Univ. Zambia

Shear Sense indicators
and
Shear zones

Davis et al, 2012)

What is a Shear Zone?

Shear zones are tabular to sheetlike, planar or curviplanar zones in which rocks are more highly strained than rocks adjacent to the zone.

At scales ranging from a thin section to an outcrop to a region, deformation is commonly not homogeneous.

But is instead concentrated into highly deformed zones within less deformed rocks.

The general term for such zones is **high-strain zones**.

But most high-strain zones have a noncoaxial shear component to the deformation and so are simply called **shear zones.**

Shear zones represent a final category of basic geologic structures.

Like faults, they accommodate offset, but the offset is distributed across the thickness of a tabular zone that is centimeters, meters , or even kilometers thick (Fig. 1.42).

Unlike ordinary fault surfaces, shear zones commonly do not display any discrete physical break.

Instead displacement is achieved without loss of cohesion and continuity, although rocks “caught up” in shear zones may undergo extreme changes in shape and orientation.

The penetrative distributed offset within shear zones can be expressed by the presence of pervasive foliation and lineations.

Shear zones typically represent the deep root of faults at levels where elevated temperature permits the crustal rocks to flow

Mylonites (Shear Zones) and kinematic indicators

Mylonites

In the central parts of some plastic shear zones, for example the one shown in Fig. 15.10, strain can get so high that pre-existing textures and structures are totally flattened and transposed.

The rock becomes strongly banded and is called a mylonite (word coined by earlier workers in the Scottish Moine Thrust Zone).

Figure 15.10 A shear zone in the Diana Syenite in Harrisville, New York State, showing profound strain increase toward the central ultramylonitic part of the zone. This is expressed by the change in orientation of the foliation and a marked decrease in grain size in the zone. Photo: Graham B. Baird.

Mylonite versus Cataclasite

The term mylonite had at least two different meanings through the last century. The word stems from the Latin word for milling or crushing into fine pieces.

But with the aid of optical and electron microscopes, we now know that mylonites are formed mainly by plastic deformation mechanisms.

The term mylonite is now being used for strongly deformed rocks that have been exposed to grain size reduction due to plastic deformation.

On the otherhand, the related term cataclasite is used where cataclastic flow dominates.

Kinematic (Shear-sense) Indicators (Determining sense of shear)

Our understanding of microstructures as kinematic indicators in shear zones and mylonite zones increased considerably during the 1970s and 1980s.

Understanding the connection between structural asymmetry and kinematics represented an important breakthrough in the study of strongly sheared rocks.

The key point is that many mylonites contain asymmetric structures.

The asymmetry is related to the rotational component or non-coaxiality of the deformation, or the fact that objects rotate in a preferred direction, as shown in Figure 15.20.

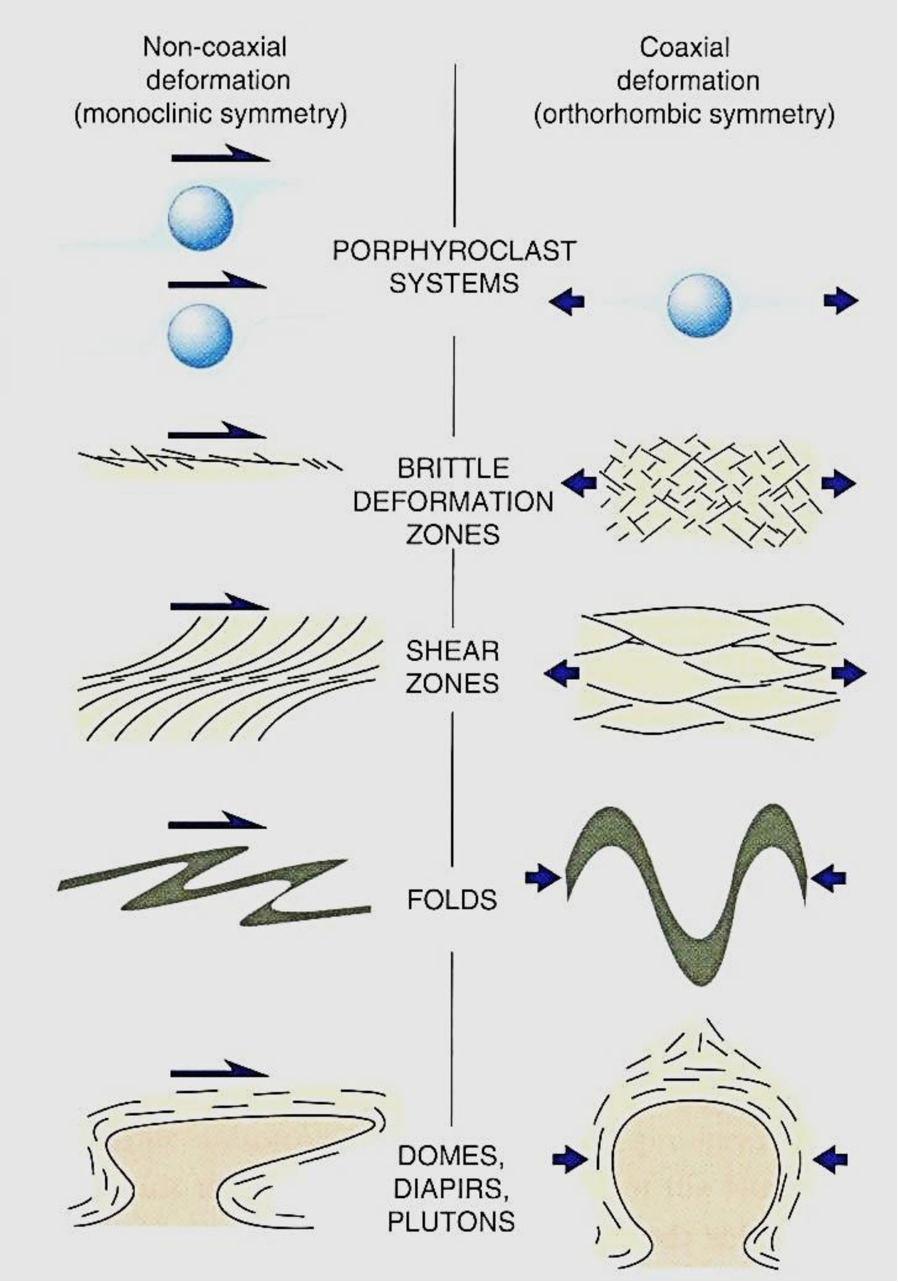

Fig. 15.20: Asymmetric structures (left side) characterize non-coaxial deformation, while coaxial deformations tend to result in more symmetric structures.

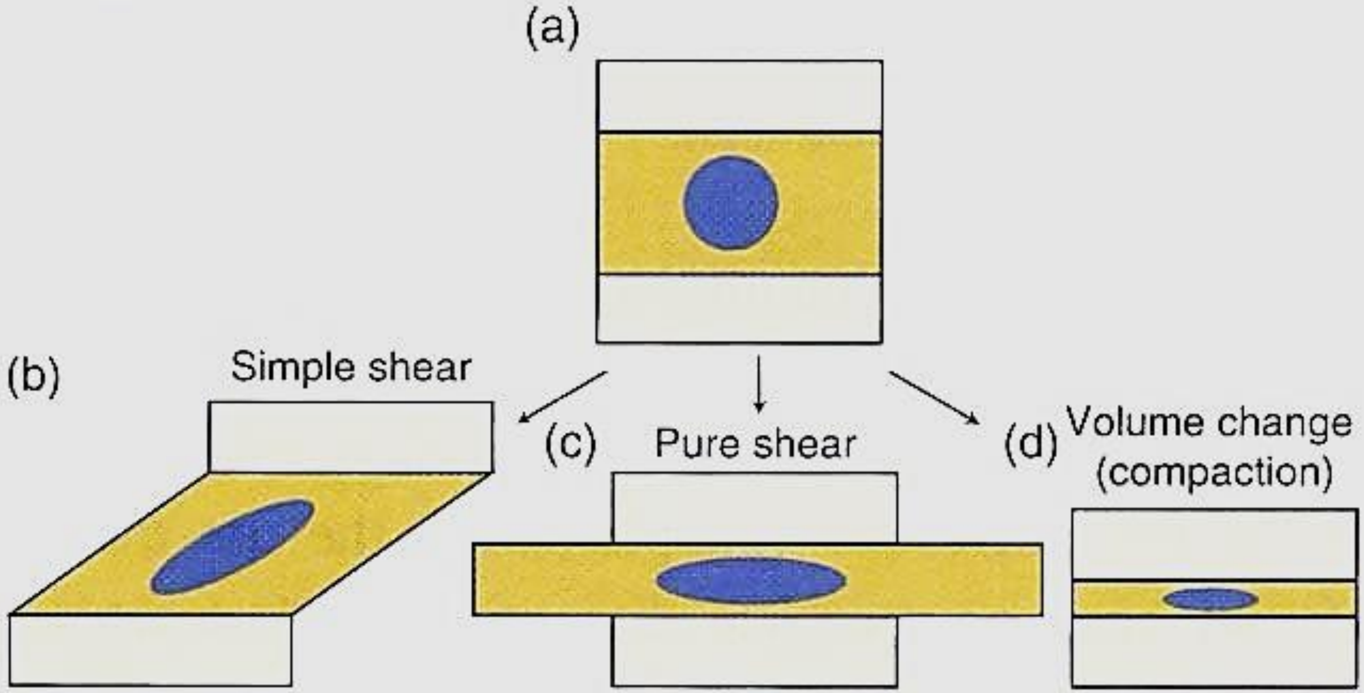

Figure 15.8 The difference between simple shear, pure shear and isotropic vertical volume change.

Ideal shear zones are perfectly ductile and involve simple shear with or without additional compaction/dilation.

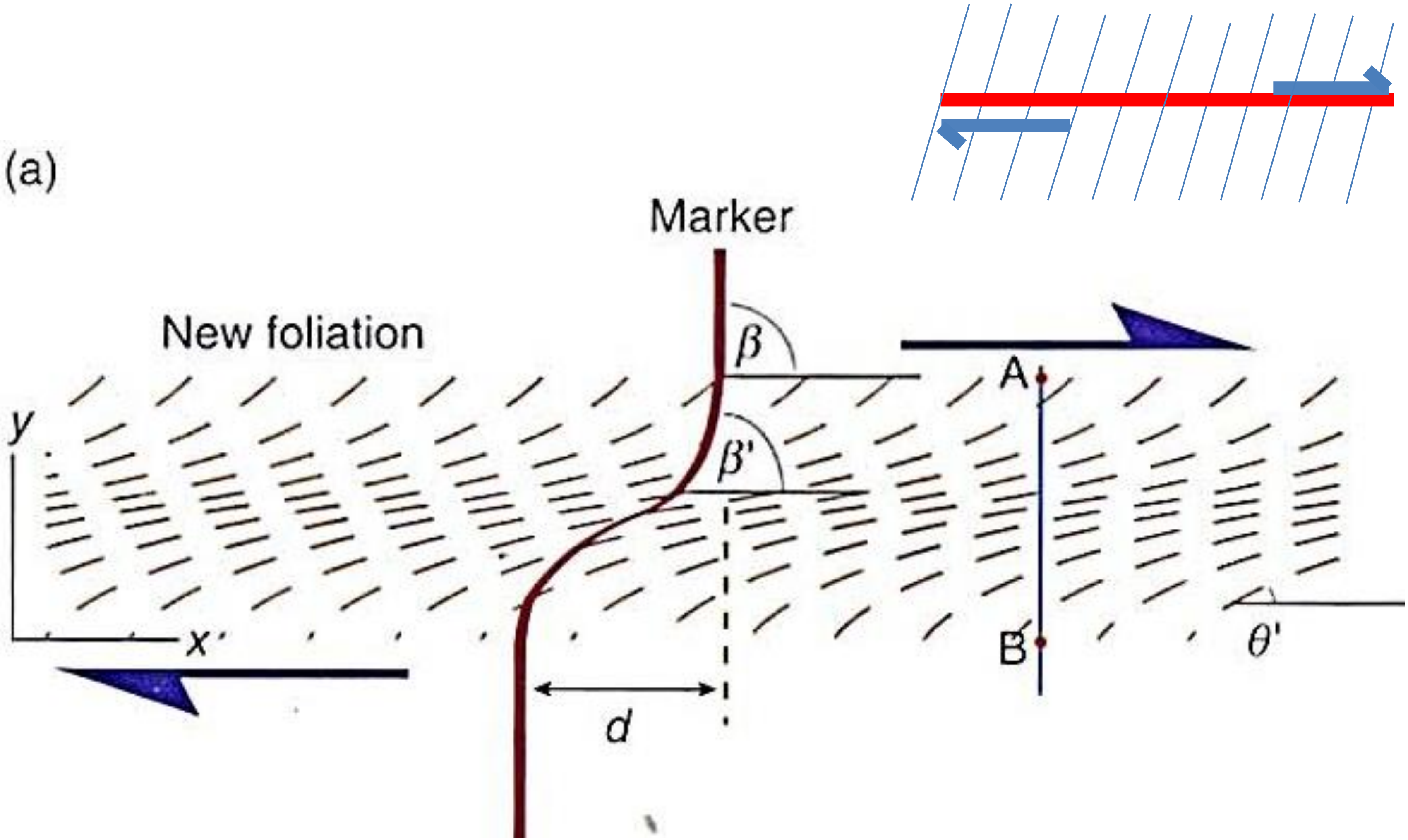

Fig. 15.7. (a) Shear zone with generically related foliation. The foliation makes 45° with the shear zone along the margins. This angle is reduced as strain increases towards the center of the zone. 0 is the angle between the shear zone and the foliation.

The (a)symmetry of mylonite structures can be used to evaluate the sense of shear.

It is the monoclinic structures that give information about the sense of displacement or sense of shear in mylonite zones.

In a shear zone we primarily study the section perpendicular to the foliation that contains the lineation (Fig. 15.21).

The section perpendicular to the lineation can also be of interest for evaluation of three-dimensional deformation.

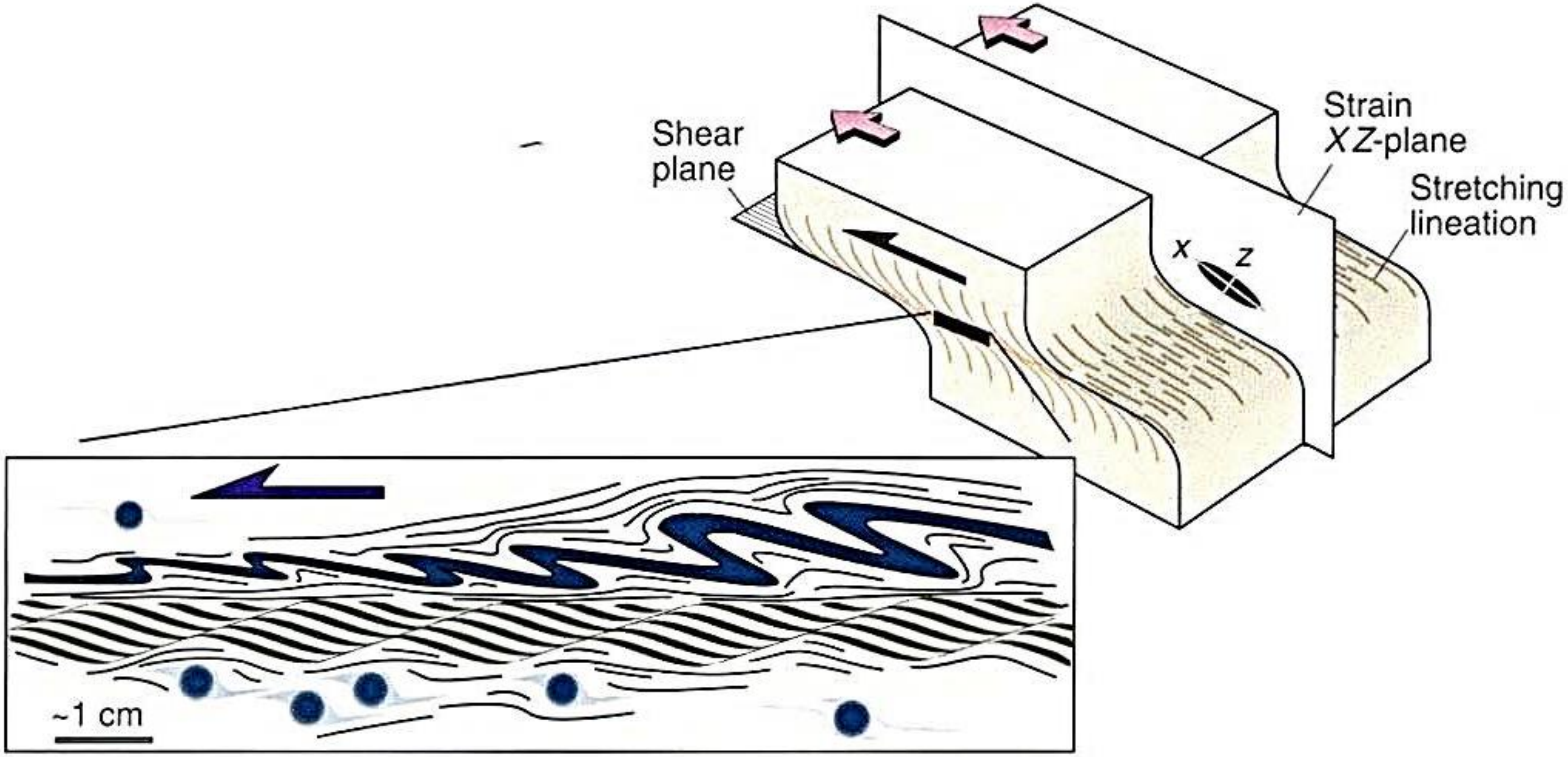

Fig. 15.21: Illustration of the section of observation for shear-sense determination, and some common asymmetric structures that consistently indicate sense of shear

Determining Sense of Shear

One of our main goals in studying shear zones is to determine the overall sense of shear- the direction one side of a shear zone is displaced laterally relative to the other side.

The study is very important in structural geology. They are the key to unraveling the tectonic history of many regions.

Shear-sense indicators are those features that reveal the sense of shear for a deformation.

They come in a variety of expressions and are most commonly observed at the scale of an outcrop or thin section.

However, they range in scale from geologic map patterns of large regions to X-ray analyses of tiny parts of a single sample.

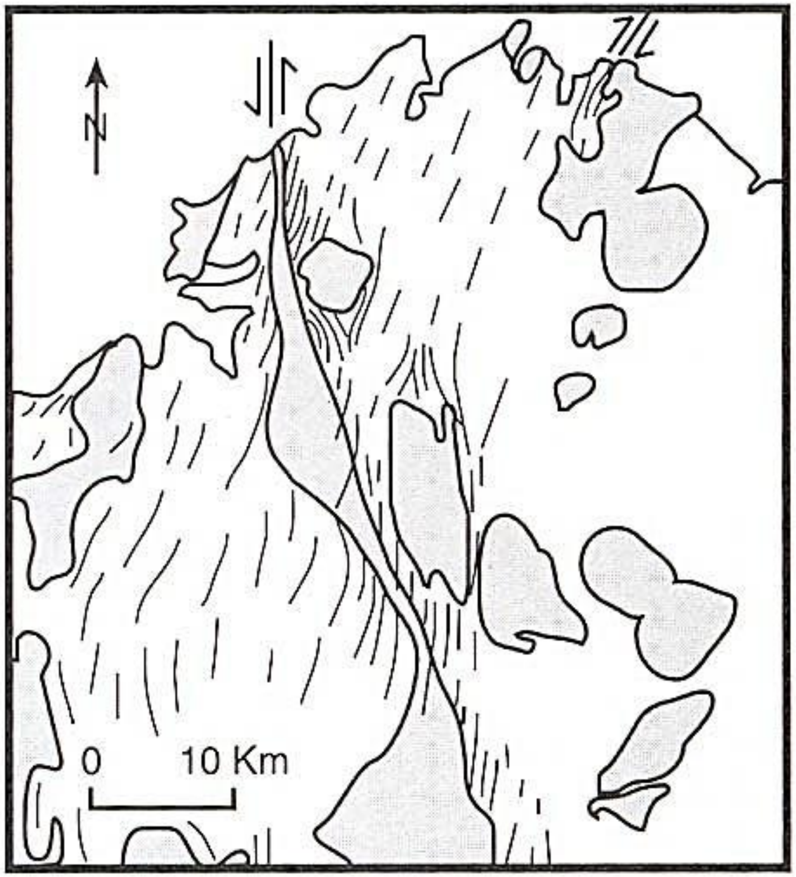

Figure 9.39 Foliation patterns in regional shear zones in the Iberian Arc, Galicia, Spain. (Reprinted with permission from *Journal of Structural Geology*, v. 2, Ponce de Leon, M. I. and Choukroune, P., Shear zones in the Iberian Arc, 1980, Elsevier Science Ltd., Pergamon Imprint, Oxford, England.)

A Frame of Reference

To determine the sense of shear for a shear zone, we need to have a convenient frame of reference and we need to know in which direction we should look (Fig. 9.34).

This is true whether we are examining a natural outcrop or a thin section.

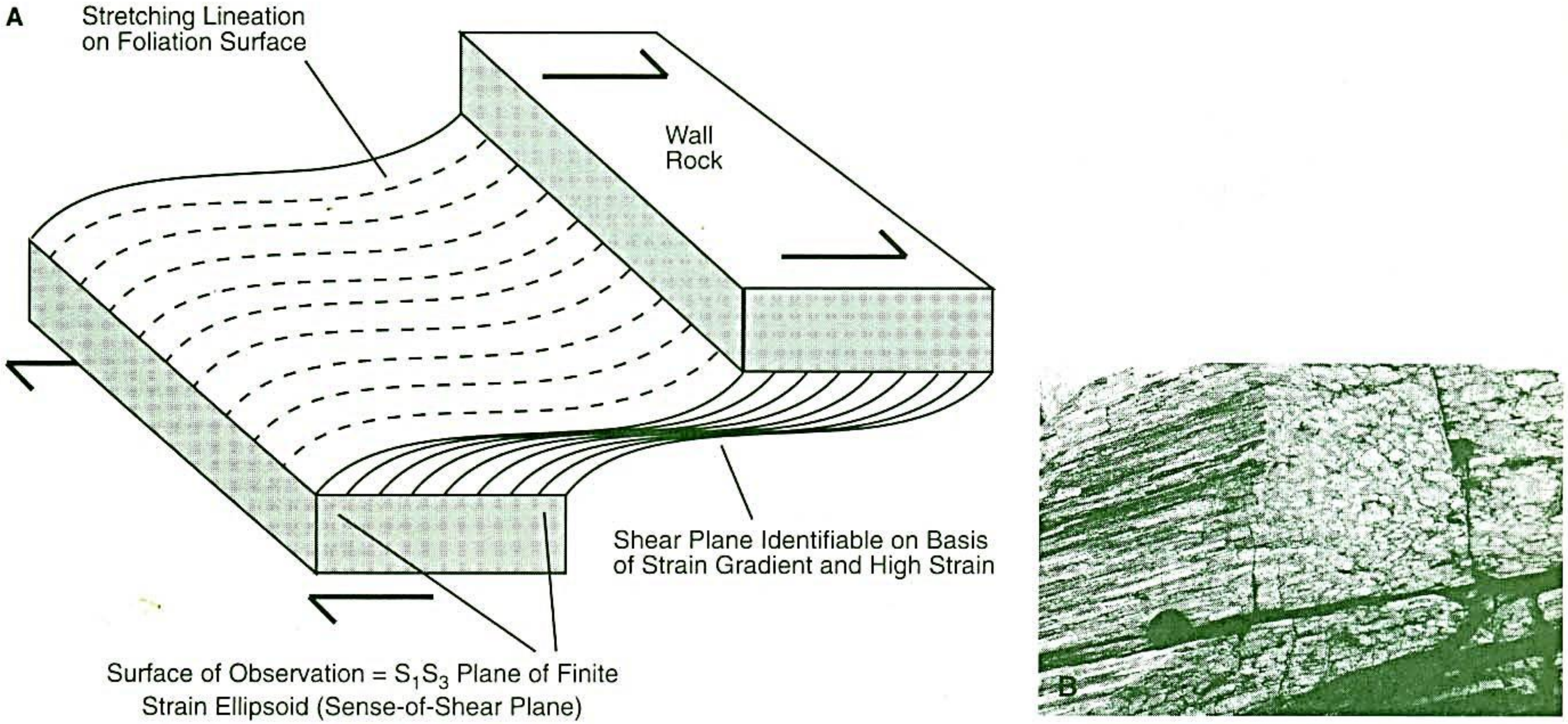

Figure 9.34 Relation of the sense-of-shear plane to structures in the rock. (*A*) Choose a rock face cut parallel to lineation and perpendicular to foliation to determine the sense of shear. This face will be parallel to the S_1S_3 plane of the finite strain ellipsoid. [Modified from Hanmer and Passchier (1991). Courtesy of the Geological Survey of Canada.] (*B*) Mylonitic quartz-pebble conglomerate, Tortolita Mountains, southern Arizona. Sense-of-shear plane is face on left, which is cut parallel to lineation and perpendicular to foliation. Face on right, cut perpendicular to lineation, reveals the conglomeratic nature of the protolith. (Photograph by S. J. Reynolds.)

For most ductile shear zones, the shear zone itself is the most convenient reference frame because generally it is a tangible feature that can be seen in the field and is parallel to the shear plane of the deformation.

The following are the most common shear-sense indicators.

We restrict the discussion to shear-sense indicators found in ductile, brittle-ductile, and semibrittle shear zones (brittle shear zones are related to faults).

The Common shear-sense indicators:

1. Offset markers
2. Deflection of markers
3. Foliation patterns
4. (a) Shear bands, (b) S-C Fabrics, and (c) Oblique Microscopic foliation
5. Mica Fish
6. Rotation of Inclusions
7. Pressure Shadows
8. Porphyroclasts and porphyroblasts
9. Foliation Fish
10. Fractured and Offset Grains
11. Veins
12. Folds

1. Offset Markers

Perhaps the most unambiguous shear-sense indicator is an offset marker, such as a distinctive dike, lithologic layer, or other rock unit (Fig. 9.35A).

In this case, we can determine both the amount and sense of displacement, as long as we are certain that the similar-appearing features on opposite sides of the shear zone are indeed equivalent and were originally continuous across the zone.

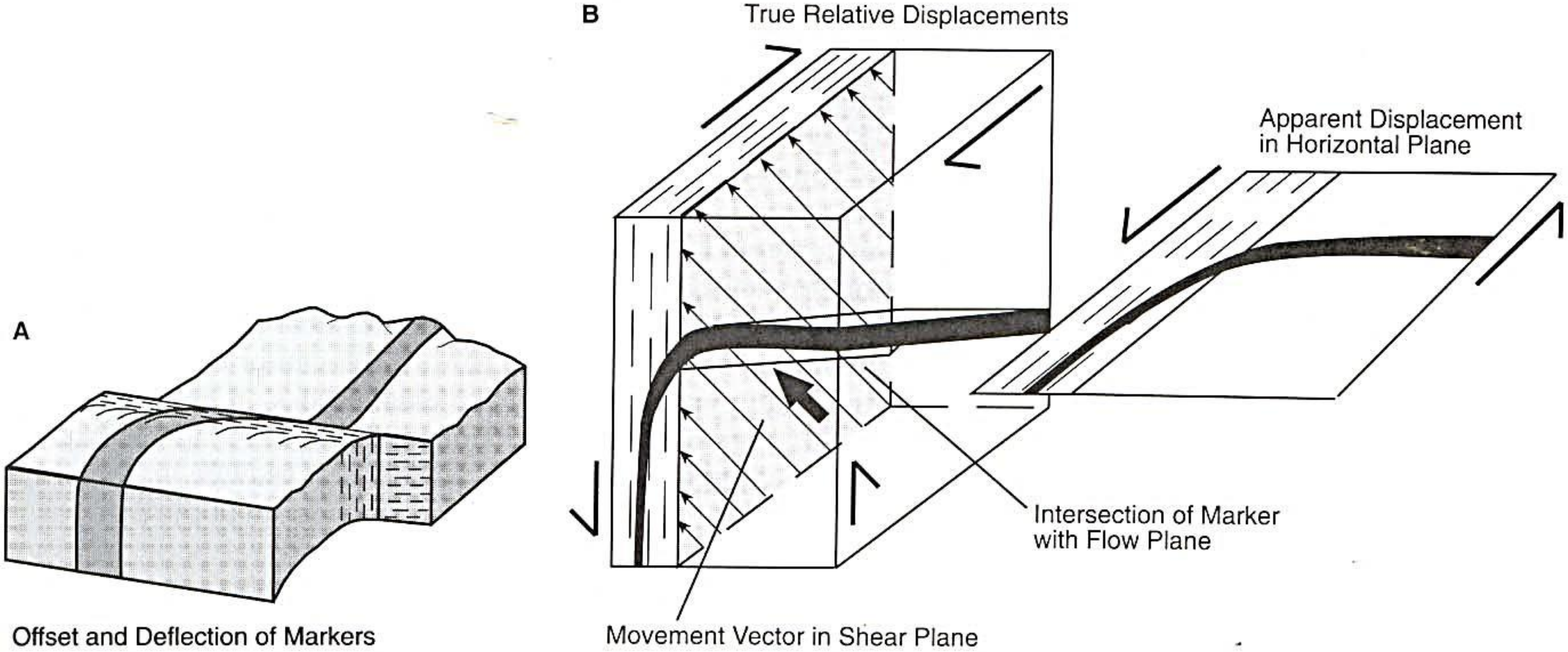

Figure 9.35 Offset and deflection of markers in ductile shear zones. (*A*) Discontinuous shear zone with dextral offset. Note deflection of marker into shear zone prior to its truncation. (*B*) Apparent relative displacement on a single improperly oriented surface (horizontal plane on right) may not reflect true displacement (arrows within plane of shear zone on left). [Modified from Hanmer and Passchier (1991). Courtesy of the Geological Survey of Canada.]

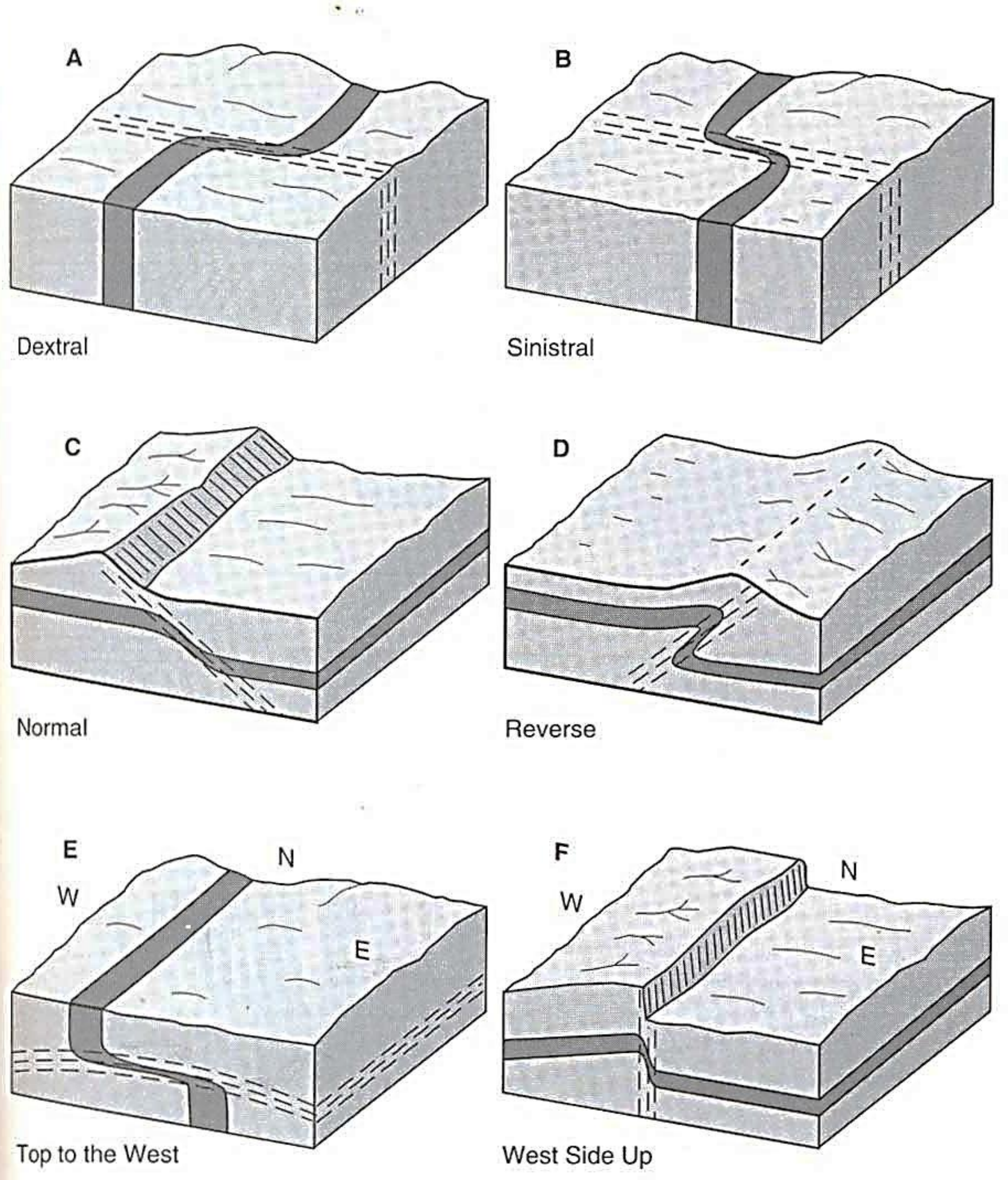

Fig. 9.13. Deflection and offset across shear zones: (A) right-handed or dextral, (B) left-handed or sinistral, (C) normal, (D) reverse, (E) top to the west, and (F) west side up.

2. Deflection of Markers
(Deflected Markers)

We have already looked at how pre-existmg markers (linear or planar) become rotated into shear zones (Figure 15.2).

Even if we do not see the shear zone margins, rotation of planar markers from an area of low strain to an area of high strain provides a very reliable criterion for sense of shear determination.

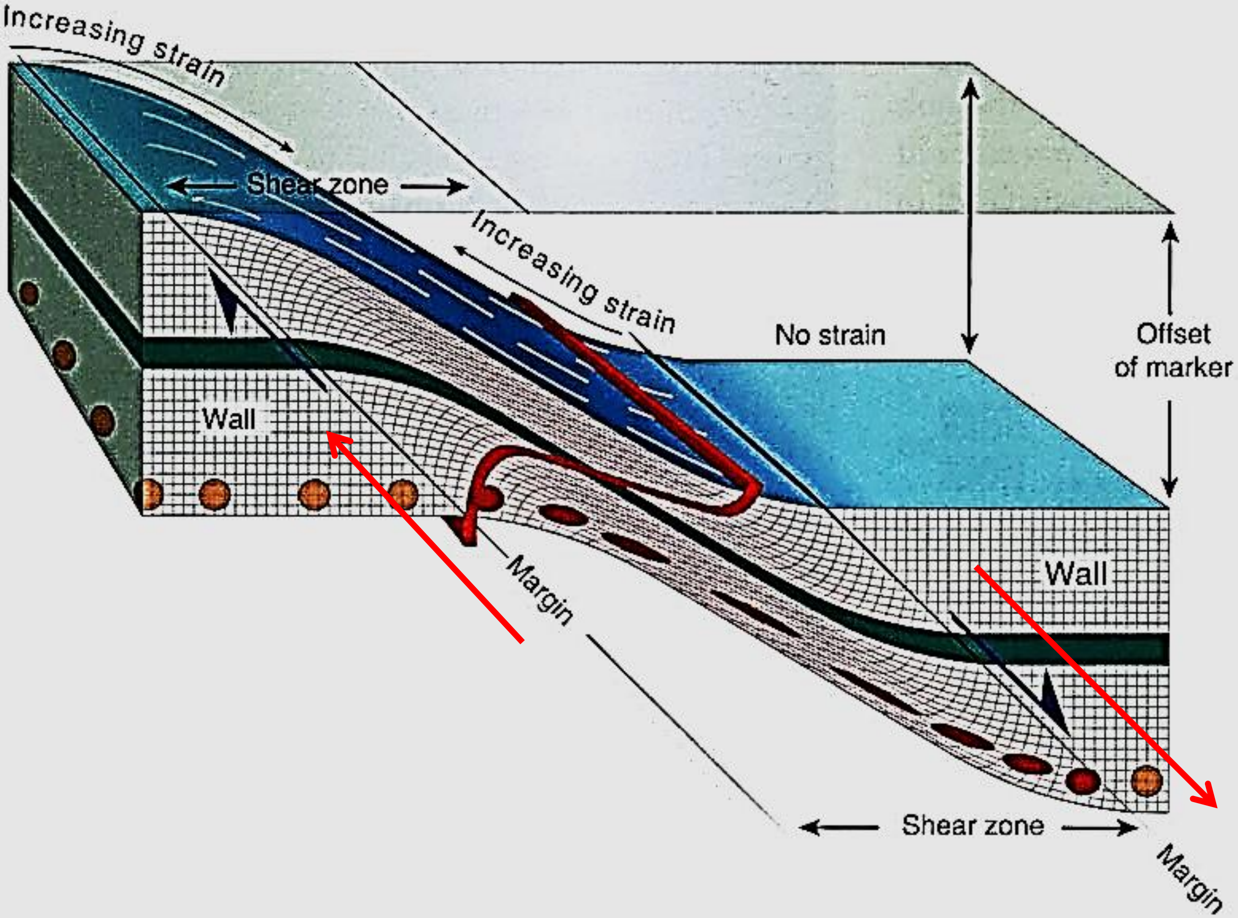

Figure 15.2 Ideal shear zone deforming a grid with two planar markers and circular strain markers. Note how the grid squares change shape and the planar markers change orientation and thickness across the zone. The strain is at its maximum in the central part of the shear zone.

It is possible to observe how a marker is deflected as it goes from the wall rocks into the shear zone (Fig. 9.35A).

The sense of the deflection reflects the sense of shear of the zone, as long as we are looking at the SOS (sense-of-shear) plane.

A dike swarm, or any other linear feature, that trends into the shear zone at a high angle is especially diagnostic, provided the shear zone actually cuts the dikes!

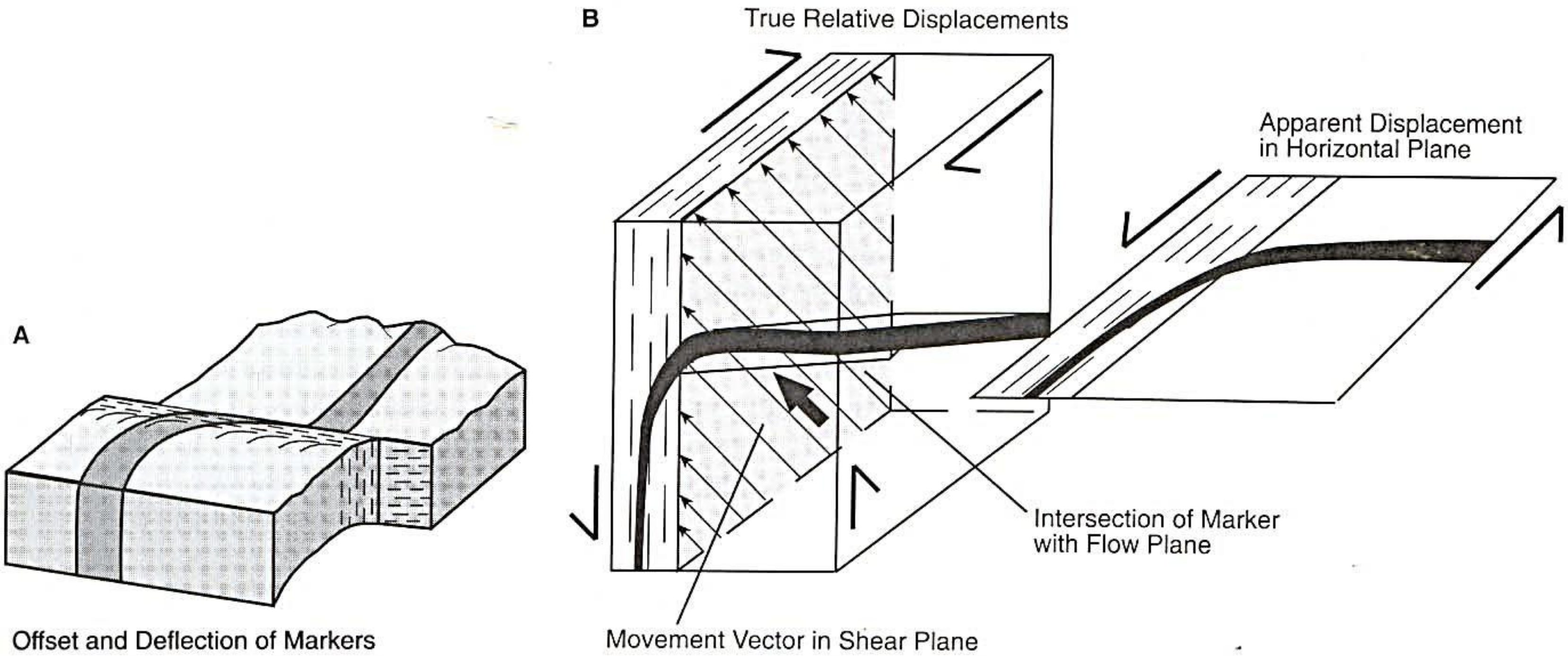

Figure 9.35 Offset and deflection of markers in ductile shear zones. (*A*) Discontinuous shear zone with dextral offset. Note deflection of marker into shear zone prior to its truncation. (*B*) Apparent relative displacement on a single improperly oriented surface (horizontal plane on right) may not reflect true displacement (arrows within plane of shear zone on left). [Modified from Hanmer and Passchier (1991). Courtesy of the Geological Survey of Canada.]

3. Foliation Patterns

Systematic variations in the orientation of foliation are common in ductile shear zones and provide one of the most useful shear-sense indicators.

Foliation, because it generally reflects the S_1S_2 plane of the finite strain ellipsoid, is inclined to the shear zone for any noncoaxial deformation and leans over in the sense of shear (Fig. 9.37A).

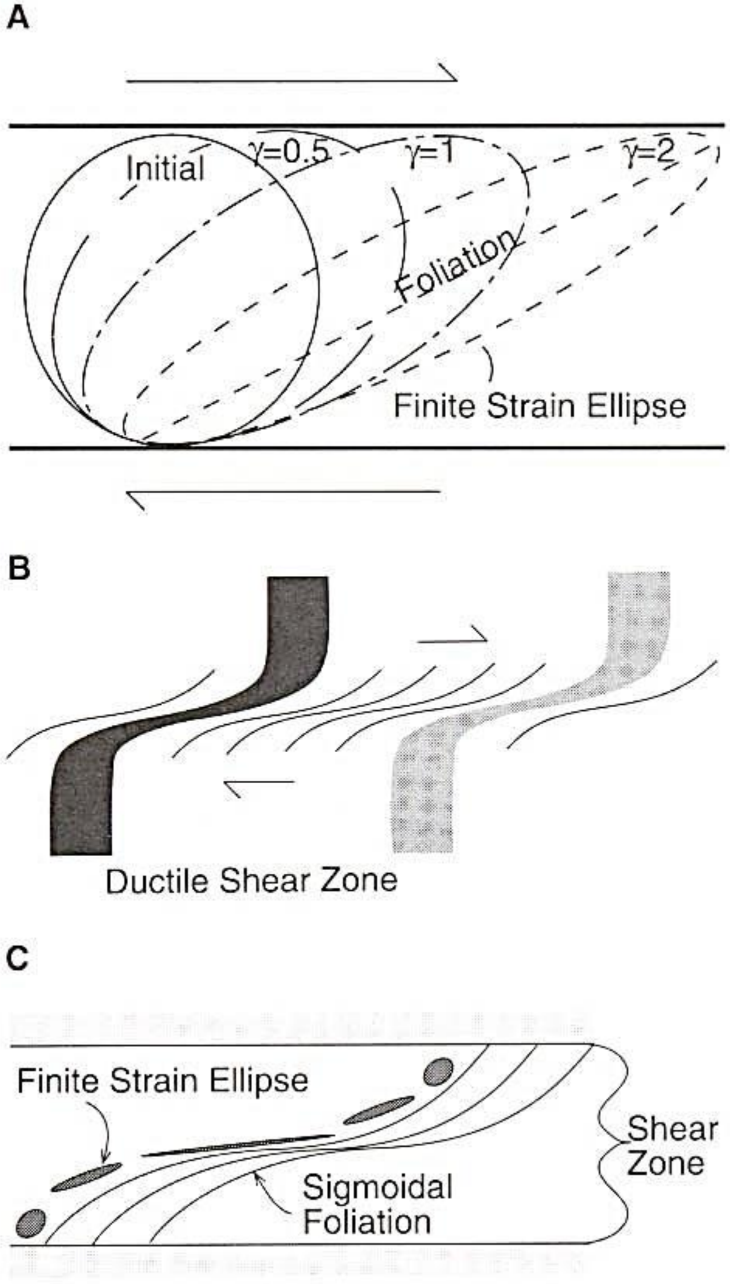

Figure 9.37 Foliation patterns in shear zones. (*A*) Finite strain ellipse and associated foliation lean over in the sense of shear and rotate toward the shear zone during progressive deformation. (*B*) Sigmoidal foliation patterns in a shear zone. (*C*) Variations in finite strain ellipse based on foliation patterns.

It also commonly has a curved or a sigmoidal shape across a shear zone, with a sense of deflection consistent with the overall sense of shear (Fig. 9.37B).

Foliation will be rotated toward parallelism with the shear zone in areas, such as the center of the zone, where the rocks are more strongly deformed, and the strain is higher (Fig. 9.37C).

Such foliation patterns are especially clear in thin shear zones, where the entire shear zone is exposed in a single outcrop.

If only one margin of the shear zone is exposed, we should expect to see the foliation curve into the shear zone (Fig. 9.38), reflecting the increase in shear strain toward the center of the zone.

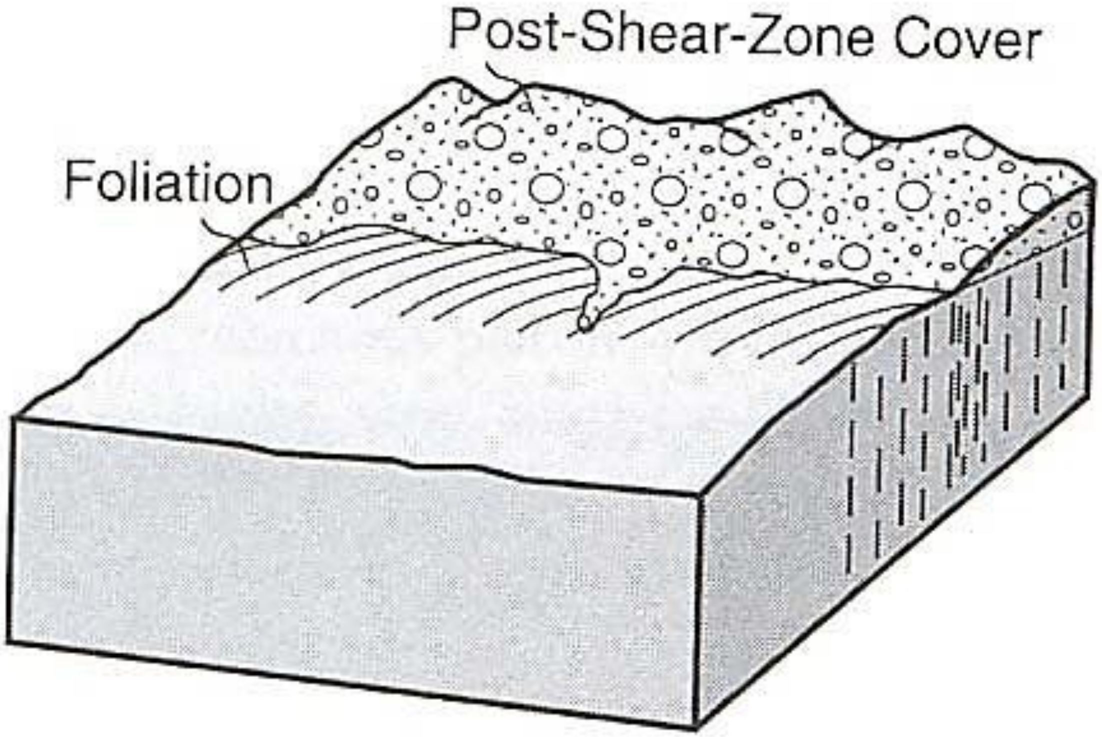

Figure 9.38 Foliation deflects into a shear zone, the far margin of which is covered by a rock unit deposited after movement on the shear zone.

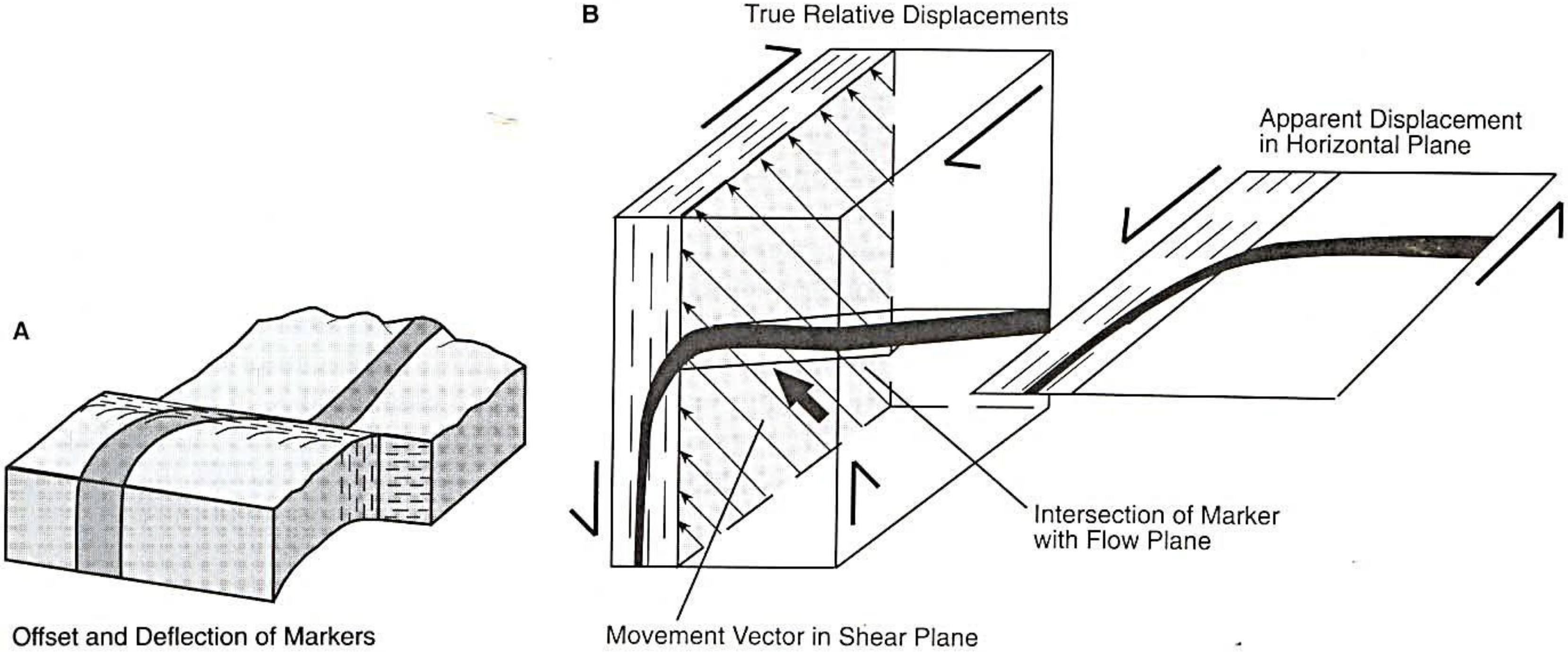

Figure 9.35 Offset and deflection of markers in ductile shear zones. (*A*) Discontinuous shear zone with dextral offset. Note deflection of marker into shear zone prior to its truncation. (*B*) Apparent relative displacement on a single improperly oriented surface (horizontal plane on right) may not reflect true displacement (arrows within plane of shear zone on left). [Modified from Hanmer and Passchier (1991). Courtesy of the Geological Survey of Canada.]

4. Shear Bands and, S-C Fabrics, and Oblique Microscopic Foliation

(a) Shear Bands (C-surfaces)

Shear bands are thin zones of very high shear strain within the main shear zone (Fig. 9.42).

They are shear zones within a shear zone. Most are less than 2-3 mm thick and less than 10-20 cm long, and many are microscopic.

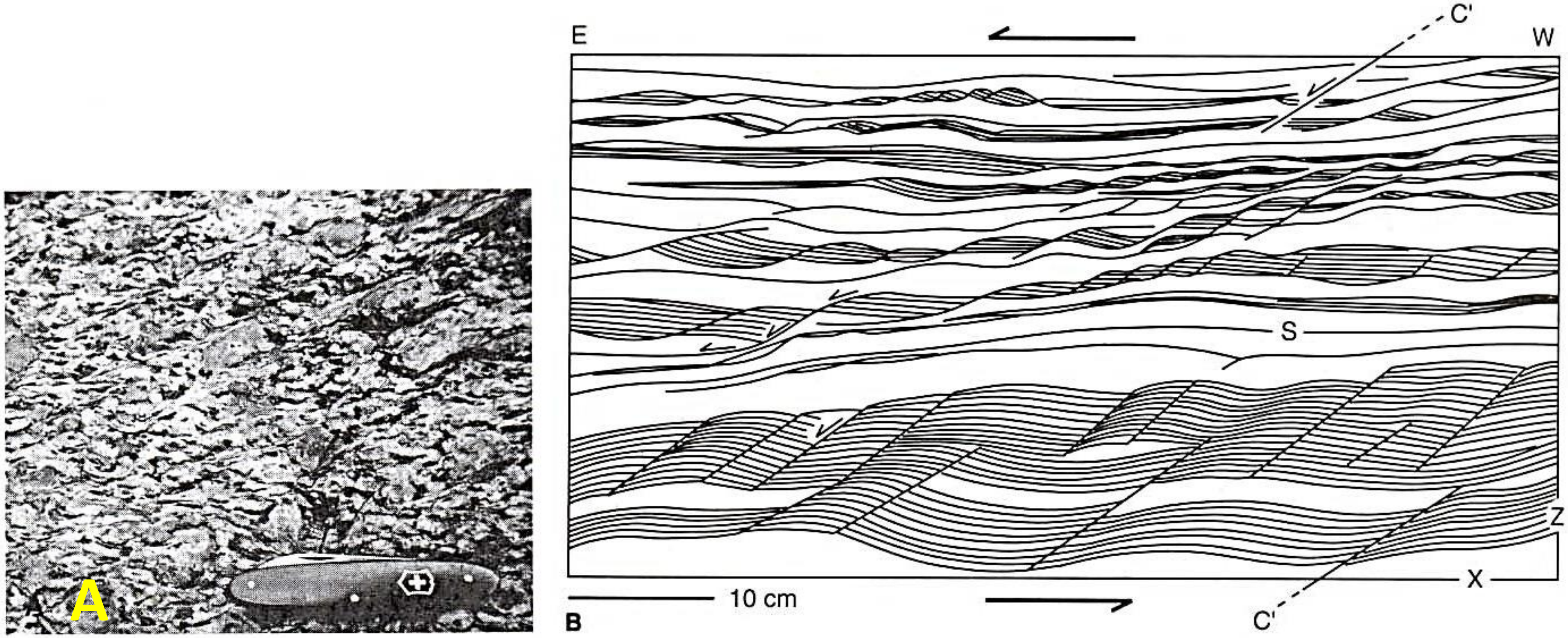

Figure 9.42 Shear bands: (*A*) Cutting Proterozoic granite, Maricopa Mountains, central Arizona. (Photograph by S. J. Reynolds.) (*B*) Cutting mica schist and quartzite, Raft River Mountains, Utah. Shear bands are labeled C'. (Reprinted with permissions from *Journal of Structural Geology*, v. 9, Malavieille, J., Kinematics of compressional and extensional ductile shearing deformation in a metamorphic core complex of the northeastern Basin and Range, 1987, Elsevier Science Ltd., Pergamon Imprint, Oxford, England.)

As strain accumulates, a set of slip surfaces or shear bands (C-surfaces) commonly forms parallel to the walls of the shear zone (Fig. I5. 22a). But they can be either parallel or oblique (Fig. 9.43A) to the main shear zone.

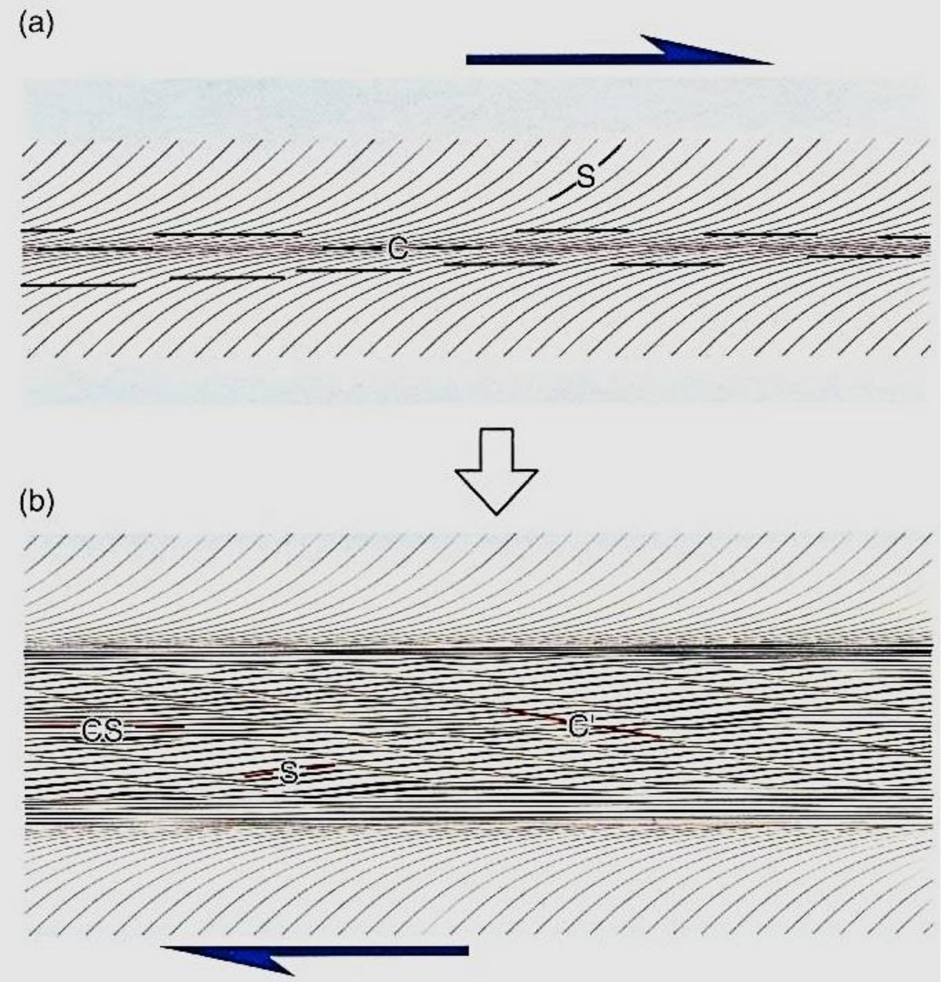

Figure 15.22 Schematic illustration of the development of S-C structures in a shear zone in a magmatic rock. (a) The new-formed foliation (S) is cut by shear surfaces (C) that parallel the shear zone margins. (b) Continued deformation rotates S into close parallelism with C, together referred to as a CS-foliation. New and oblique shear bands (C′) form and back-rotate the CS-foliation, which then is called S.

C-surfaces are not really surfaces, but small-scale shear zones that affect the foliation within the main shear zone.

A shear band is synthetic if it is inclined in the same direction as the overall sense of shear, and it is antithetic if inclined in the opposite direction (Fig. 9.43B).

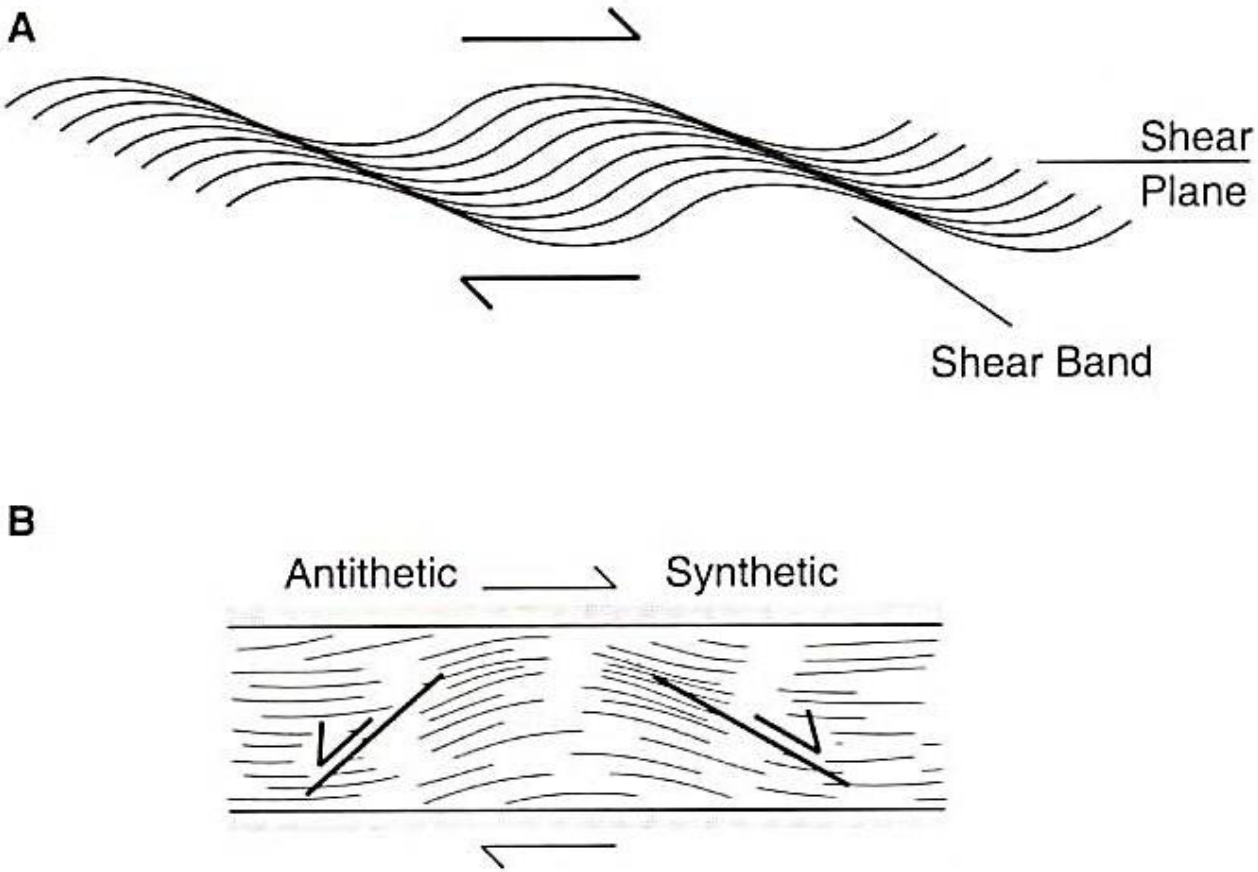

Figure 9.43 Geometries of extensional shear bands: (*A*) Shear bands commonly cut across the shear plane at approximately 30°. [Modified from Hanmer and Passchier (1991). Courtesy of the Geological Survey of Canada.] (*B*) Synthetic versus antithetic extensional shear bands.

In detail, the foliation curves into and out of the C-surfaces, and the sense of deflection shown by the curving foliation reflects the sense of shear of the entire shear zone.

C-surfaces are particularly common in shear zones in magmatic rocks (Fig. 15.23).

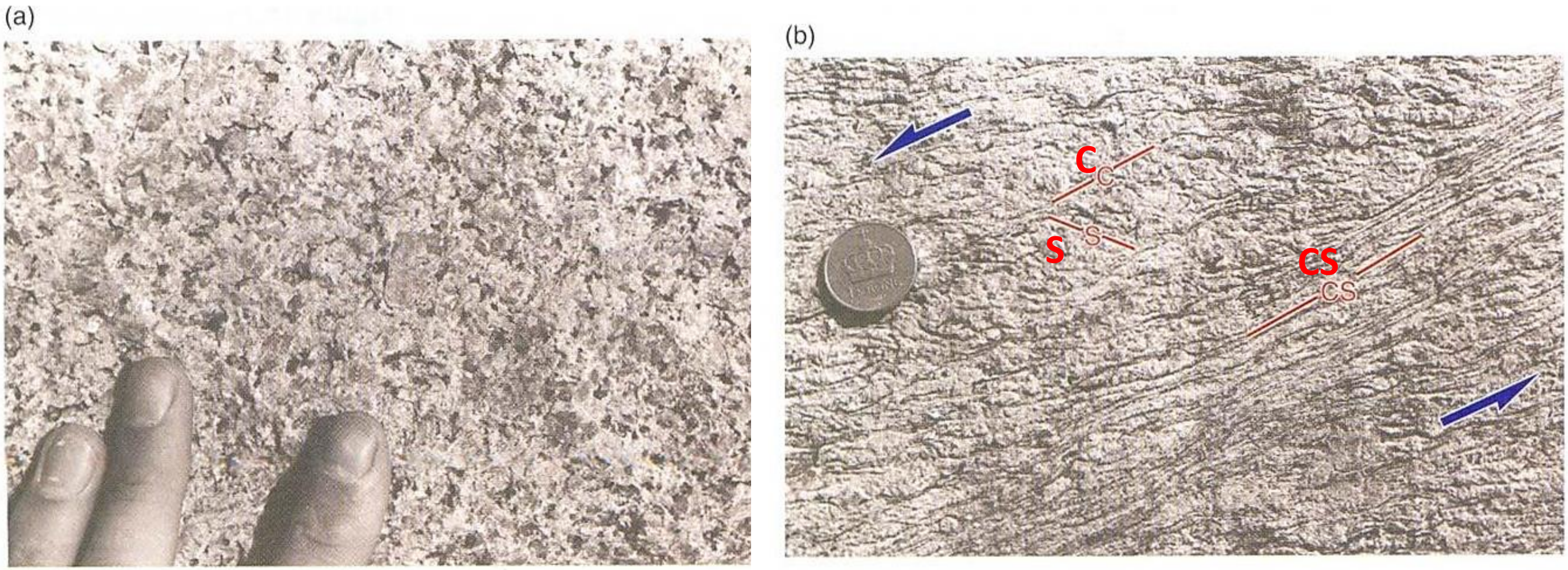

Figure 15.23 (a) Undeformed granite. (b) Sheared version of the same rock. Two sets of planar surfaces (S and C) are developed. S rotates to become subparallel with C in the zone of high strain. The combined foliation is named CS.

(b) S-C fabrics or S-C structures

S-C fabrics are among the most useful sense-of-shear indicators in ductile shear zones. They consist of two sets of planes or surfaces: foliation and shear bands (Fig. 9.44A-C).

The foliation planes are called S- surfaces (from the French term for schistosity or "schistosite").), whereas the shear bands are denoted C-surfaces because they are zones of high shear strain ("cisaillement" is French for shear, which relates to the movement of scissors).

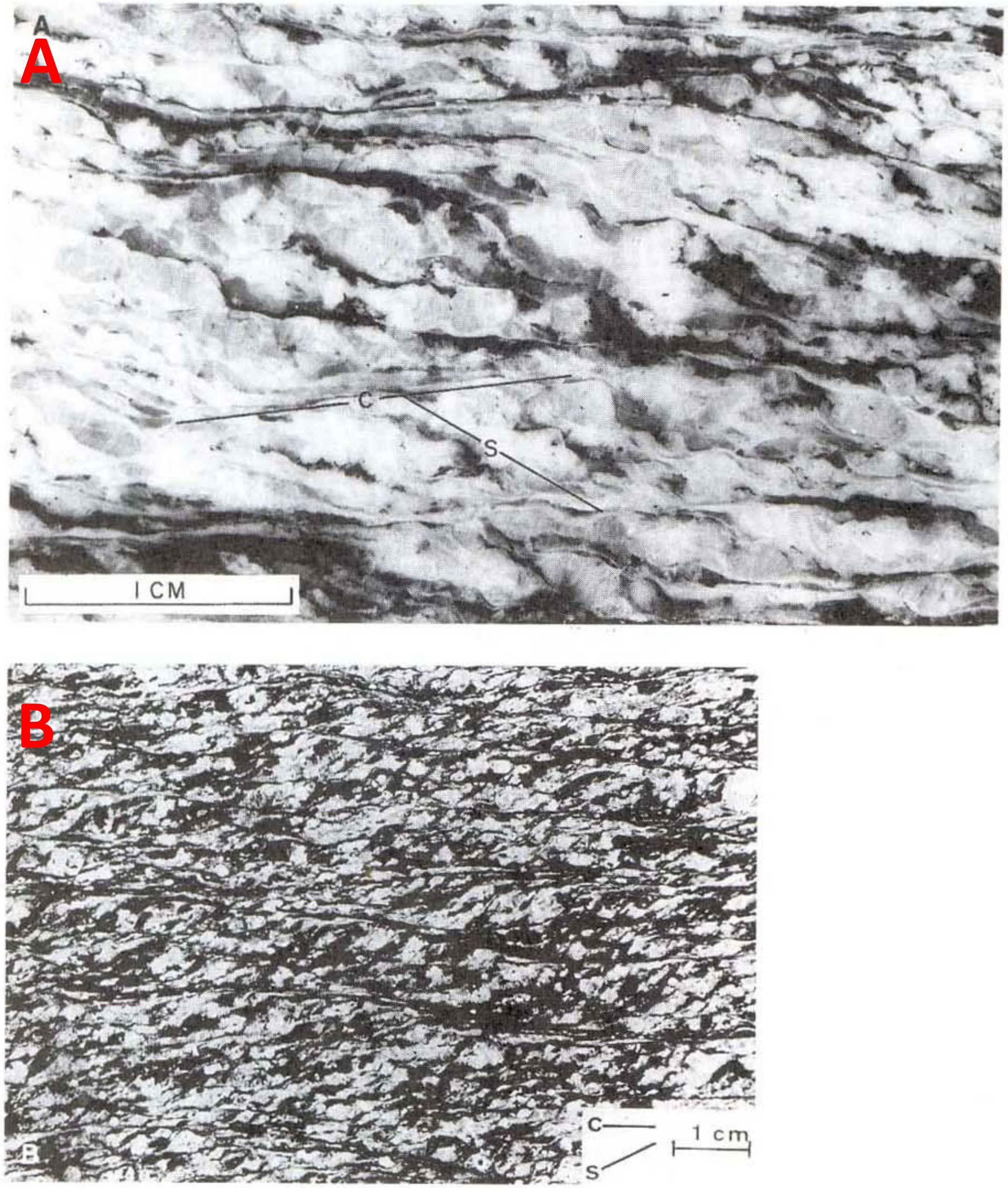

Figure 9.44 S-C fabrics. (*A*) S-C fabric in polished slab of Tertiary granodiorite, South Mountains, Arizona. Sense of shear is sinistral. (Photograph by S. J. Reynolds.) (*B*) S-C fabric in late Cretaceous pluton within the Santa Rosa mylonite zone, southern California. Sense of shear is dextral. [From Simpson and Schmid (1983). Published with permission of the Geological Society of America and the authors.] (*C*) S-C fabrics mimic the sigmoidal foliation patterns in the host shear zone. [From Hanmer and Passchier (1991). Courtesy of the Geological Survey of Canada.]

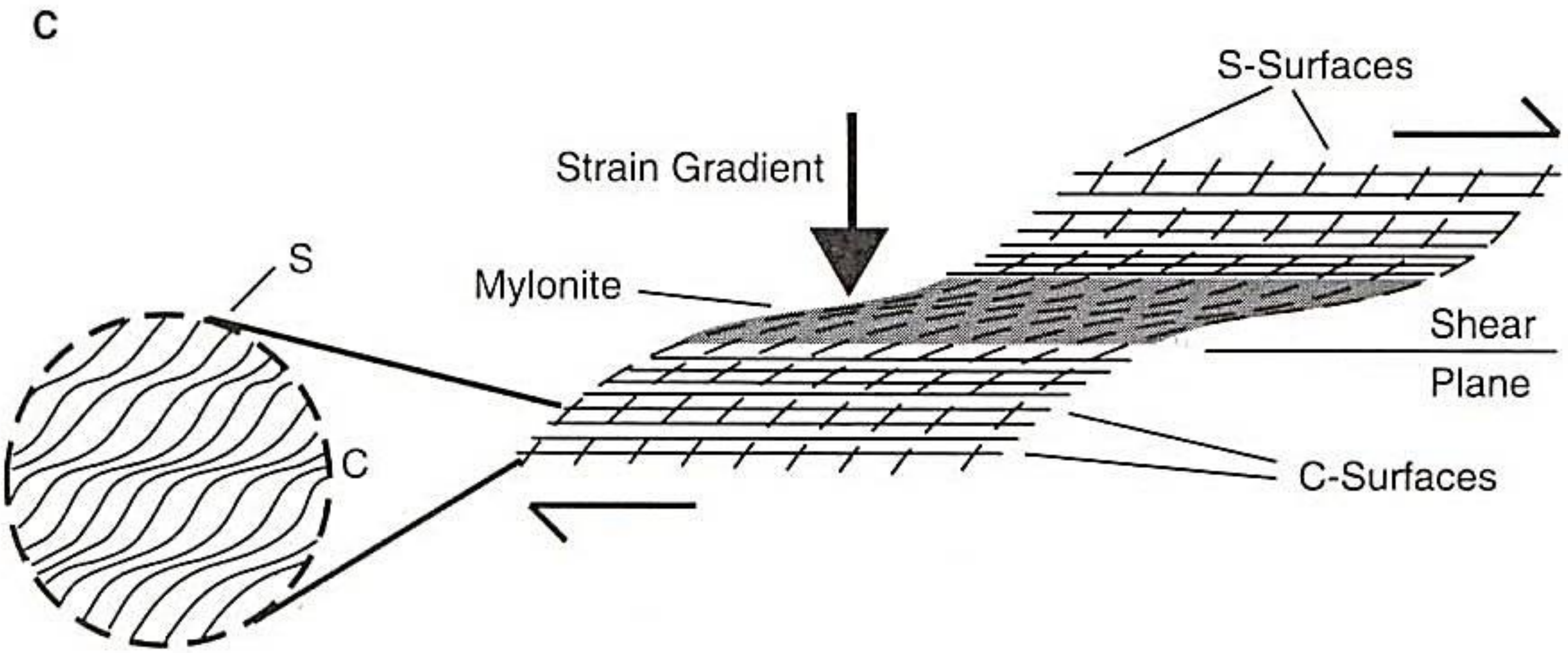
C
S-Surfaces
Strain Gradient
S
Mylonite
Shear
Plane
C
C-Surfaces

Fig. 9.44C

C-surfaces typically are discrete zones of high shear strain 2-20 cm long and less than 1 mm thick. Most are aligned parallel to the shear zone and crosscut foliation.

S-surfaces (i.e., foliation) deflect toward parallelism with a C-surface as they approach it and have a distinctive sigmoidal shape between adjacent C-surfaces.

S-surfaces lean over in the direction of shear, relative to the C-surfaces.

S-C fabrics are commonly visible in outcrop, once we have trained our eyes to recognize them.

The clearest examples are in mylonitic granitic and gneissic rocks that contain coarse porphyroclasts or augen of feldspar.

The angle between S and C can vary, but is typically about 25-45°. The angular relationship between the foliation and shear bands (C) (Figs. 15.24 and 15.25) is a reliable shear indicator if the angular relation is consistent.

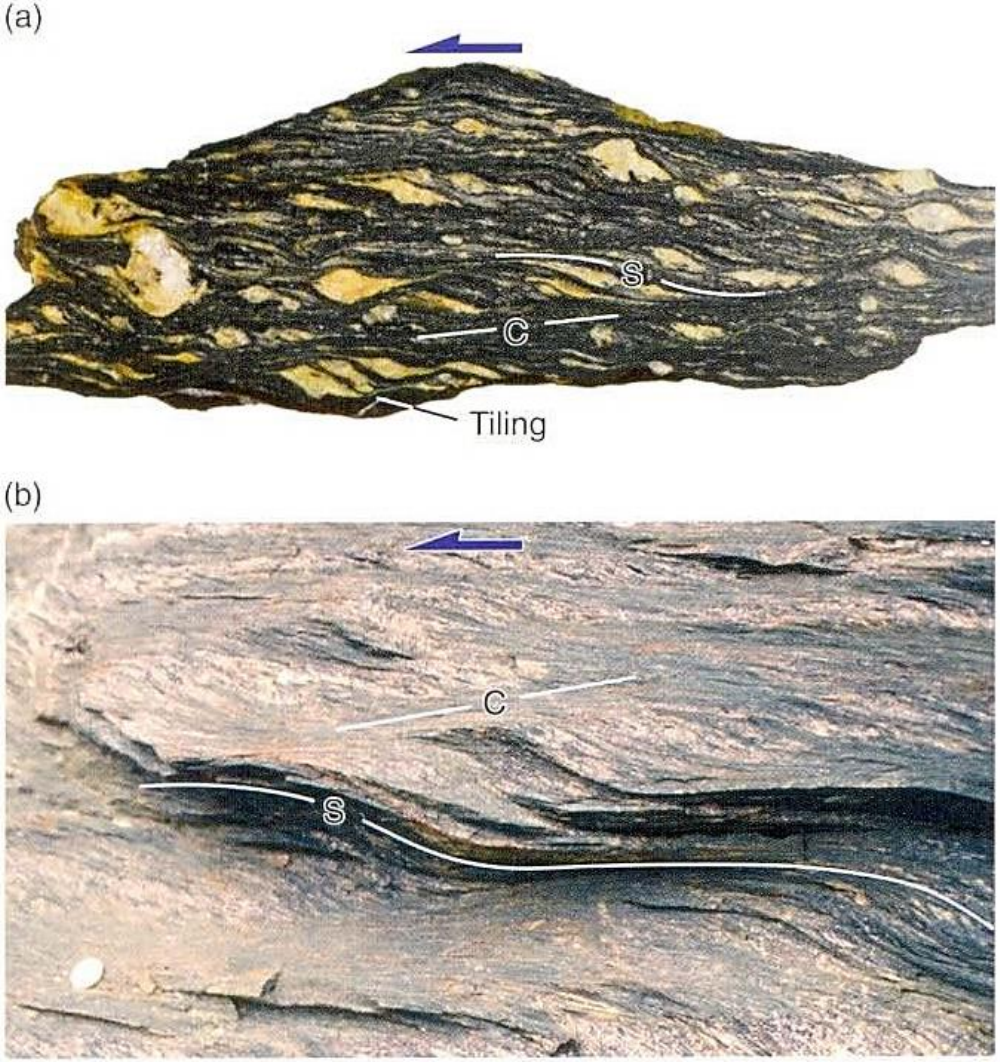

Figure 15.24 (a) S-C structure in protomylonitic granite, Antarctica. Note tiling of feldspar porphyroclasts. (b) Shear bands in phyllite, together with asymmetric folds. Caledonian basal décollement. (c) Asymmetric boudins in granitic gneiss.

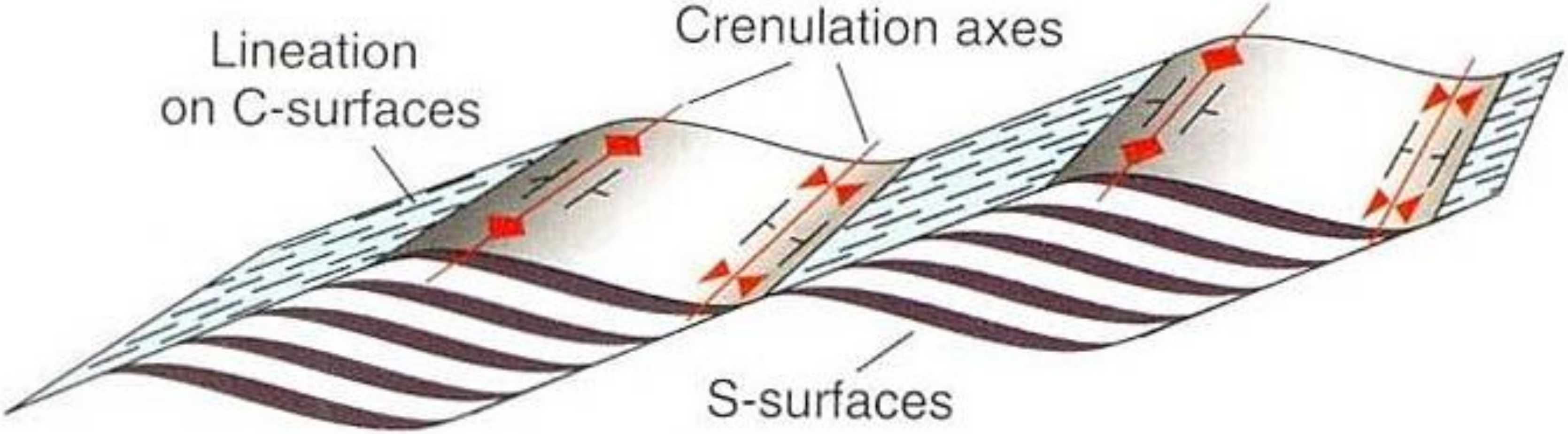

Figure 15.25 Schematic illustration of the geometry of shear band-type S-C structures. The crenulation axis is typically at a high angle to the sense of shear, which is reflected by a lineation that may appear on the shear bands (C-surfaces). Slip may or may not occur on the S-surfaces.

(c) Oblique microscopic foliation or Microscale Foliations

Thin sections of mylonitic rocks may also contain another shear-sense indicator, expressed as a microscopic foliation oblique to the main mylonitic foliation.

Foliations that are oblique to the main foliation or the mylonitic banding occur in mineral aggregates that dynamically recrystallize during the deformation. Quartz aggregates are typical examples.

The aggregates themselves form part of the main mylonitic foliation, while the long axes of its deformed grains define an oblique foliation (Figs. 15.26 and 15.27).

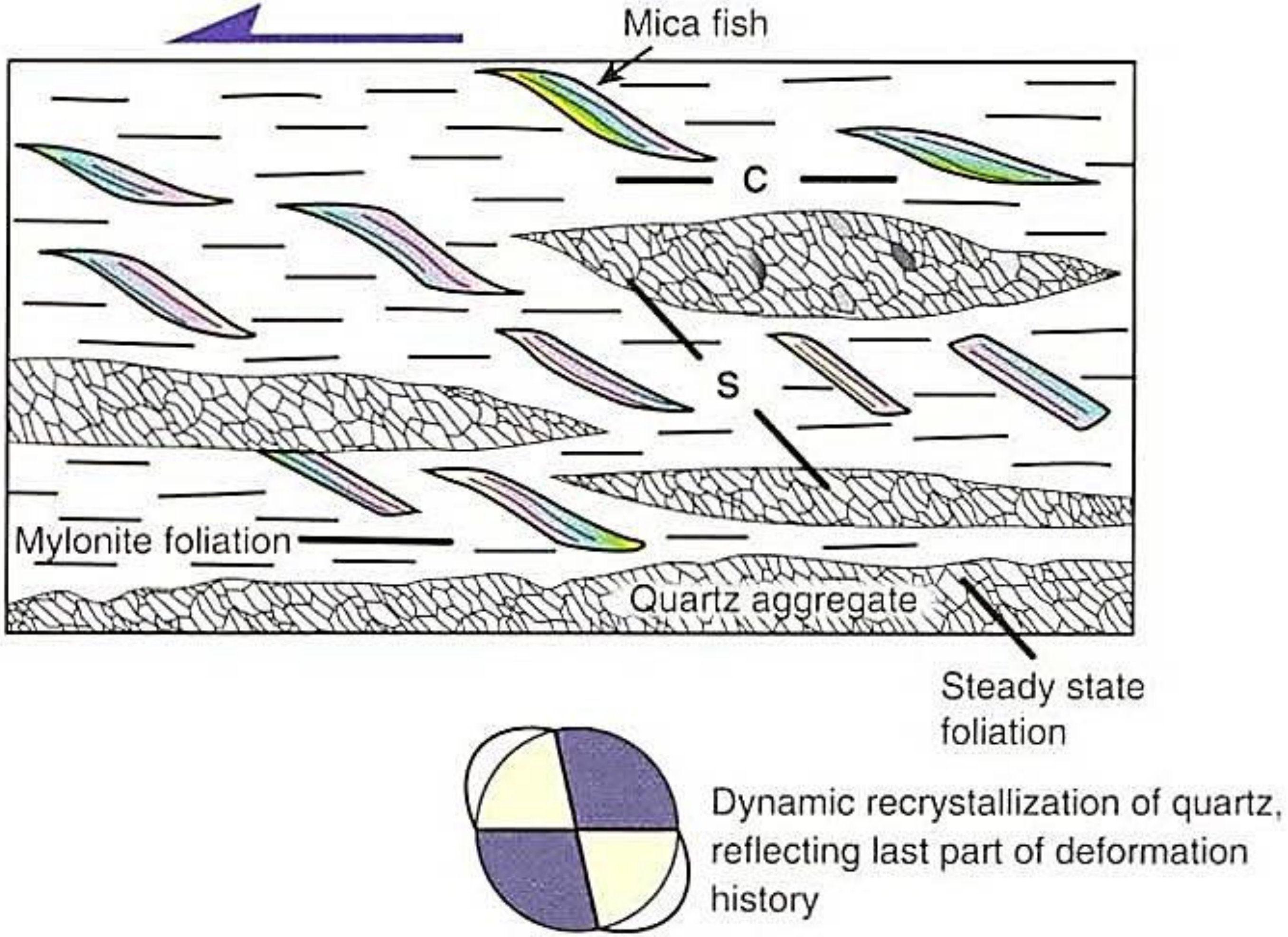

Figure 15.26 Typical S-C structures in quartz–mica-dominated mylonites.

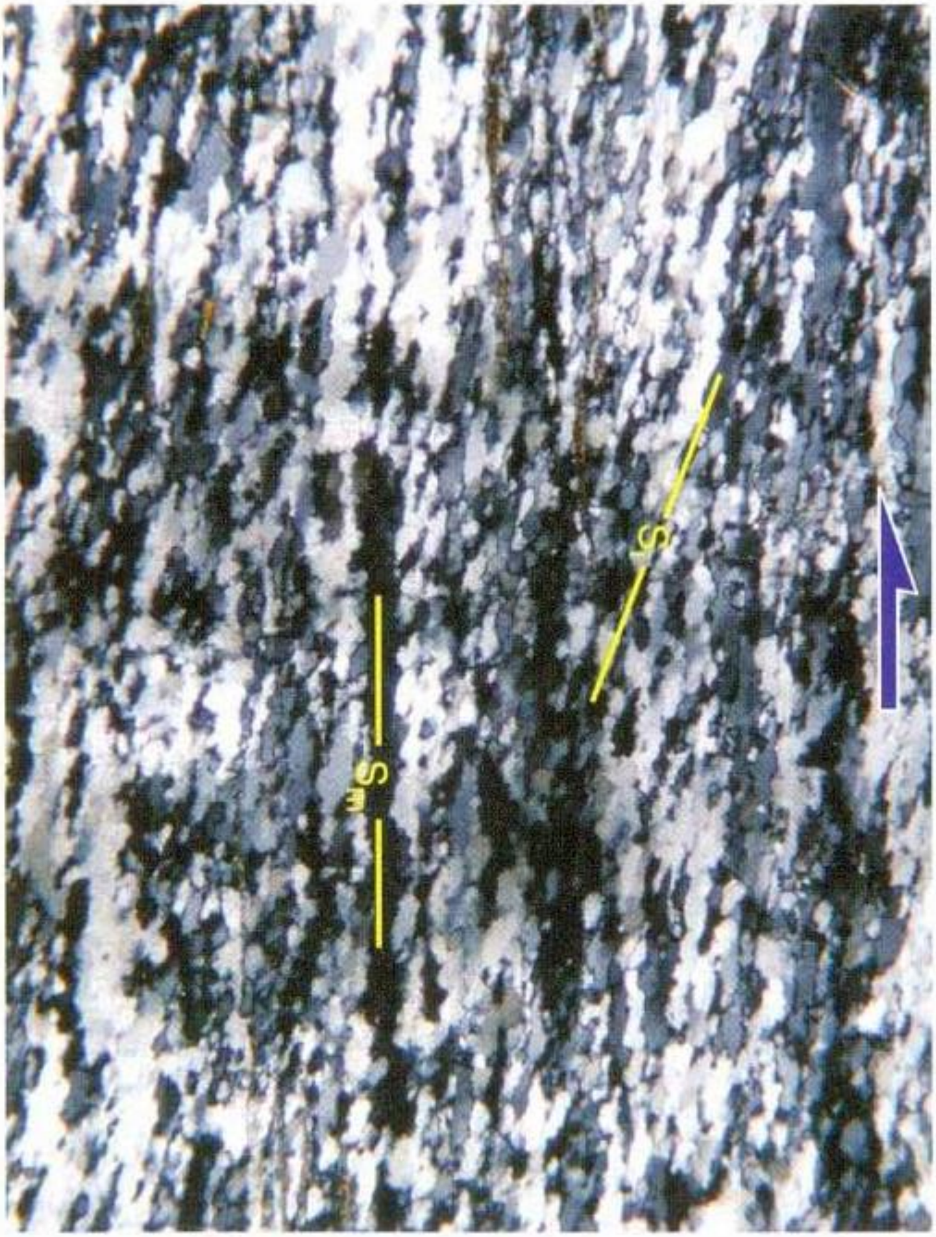

Figure 15.27 Thin section of a mylonite with a horizontal mylonitic foliation (S_m). The quartz grains are stretched in a direction S_i oblique to S_m, and the angular relations are consistent with top-to-the-left sense of shear. We could also use S-C terminology, where S_m represents C and S_i corresponds to S.

5. Mica Fish

Many mylonitic rocks contain lenticular porphyroclasts of muscovite and biotite, which have been termed mica fish (Lister and Snoke, 1984). The name refers to their troutlike shape (Fig. 9.46).

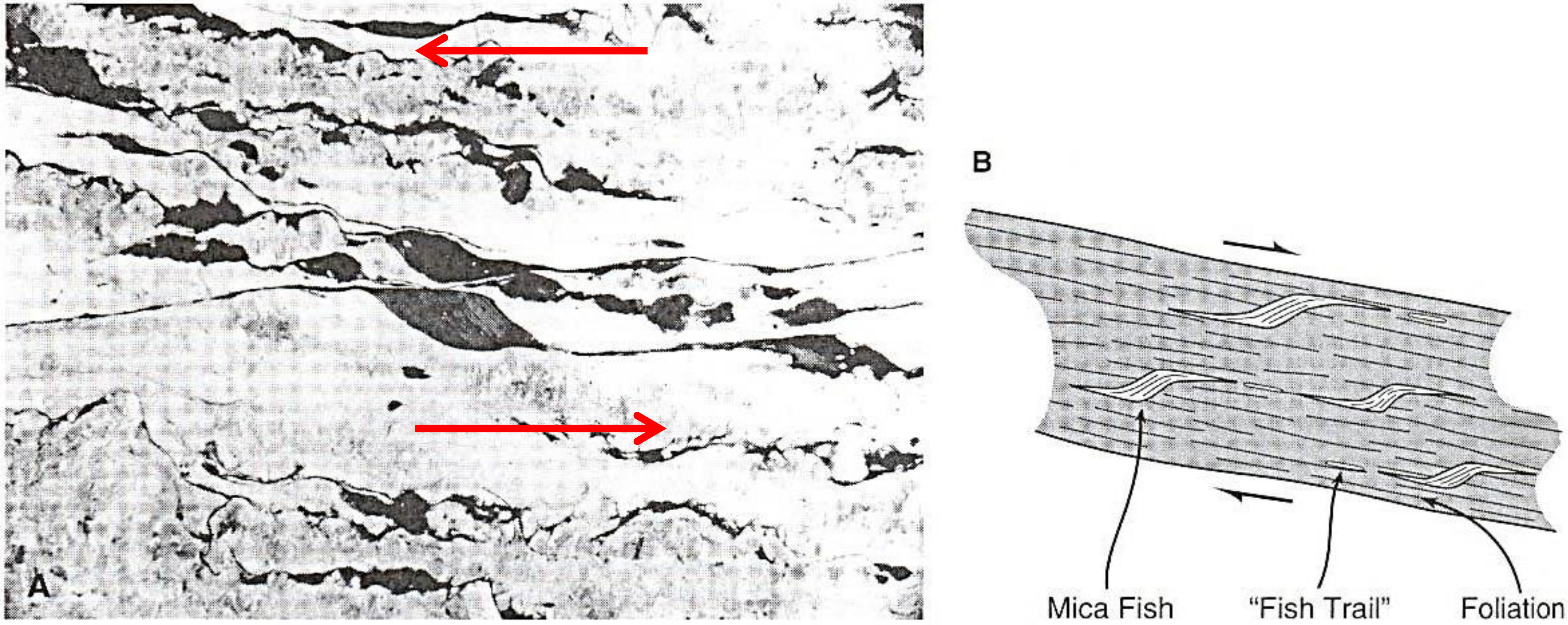

Figure 9.46 Mica fish. (*A*) Mylonitic Tertiary granodiorite, South Mountains, Arizona. Thin, dark tails streaming off the dark, 1 mm long, fish-shaped biotite crystal in the center of the photograph reflect sinistral shear. (Photograph by S. J. Reynolds.) (*B*) Mica fish lean over in the sense of shear, and their tails are commonly parallel to C-surfaces and to the shear zone.

The mica porphyroclasts tend to have tails that systematically curve away from the general orientation of the porphyroclasts, as shown in Figure 15.26.

Mica fish, which are commonly asymmetric with respect to the mylonitic foliation or to shear bands, make excellent shear-sense indicators.

Mica fish are commonly seen to be confined by shear bands, and can be regarded as a type of S-C structure.

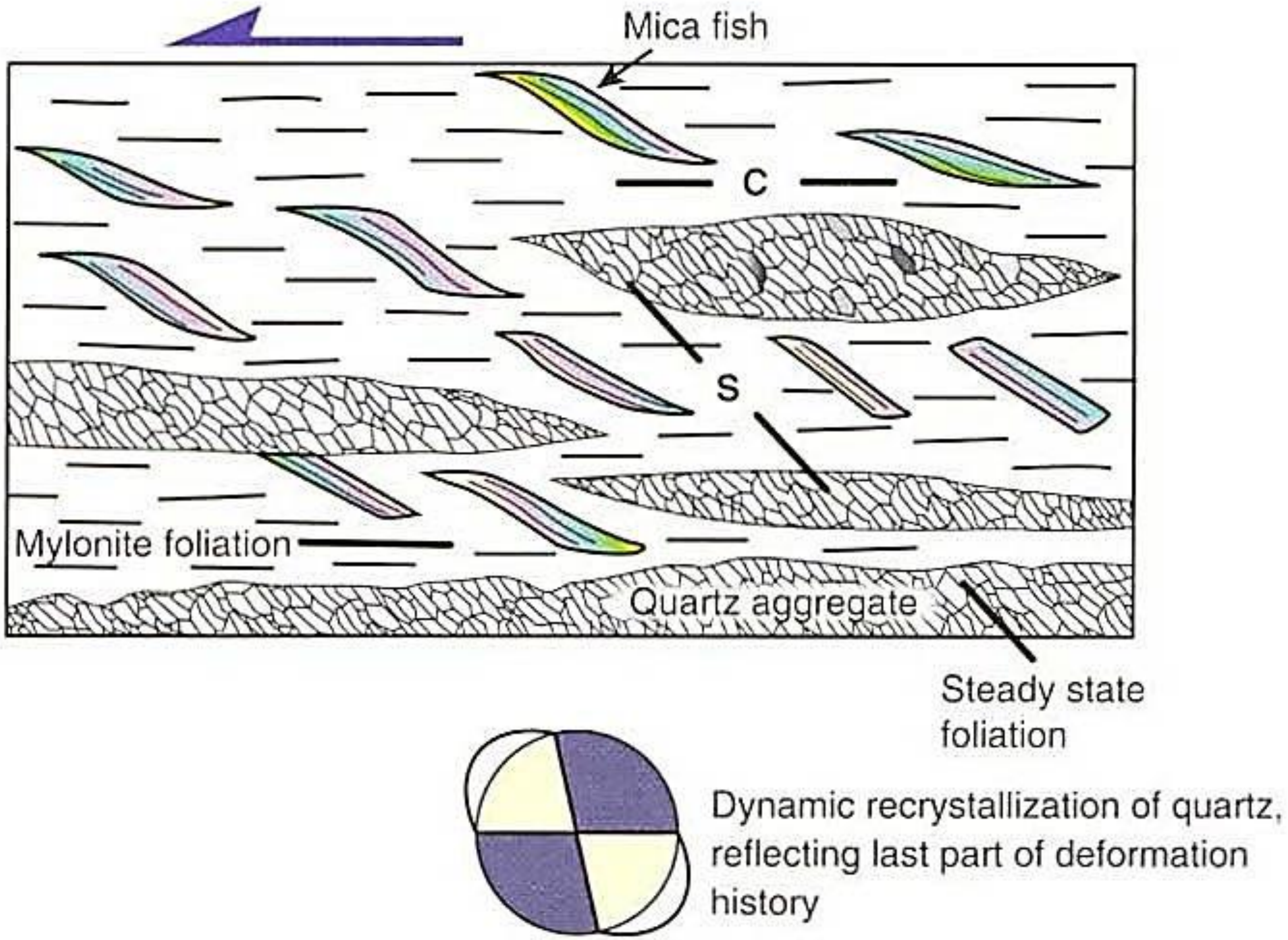

Figure 15.26 Typical S-C structures in quartz–mica-dominated mylonites.

Asymmetric mica fish are generally observed in thin section but can also be visible in hand specimen. They are commonly aligned with S-surfaces in S-C fabrics, and thus lean over in the sense of shear.

10. Veins

As we map and analyze shear zones, we are generally impressed with the abundance of veins (Fig. 9.64). Most shear zone-related veins contain quartz and calcite.

These minerals are deposited from the fluids that helped "prop" open the fracture filled by the vein material.

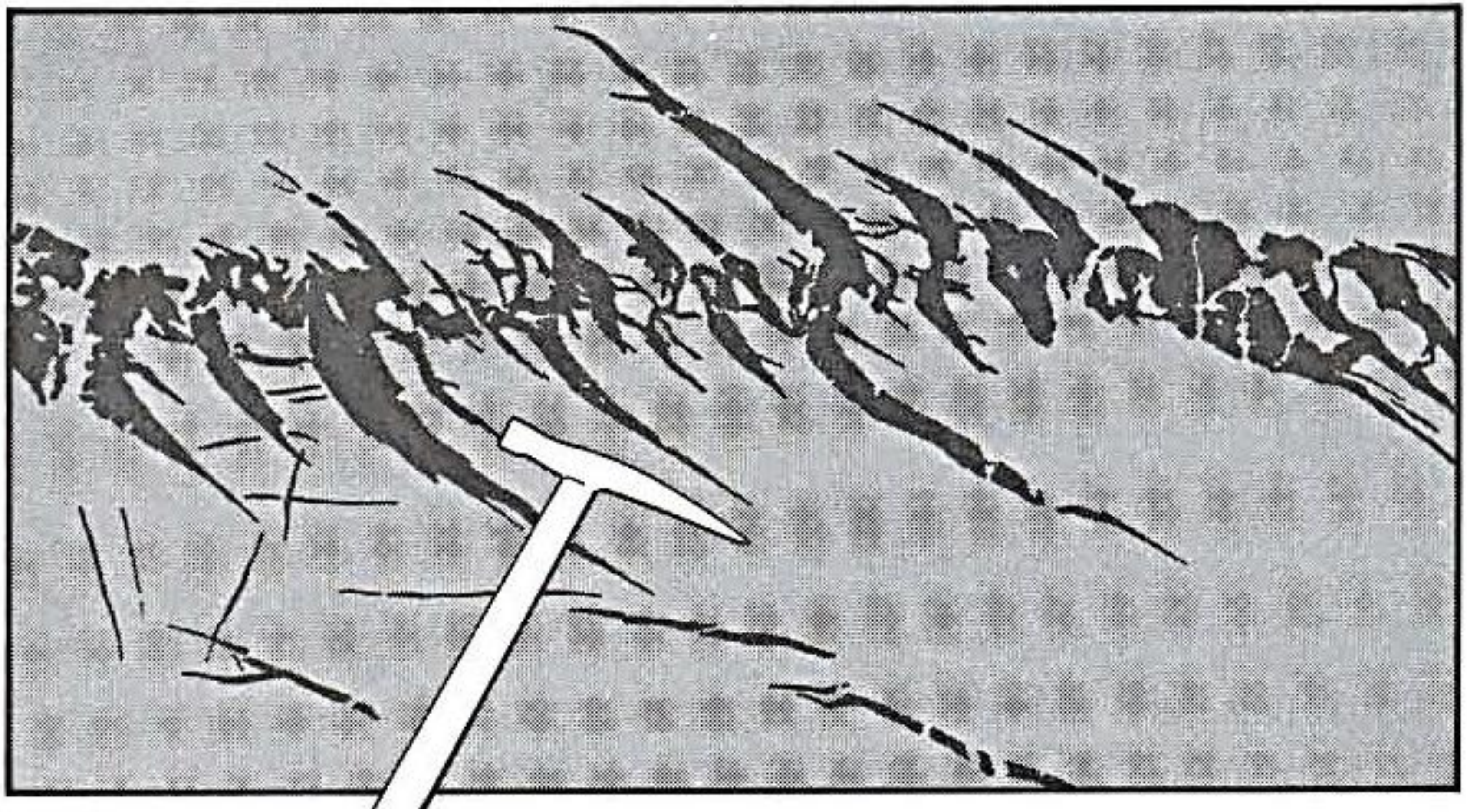

Figure 9.64 En echelon, sigmoidal quartz veins defining a dextral shear zone.

Veins can be excellent and reliable shear-sense indicators because their orientations are commonly controlled by the instantaneous stretching axes.

Most veins form perpendicular to the axis of maximum instantaneous extension, because this is the direction in which tension fractures form.

Veins should be oriented perpendicular to foliation and lineation for coaxial deformation, but not for noncoaxial deformation (Fig. 9.65).

This results in a sigmoidal geometry that can be used to determine the sense of shear, as illustrated in Fig. I5.36b and 15.37.

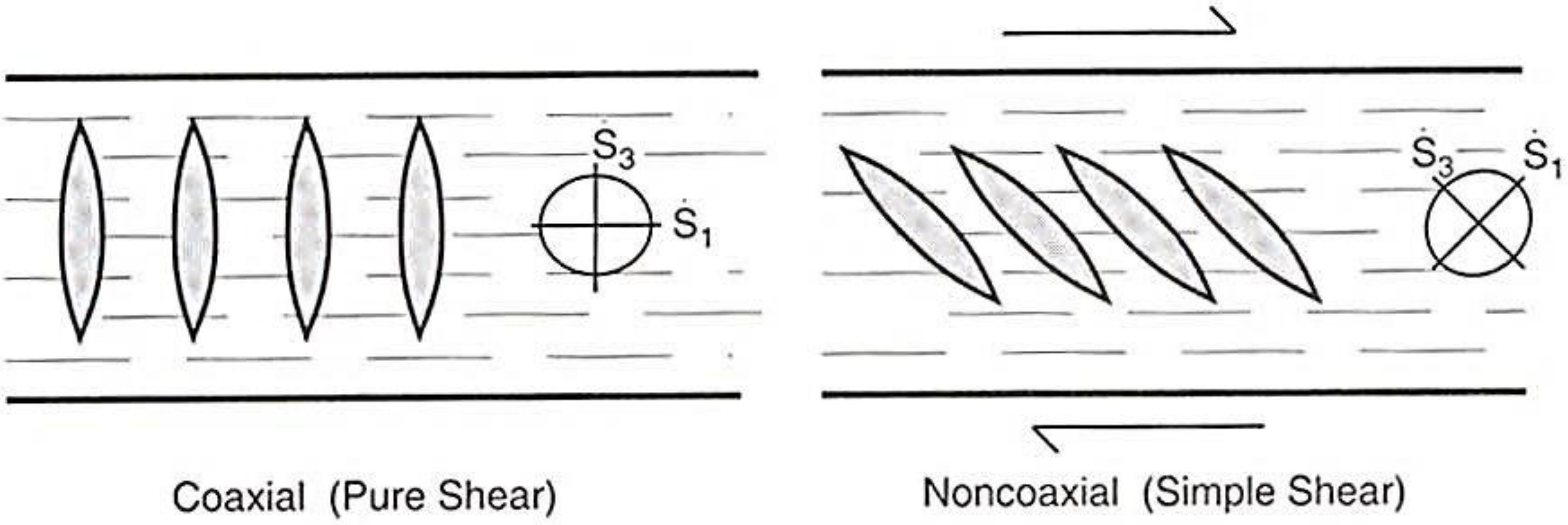

Figure 9.65 Orientation of veins compared to the instantaneous stretching axes for coaxial and noncoaxial deformation. Veins form parallel to the maximum shortening rate ($\dot{S}_3$) and perpendicular to the maximum stretching rate ($\dot{S}_1$).

For simple shear, veins will form at 45° to the shear zone- that is opposed to the direction of foliation and to the inclination of most other shear- sense indicators we have examined so far.

Veins forming under non-coaxial deformation will rotate from the moment they form.

Once formed, the veins may be shortened and partially rotated over, toward the direction of shear (Fig. 9.66).

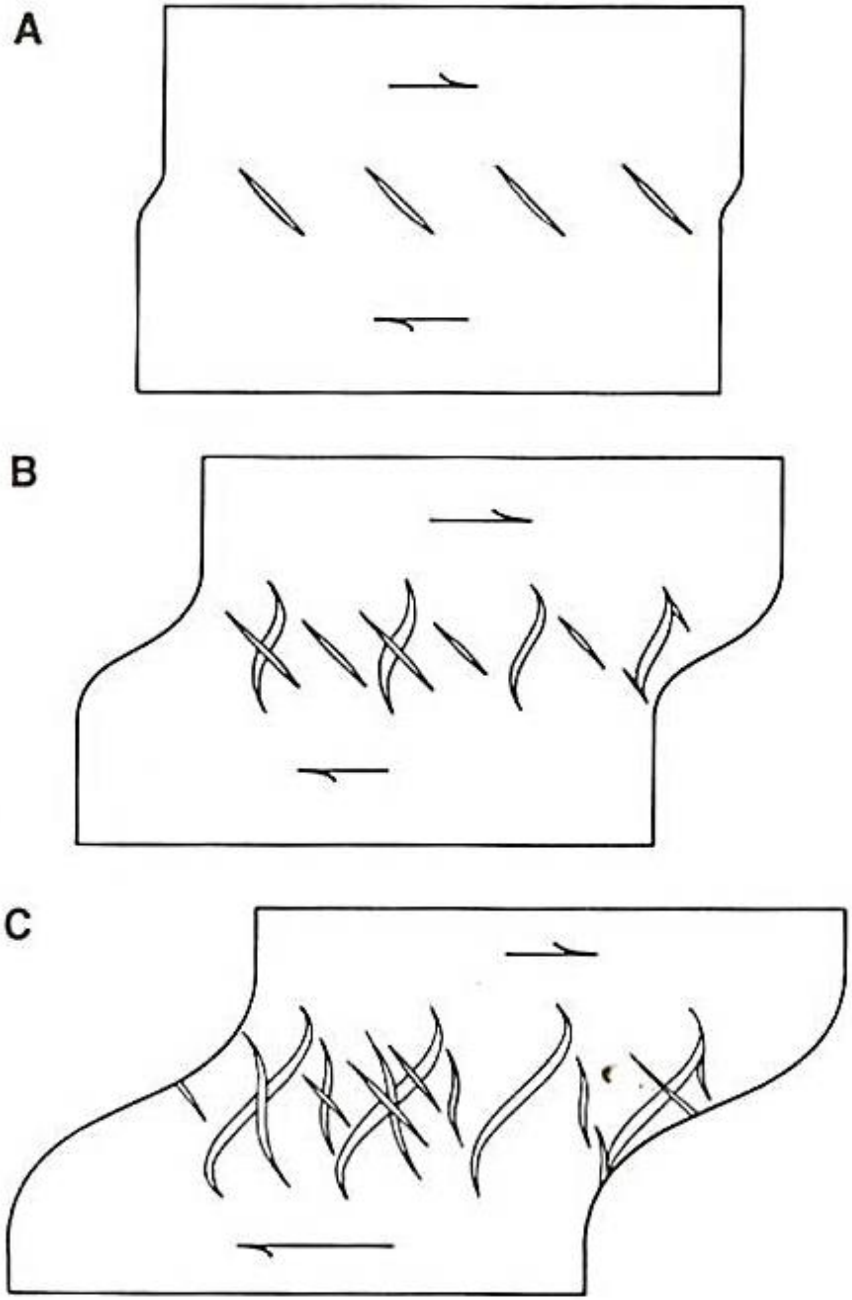

Figure 9.66 Progressive formation and folding of en echelon veins within a zone of simple shear. Tension fractures are initially oriented at 45° to the shear zone and progressively rotate in the direction of the sense of shear during subsequent deformation. Later veins form in the original orientation. (From Durney, D. W. and

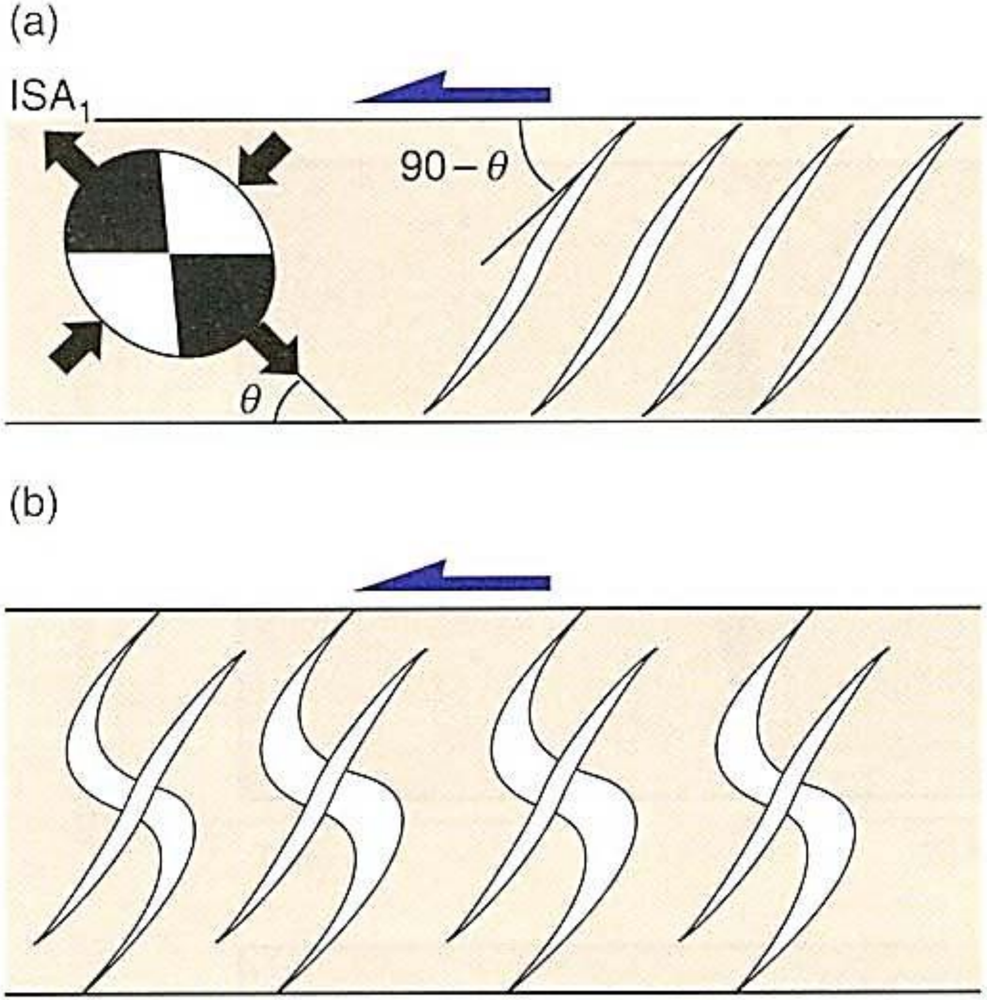

Figure 15.36 En-echelon-arranged extension veins in a shear zone. The vein tips are oriented perpendicular to ISA_1. They are sheared into sigmoidal shapes and may be cut by younger veins.

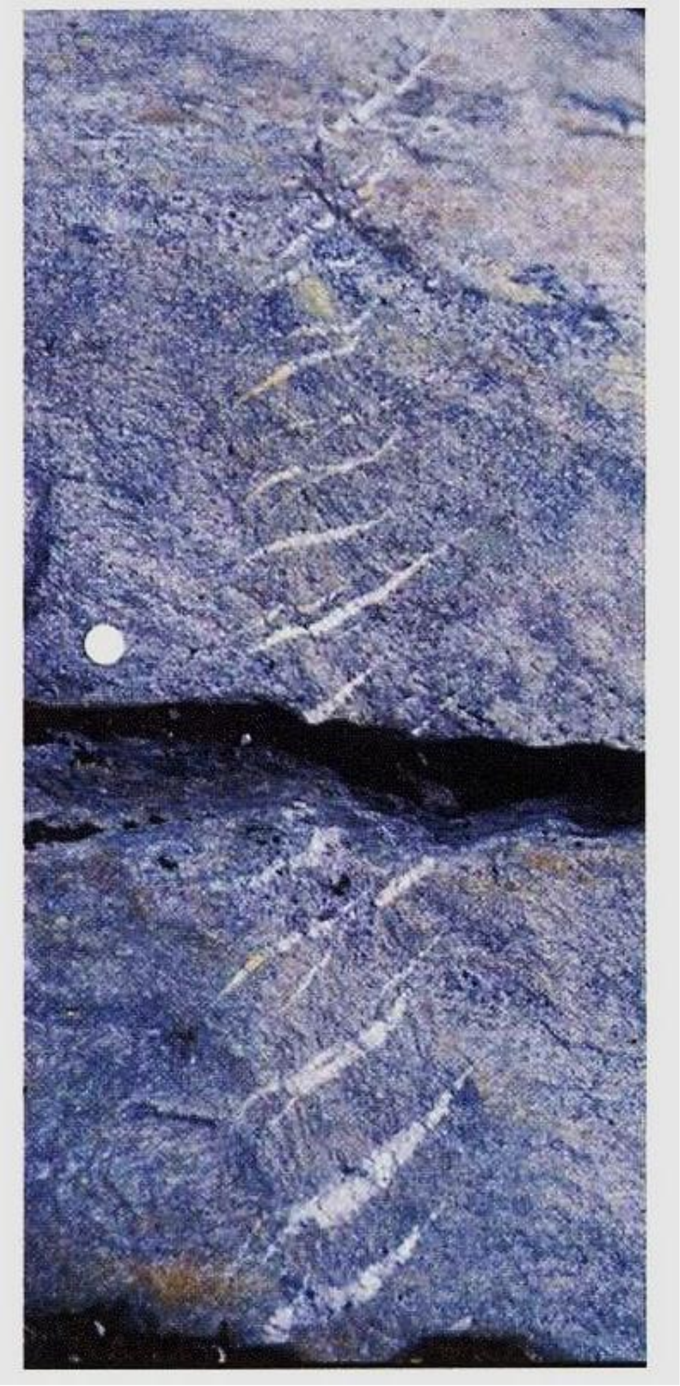

Fig. 15.37. En-echelon-arranged extension veins defining a shear zone. Note the foliation that is oriented at a high angle to each vein.

New veins, however, will continue to form in the same original orientation, with their tips aligned in accordance with the instantaneous stretching axes.

Multiple generations of earlier, deformed veins and younger, less deformed ones are commonly present in a single outcrop, and the deflection of the older veins and how they are buckled are kinematic indicators (Fig. 9.64, 9.66).

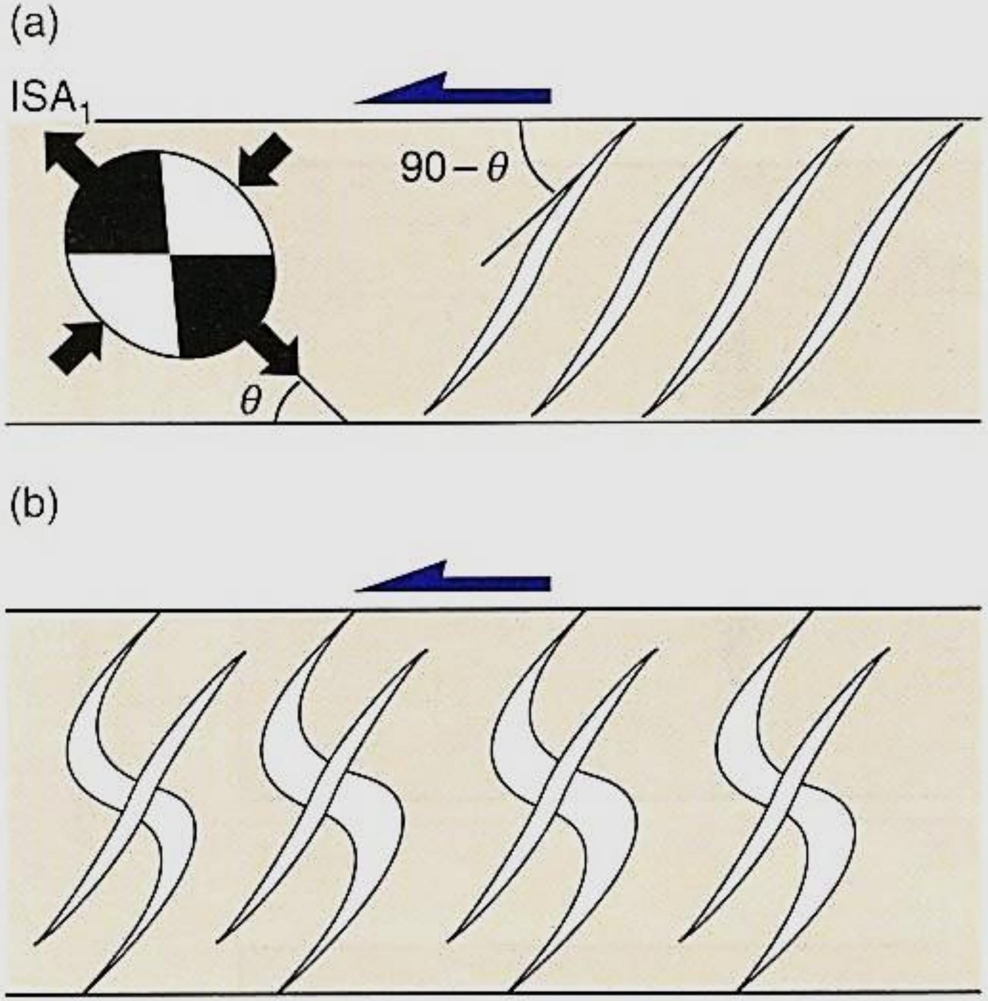

Figure 15.36 En-echelon-arranged extension veins in a shear zone. The vein tips are oriented perpendicular to ISA$_1$. They are sheared into sigmoidal shapes and may be cut by younger veins.

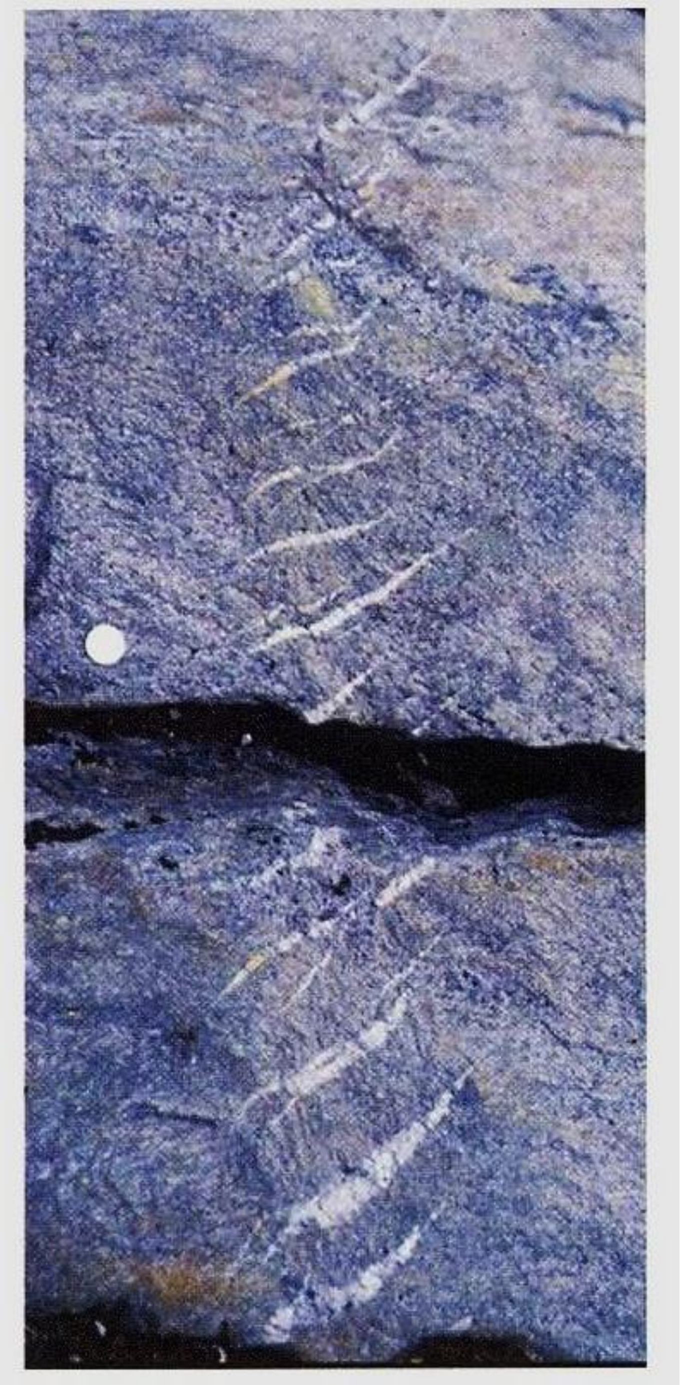

Fig. 15.37. En-echelon-arranged extension veins defining a shear zone. Note the foliation that is oriented at a high angle to each vein.

Thank you

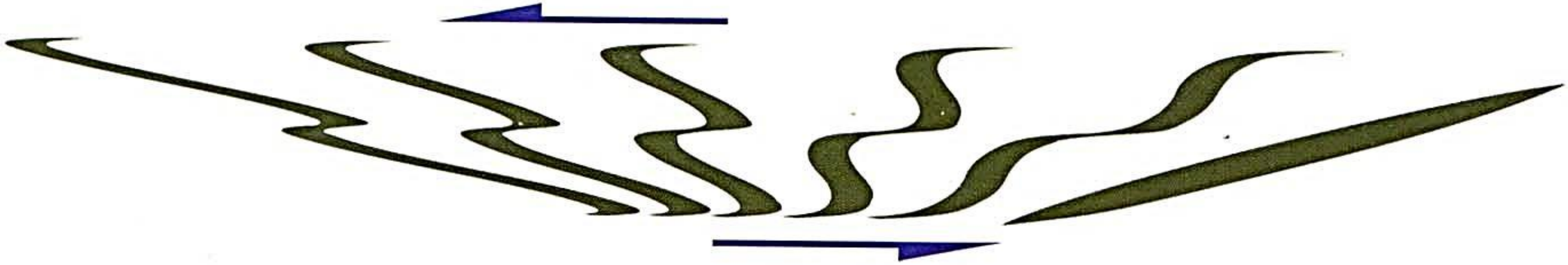

Fig. 15.31: Progressive development of folds in simple shear (strain increasing to the left). This particular initial orientation can result in a vergence apparently inconsistent with the sense of shear.

Figure 15.32 Folds formed in non-coaxial deformation in gneisses. The vergence of the asymmetric folds indicate top-to-the-left transport. A small thrust-like structure (arrow) cuts off the inverted fold limb. The complete structure can be considered to be an S-C structure where the intrafolial fold train is caught between two C-bands.

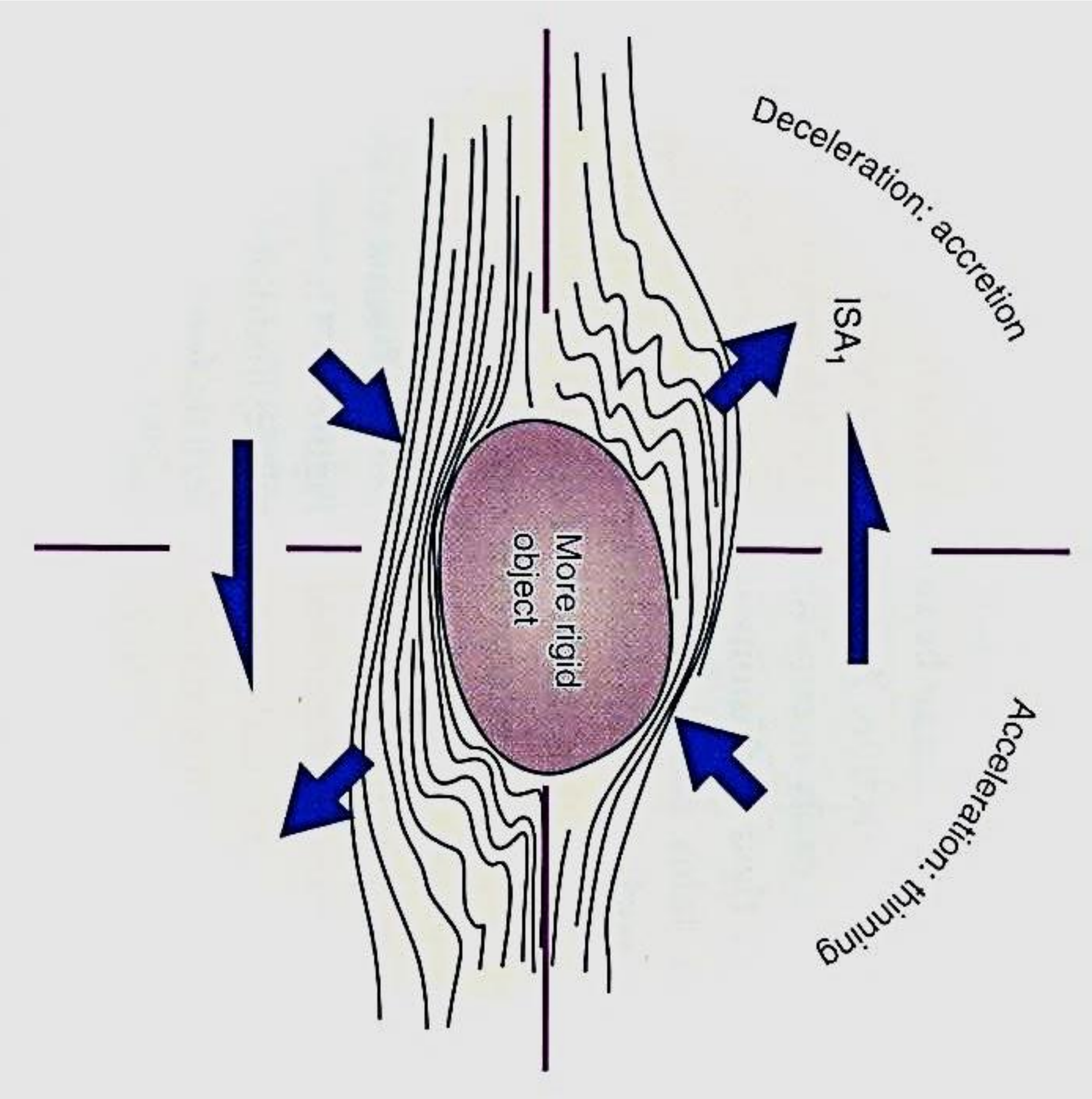

Figure 15.33 Sectors (quarters) of layer thinning/thickening around a rigid object in a mylonite zone indicating sense of shear. The structures are related to particle acceleration/deceleration and are called quarter structures.

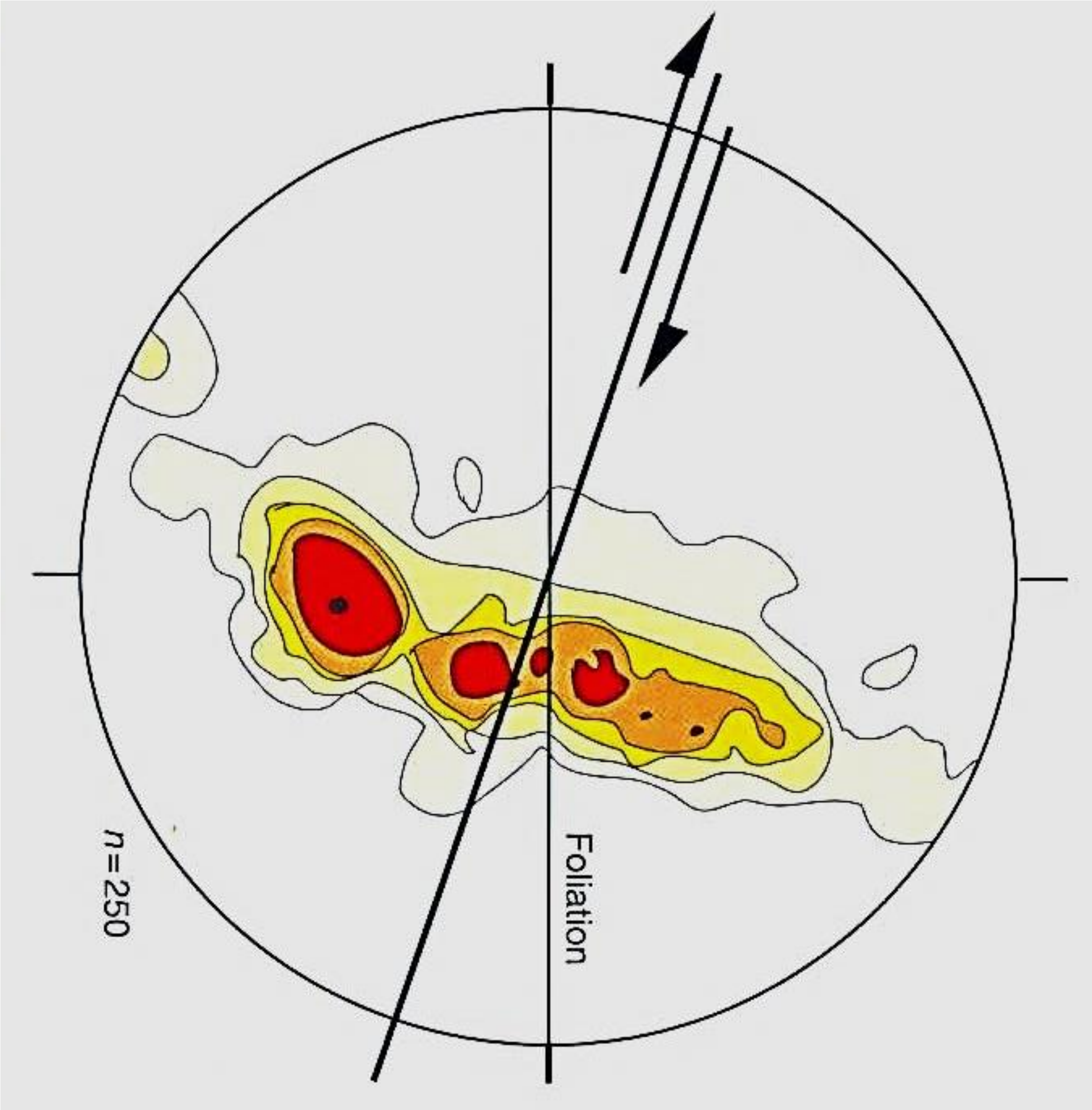

Figure 15.34 Two hundred and fifty quartz *c*-axes measured on the U-stage and plotted in the stereonet. An asymmetrical pattern with respect to the foliation (trending E–W in the plot), such as the one shown here, indicates the sense of shear. From Fossen (1993).

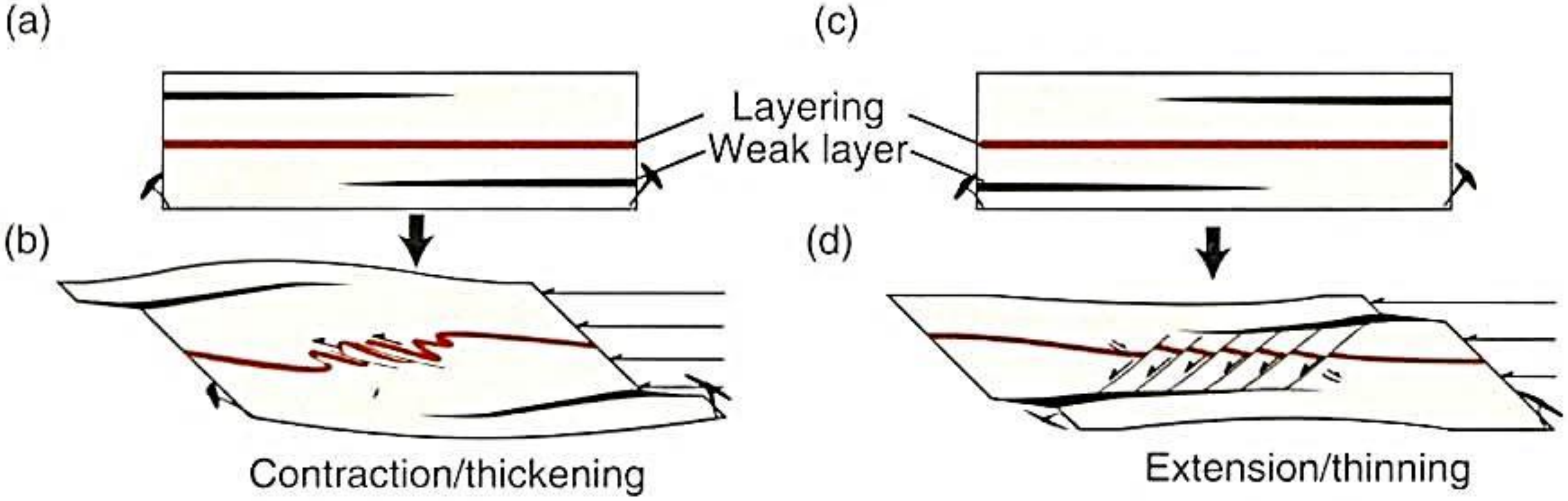

Figure 15.35 Transfer of localized shear strain from one weak layer to another can give contractional or extensional structures. Based on Rykkelid and Fossen (1992).