dimensions (Fig. 12.2i); however, if A and B are not in contact in the section, they may or may not be in contact in three dimensions. This principle is important for the reconstruction of metamorphic reactions between minerals in rocks (Sect. 7.8).

Lobate grains. Large grains with a lobate shape may appear as such in thin section, but may also occur as isolated small sections through the grain that may resemble separate grains (Fig. 12.2j); the latter can lead to misinterpretation of grain size in a rock. However, isolated sections through lobate grains can usually be recognised since they all have the same crystallographic orientation. Lobate grains are common in high-grade gneisses and quartzites, and in dunites.

Complex arrangement of inclusions in porphyroblasts. Some porphyroblasts such as garnets can have a complex three-dimensional arrangement of inclusions that show completely different geometries in different sections (Figs. 7.36, 7.38). These complex patterns and their interpretation are discussed in Sects. 7.4–7.7.

Structures indicative of area change. Some structures such as those due to pressure solution (Figs. 3.7, 4.4, 4.20) can be interpreted in terms of an area increase or decrease in the plane of observation. Commonly such structures are erroneously interpreted to imply volume change; however, the presence or absence of volume change cannot be assessed in a single thin section, since information on the third dimension is lacking (Box 4.8).

12.8 Choosing the Orientation of Thin Sections

Thin sections should be cut in such an orientation as to obtain a maximum amount of information from a structure. From the examples given above, it may be clear that it is important to take the three-dimensional geometry of structures into consideration, before a choice of sectioning plane is made.

Lineations play an important role in determining how a thin section is to be cut. Object lineations, both as aggregate and grain lineations (Sect. 4.3, Fig. 4.2) are most useful if it can be shown that they represent the long (*X*) axis of the strain ellipsoid; in such cases, aggregate lineations can be referred to as stretching lineations (Sect. 4.3.1). This can be proven if, for example, clearly recognisable objects such as pebbles, enclaves or fossils are deformed. Note, however, that not all object lineations represent the *X*-direction of finite strain, and that some trace lineations can look very similar to object lineations.

Non-coaxial deformation histories (Sects. 2.7, 5.3) give rise to planar and linear fabrics with a monoclinic shape symmetry; sections normal to the symmetry axis, i.e. normal to the main foliation and parallel to a stretching or mineral lineation will give a maximum amount of information; they will show the true angle between foliation planes, the most asymmetric shape of porphyroclasts and sheath folds, and spiral structures in garnets. In principle, at least some thin sections should be cut normal to the lineation to check the nature of the fabric in this section; in rocks with a truly monoclinic shape symmetry in three dimensions, the fabric should have an orthorhombic symmetry in this section.

If folds are present with a fold axis parallel to the stretching lineation (curtain folds; Sect. 5.3.2), another section should be cut perpendicular to the fold axis if the folds are to be studied. Crenulation cleavages are best cut at right angles to the crenulation axis. If two intersecting foliations are present, sections should be cut perpendicular to the intersection lineation.

Porphyroblasts with inclusion patterns are best cut in several directions, e.g. parallel and normal to a stretching lineation of the same age as the blasts. If the internal structure of porphyroblasts is not clear, or if no lineations are visible in the rock, it may be useful to make a section parallel to the foliation in order to determine which section normal to the foliation is most advantageous. It is important to check whether a lineation is a stretching lineation or an intersection lineation (or both), and also whether it belongs to the same phase of deformation as the other fabric elements in the rock. If several lineations are present, if the internal structure of porphyroblasts is not clear, or if no lineations are visible in the rock, it may be useful to cut the sample in several directions and slightly polish the surfaces. If this does not help to decide which plane to choose for thin section preparation, thin sections should be cut from a single sample in several directions. Especially sections parallel to the foliation may help in such cases.