Abstract – The direction of movement on shear zones is important for reconstructions of the tectonical history in an area, but most important is the sense of displacement, which can be dextral or sinistral, normal or reverse. There is a large number of useful criteria for the deduction of the sense of shear in mylonites on a microscopic scale, and most are empirically established. A short summarize about porphyroclasts, mica fish and porphyroblasts as shear sense indicators is given. In use are porphyroclasts of relatively strong minerals with tails of dynamically recrystallized material known as mantled porphyroclasts. Different types of mantled porphyroclasts can be distinguished based on the geometry of the porphyroclast system: \( \Theta \)-type-, \( \sigma \)-type-, \( \delta \)-type- and complex objects. Often mantled porphyroclasts show stair-stepping, a reliable shear sense indicator if well developed. Mica fish, large isolated crystals of mica in a fine-grained recrystallized matrix, can also show stair-stepping. Large crystals grown during the deformation are called porphyroblasts. The classification of porphyroblasts is based on the porphyroblast-matrix relationship. For spiral-\( \delta_i \) porphyroblasts two models are discussed: rotational or non-rotational development (in respect to a geographical reference frame).
**Introduction**

When rocks are deformed, the distribution of deformation is not homogeneous, there are rather parts of high or low strain respectively. One of the most common patterns of this heterogeneous deformation is the concentration of deformation in planar zones that accommodate movement of relatively rigid wall-rock blocks. Deformation of such high-strain zones usually contains a rotation component, reflecting lateral displacement of wall rock segments with respect to each other; this type of high-strain zone is known as a shear zone.

Shear zones can be subdivided into brittle zones or faults, and ductile zones. Ductile shear zones are usually active at higher metamorphic conditions than brittle shear zones (Fig. 1). In major shear zones which transect the crust or upper mantle, the depth of the transition between brittle and ductile behaviour changes. It depends on many factors such as bulk strain rate, geothermal gradient, grain size, lithotype, fluid pressure, orientation of the stress field and pre-existing fabrics. Rocks in major shear zones commonly show evidence of several overprinting stages of activity at different metamorphic conditions since shear zones are easily reactivated.

![Fig. 1: Distribution of the main types of fault rocks with depth in the crust. From [6]](image_url)

A special terminology is used for rocks that have been deformed in shear zones, partly independent of their lithology. They are usually referred to as fault rocks, even if deformed in ductile shear zones. The most common types are brittle fault rocks, mylonites and striped gneiss. This paper deals only with ductile deformation and some of its geometric patterns, so mylonites or rocks with a mylonitic fabric are briefly to discuss.

**Mylonites**

A mylonite is a foliated and usually lineated rock that shows evidence for strong ductile deformation (Fig. 2). Originally it was defined as a brittle fault rock, the word derives from the Greek ‘μυλόν’, a mill, but now mylonites are thought to have formed predominantly by crystalplastic flow of the matrix. The term ‘mylonite’ is not to be used as a rock name in a stratigraphic sequence, because it does not give any information about the mineral composi-
tion of the rock, it rather describes the fabric containing elements with a monoclinic [inclined to one side] shape symmetry.

![Mylonite derived from pelitic gneiss with quartz, feldspar, garnet and micas, in a section parallel to the stretching lineation and normal to the foliation. Alternating layers rich in quartz (clear) and feldspar (grey), with porphyroclasts of garnet define the mylonitic foliation. Marsfjällen, Sweden. Width of view 13 mm. PPL. From [6]](image)

Mylonites occur in high-strain zones (mylonite zones) and are interpreted as exhumed ductile shear zones. They can be found in any rock type. Grain size in the mylonite is usually smaller than that in the wall rock and they can be recognised in the field by their characteristic fabric elements such as stretching lineation, low strain lenses, oblique folds, C-type shear bands and mantled porphyroclasts.

The direction of movement on a shear zone is usually assumed to lie subparallel to striations, slickenfibres or stretching and mineral lineations. In addition to the direction the sense of displacement, the sense of shear, has to be determined (sinistral or dextral, normal or reverse). This can be done by using markers in the wall rock such as displaced layering and dykes or deflection of layering or foliation into a shear zone. Additionally, the geometry of structures in the zone on a microscopic scale can be used. Microscopic shear sense indicators in mylonites can be (for example): Foliation orientation; oblique foliations; shear band cleavages; mantled porphyroclasts; mica fish; porphyroblasts; quarter structures; strain shadows. Porphyroclasts, mica fish and porphyroblasts are discussed in this paper.

**Mantled Porphyroclasts**

Porphyroclasts are single crystals of a size exceeding the mean grain size in the surrounding matrix and typical for mylonites. They are relic structures of a more coarse-grained original fabric. Common minerals that form porphyroclasts are feldspar, garnet, muscovite, hornblende and pyroxenes.
Porphyroclasts are often flanked by tapering grain aggregates which form a structural unit with the porphyroclasts (Fig. 3). If such aggregates have the same mineral composition as the porphyroclast, they are called mantles, and the hole structure as a mantled porphyroclast. If the flanking aggregate consists of another material as the porphyroclast, they are called strain

**Fig. 3:** Mylonite derived from a narrow shear zone transecting a weakly deformed granodiorite. Numerous mantled porphyroclasts mostly of feldspar. Section normal to the foliation and parallel to the stretching lineation. Saint Barthélemy Massif, Pyrenees, France. Width of view 4 mm. PPL. From [6]

**Fig. 4:** Quartzite mylonite with a $\delta$-type (centre) and small $\sigma$-type porphyroclasts of K-feldspar. Section parallel to the stretching lineation and normal to the foliation. Dextral shear sense. St. Barthélemy Massif, Pyrenees, France. Width of view 6 mm. PPL. From [6]
Important mechanisms for the development of mantled porphyroclasts are crystalplastic deformation and storage of dislocation tangles in the rim of a porphyroclast due to flow in the matrix. The mantled structure results from recrystallization of the rim to a core-and-mantle structure with the mantle being softer than the porphyroclast.

The mantle can be deformed into wings (or tails) that extend on both sides of the porphyroclast parallel to the shape fabric in the mylonite (Fig. 4). These wings stretch and change shape while the porphyroclast core remains rigid or continues to recrystallize in the rim, shrinking in size.

The interpretation of such porphyroclast systems in the study of flow patterns in rocks has been hampered by their often highly variable shape. Five types of mantled porphyroclasts have been distinguished in the literature (PASSCHIER and TROUW 1998).

Classification of Porphyroclast Systems

As illustrated in Fig. 5, the five main types are:

Θ-type: Lack of wings; internal symmetry.

φ-type: Mantle with orthorhombic symmetry; no stair-stepping.

σ-type: Monoclinic shape symmetry; wide mantles near the porphyroclast with two planar faces and two curved faces that define an internal asymmetry; the wings lie at different elevation on both sides, what is referred to as stair-stepping. σ-type objects can be subdivided into two groups:

σa-type: Isolated in a mylonitic matrix; consist of weakly anisotropic minerals such as feldspar, hornblende or apatite; recrystallized wings are usually equigranular and structureless.

σb-type: Part of developing C/S-fabrics: In quartz-feldspar mylonites the C-planes tend to enclose large porphyroclasts of feldspar, and dynamically recrystallized material from the feldspar grain mantle is deflected along them; tend to occur in clusters.

δ-type: Monoclinic shape symmetry; narrow wings and characteristic bends in the wings adjacent to the porphyroclast; as a result, two embayments of matrix material occur adjacent to the porphyroclast; not all δ-type objects have stair-stepping; occur only around equidimensional or very slightly elongate porphyroclasts.

Complex objects: Monoclinic shape symmetry; more than one set of wings.
Development of Mantled Porphyroclasts

A porphyroclast in a flowing fine-grained matrix will cause a perturbation of the flow field (Fig. 6). With progressive deformation, particles adjacent to the porphyroclast move in ellipses, but further away the presence of the porphyroclast causes only a deflection of the displacement paths. In simple shear, a boundary can be defined between the far field displacement paths and the elliptical paths, known as separatrix. Experimental data (PASSCHIER et al. 1993) show that the separatrix around a spherical porphyroclast can have an ‘eye-shape’ or a ‘bow-tie-shape’ in a section normal to the rotation axis of the porphyroclast (Fig. 6). If a soft mantle exists around the porphyroclast, it will be deformed in the flow and the geometry of the deformed mantle depends, for a spherical porphyroclast, on the thickness of the mantle and the exact shape of the separatrix. Wide mantles (separatrix in mantle) give rise to $\phi$- or $\sigma$-type objects in eye- or bow-tie shaped separatrices respectively, thinner mantles (separatrix intersects mantle) to $\delta$-type objects by wrapping of the wings around the rotating central porphyroclast, and very thin mantles (mantle in separatrix) give no wings at all ($\Theta$-type objects).

Only a bow-tie-shaped separatrix leads to stair-stepping. If the porphyroclast is recrystallising syntectonically, the separatrix will shrink and $\sigma$-type objects will develop; if the porphyroclast has an elongate shape, the separatrix will change shape while the object rotates and secondary wings may form, resulting in complex objects.

Porphyroclasts as Shear Sense Indicators

$\sigma_a$-type-, $\sigma_b$-type-, $\delta$-type- and complex objects can be used as shear sense indicators using their internal asymmetry, and the stair-stepping of the wings; the wings step up in the direction of movement of the upper block. To determine the stair-stepping symmetry, a reference plane (Fig. 7) has to be defined that contains the symmetry axis of the porphyroclast system ($x_3$) and its normal ($x_1$) parallel to the relatively planar trace of the tail outside the complex deformation domain bordering the central porphyroclast.
Care should be taken in inhomogeneous mylonite with many large porphyroclasts; if a mantled porphyroclast lies between two large rigid objects, its asymmetry may reflect the relative movement of these two objects rather than the bulk shear sense in the shear zone. If the wings are long, stair-stepping is easily detectable and wings trend subparallel to the main foliation in the rock (Fig. 8).

**Fig. 8:** Tails of porphyroclast systems stretch far away from central clasts. Types can be distinguished, reference planes drawn and sense of vorticity determined from stair stepping of tails and other internal asymmetry markers. From [4]

### Mica-Fish

Single crystals of mica in a fine-grained mylonitic matrix are called mica fish. They are most common in micaceous quartzite mylonite and ultramylonite. Characteristic for mica fish are their lozenge shape and monoclinic shape symmetry with one curved and one planar side (Fig. 9), similar to $\sigma_a$-type porphyroclasts. They lie with their long axis in the extensional quadrant of the deformation and show a steeper inclination to the fabric attractor (thought line towards rigid objects rotate during deformation) than mylonitic foliation (Fig. 9), which can be used as a shear sense indicator together with their asymmetry. The stair-stepping of trails of small mica fragments, commonly extending into the matrix from the tips of isolated mica-fish (Fig. 10), can also be used as a shear sense indicator. Little is known about the evolution of mica fish, but their development probably results according to PASSCHIER and TROUW (1998) from combined slip on the basal plane, rigid body rotation, boudinage and recrystallization at the edges.

In some cases, other minerals such as kyanite and feldspars can show a similar geometry as mica fish, what may have a similar kinetic significance.
Porphyroblasts

As porphyroclasts, porphyroblasts are relatively large, single crystals in a fine grained matrix. But whereas porphyroclasts (from ‘clasis’ - breaking) are inferred to have formed by diminuation of the grain size in the matrix, porphyroblasts (from ‘blasis’ - growth) have formed by metamorphic growth of crystals of specific mineral species while crystals in the matrix did not grow to the same extend. Due to inclusion patterns which can mimic the structure in the rock at the time of growth, porphyroblasts are a valuable source of information on local tectonic and metamorphic evolution, in special cases also as shear sense indicators.

The distribution and size of porphyroblasts in a metamorphic rock depend on the amount of nucleation sites and the rate at which the nuclei grow. If many suitable sites are available, many small porphyroblasts may form, if few suitable sites are present, isolated large crystals develop. The growth process is mainly controlled by diffusion. Elements necessary for growth that are not present have to be transported to the surface of the porphyroblast. Minerals adjacent to the growing grain that do not participate in the mineral reaction have to be removed by dissolution and diffusion. In most cases, especially at low to medium-grade metamorphism, these minerals are not removed completely but are overgrown and enclosed by the porphyroblast as passive inclusions. A compositional layering or a shape-preferred orientation of grains is preserved by the included grains resulting in an inclusion pattern (Fig. 11 a). In this way, straight foliation can be visible, but also more complex patterns such as folds or crenulation cleavages.

Surfaces of aligned elongate inclusions within porphyroblasts are referred to as S₁ (i for internal) whereas the foliation outside the porphyroblasts is called Sₑ (e for external) (Fig. 11 b).

Fig. 10: Mica fish from a quartzite mylonite, wings of mica fragments show stair-stepping. Quartz in the matrix is dynamically recrystallized and developed an oblique foliation. Dextral shear sense. Minas Gerais, Brazil. Width of view 4 mm. CPL. From [6]
Fig. 11: a Diagram illustrating how an Al-silicate porphyroclast may grow in a mica-rich matrix. Opaque minerals and quartz are taken up as inclusions and their preferred orientation and distribution is mimicked by the inclusions. b Commonly used terminology for porphyroblasts. From [6]

If deformation occurs after porphyroblasts growth, $S_i$ may have a different orientation from $S_e$. The deformation will affect the matrix but not change the included structure. The inclusion patterns may undergo rigid body rotation but will retain a record of the structure in the rock at the time of porphyroblast growth (Fig. 12).

Fig. 12: Intertectonic garnet porphyroblast in garnet-mica schist. The garnet overgrew a straight fabric ($S_i$) that has been deformed in the matrix by later deformation resulting in crenulation and relative rotation of about 90° of the garnet with respect to $S_e$. Tärneby, Norrbotten, Sweden. Width of view 20 mm. Polarisers at 45°. From [6]

Classification of Porphyroblasts
The classification of porphyroblasts is based on the porphyroblast-matrix relation. Describing the time relation between porphyroblast growth and one or two specific phases of deformation, the terms pre-, inter-, syn- and posttectonic are used (PASSCHIER and TROUW 1998). The matrix-deformation in the surroundings of the porphyroblast is normally represented by a foliation or by folding (Fig. 13).

The four types can be explained shortly as follows:

- **Pretectonic** porphyroclasts grow in a deformation-free rocks, particularly under contact-metamorphic conditions (low pressure-high temperature metamorphism). Inclusions are randomly oriented (A, B in Fig. 13) or show sector zoning.
- **Intertectonic** grow of porphyroclasts is interpreted as grown over a secondary foliation. They are surrounded by a matrix affected by a later deformation phase that did not leave any record in the inclusion pattern of the porphyroblast (C, D in Fig. 13).
- **Syntectonic** porphyroblasts are the most frequently encountered type of porphyroblasts and have grown during a single phase of deformation. A large variety of microstructures can form in this group (E, F in Fig. 13). Inclusion patterns are generally curved in these porphyroblasts; included folds are known as helicitic folds.
- **Porphyroblasts** grown after the deformation are posttectonic. They are defined by the absence of deflection of $S_e$, strain shadows, undulose extinction or other evidence of deformation which is common to pre-, syn- and intertectonic porphyroblasts.

**Fig. 13 A-H:** Schematic representation of pre-inter-, syn- and posttectonic porphyroblast growth. The left-hand part of the diagram refers to deformation resulting in a single foliation or deformation of an earlier foliation without folding; the right-hand part considers deformation resulting in crenulation of an older foliation. From [6]
Porphyroblasts

Intertectonic and especially syntectonic porphyroblasts are of interest for shear sense analysis. Rigid objects suspended in a deforming matrix rotate with respect to the instantaneous stretching axes (ISA) of flow. Equidimensional inter- and syntectonic porphyroblasts with oblique (Fig. 15 a) and spiral-shaped $S_i$ patterns (Fig. 14) are believed to be natural examples of such objects that rotated with respect to ISA, capable of indicating sense of shear.

Two basic types can be distinguished:
- Oblique-$S_i$ porphyroblasts;
- Spiral-$S_i$ porphyroblasts.

The development of oblique-$S_i$ porphyroblasts seems clear: 1. creation of a foliation $S_e$; 2. growth of the porphyroblast; 3. deformation that causes relative rotation of the porphyroblast and $S_e$.

![Fig. 14: Syntectonic spiral-$S_i$ garnet in micaschist, showing a double spiral of inclusions. One spiral consists of coarse quartz grains that nearly divide the garnet into two parts; the other spiral consists of fine graphite inclusions in massive garnet. Aiuruoca, Minas Gerais, Brazil. Width of view 10 mm. PPL. From [6]](image)

Such porphyroblasts are intertectonic. But the interpretation of the porphyroblast in Fig. 15 a has to be done carefully. It could be formed in dextral non-coaxial flow causing a dextral rotation with respect to a stable $S_e$ and to flow ISA (Fig. 15 b). Another explanation could be sinistral rotation of $S_e$ with respect to ISA and to a stationary porphyroblast in coaxial flow (Fig. 15 c) or even a stationary porphyroblast in sinistral non-coaxial flow (Fig. 15 d). These alternatives would give an entirely different tectonic significance to the structure. Oblique-$S_i$ porphyroblasts have to be used with care as shear sense indicators.

Spiral-$S_i$ porphyroblasts are relatively common in garnet, staurolite, albite and several other minerals, but well-developed spirals of $S_i$ with a relative rotation angle exceeding 180° (also known as snowball structures (Fig. 14)) seem to be restricted to garnet.
The development of spiral-$S_i$ garnets by porphyroblast rotation with respect to ISA of bulk flow has been questioned by BELL et al. (1985, 1986, 1989). They advocated the theory of non-rotating porphyroblasts, which is based on so-called truncation planes where the inclusion pattern is interrupted. They interpreted $S_i$ on both sides of a truncation plane (Fig. 16 b) as representing separate deformation phases and the spiral fabrics as successively overgrown helicitic folds during up to eight subsequent deformation phases, included without rotation of the porphyroblast with respect to geographical coordinates.

PASSCHIER (1998), advocate of the rotation model, gives an explanation of these truncation planes including rotation of the porphyroblast (Fig. 16): “If development of a syntectonic porphyroblast is temporarily interrupted by local dissolution in the strain caps, renewed growth over the strain caps causes development of truncation planes.” The debate about the two models how spiral-$S_i$ porphyroblasts grow is still going on. Careful investigation of the geometry of spiral-$S_i$ porphyroblasts is therefore needed as well as other shear sense indicators before an attempt is made to give an explanation of the structure.

**Fig. 15:** a Intersectonic porphyroblast with straight $S_i$ oblique to $S_e$ (oblique-$S_i$ porphyroblast). This structure can be formed by: b dextral rotation of the porphyroblast with respect to a less-rotating foliation in dextral non-coaxial flow; c rotation of the foliation around a stationary porphyroblast in coaxial flow and d if it lies in, and is coupled with a non-deforming or coaxially deforming microlithon (grey). From [6]

**Fig. 16 a, b:** Development of deflection planes and truncation planes around a syntectonic periodically growing porphyroblast in non-coaxial progressive deformation. The foliation and the porphyroblast rotate with respect to each other. Strain caps and strain shadows develop around the porphyroblast during progressive deformation. From [6]
References