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SHEAR ZONES: A Tutorial[+]

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1. Introduction

In the last three decades, some revolutionary concepts have emerged which led to change in earlier thinking significantly in Structural geology and also have important implications to the scenario of Global tectonics. The notable one amongst them is the Shear Zones. In the light of their significance, several areas are being revisited, studied and reinterpreted. It has been well recognized that large tracts of Archean terrains were reworked during the early Proterozoic in many parts of the world. In many cases, the reworking occurred along essentially linear zones in the earth's crust, found to be made up in detail of many shear zones, often recording large amounts of overthrust or transcurrent displacement. Individually, shear zones like faults may be compressional (thrust), extensional (normal or lag), strike-slip or oblique-slip. The determination of the movement direction, not always obvious, is critical to the kinematic interpretation. The most useful guide to the movement direction is the orientation of elongation lineations (parallel to the axis of greatest extension) in zones of high strain.

2. Significance of shear zones

Shear zones are useful in several ways. They are: (i) the prime targets for mineral exploration. Mineralisation is commonly associated with specific geometrical features such as bends and intersections, and (ii) the sites of very large strain. They offer some of the strongest tools to unravel the complex deformation features of the Earth's crust, (iii) the sites for igneous intrusions like alkaline rocks and anorthosites, etc., (iv) the only permeable pathways for the large continental crust and they act as effective fluid conduits during active deformation, (v) the potential hazardous sites because of enhanced concentration of radon gas in soils, sometimes related to the uranium concentration, (vi) the belts of extensive mylonitisation, repeated reactivation and chemical transfer, (vii) a possible correlation between the shear zone and U and The content suggests a progressive increase in U enrichment with deformation, (viii) the terrane boundaries, (ix) the zones of marked geophysical anomalies, (x) the hazardous sites in terms of seismicity and Engineering geology, (xi) the zones of grain size reduction and metamorphic retrogression and finally, (xii) the shear zones form natural laboratories for understanding fluid transport, deformation and metamorphic processes.

The structure of shear zones is typically dependent on fluid-rock ratios. The mineralogical and chemical changes in shear zone rocks are a function of strain and fluid transport. Shear zone rocks show substantial adjustments in elements such as $TiO_{2,}$, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O and K_2O. For instance, mylonites, the characteristic features of ductile shear zones, are enriched in - TiO_2, P_2O_5, MnO, Zr, Y, V, Fe_2O_3 and MgO; and depleted in alkalies and silica. From the foregoing, it is clear that - *"Sufficient care should be taken in sampling of rock specimens for laboratory studies. Samples from shear zones must be treated separately. Interpretations in Geosciences, be it geological, geochemical, geochronological or geophysical, are likely to be misled if the presence of shear zones is not considered."*

3. Definition

Shear zones are by definition much more strongly deformed than the surrounding rocks. It is a zone of faulting in which the displacement is accommodated across and along a zone rather than on a single plane. A shear zone is a tabular zone in which strain is notably higher than in the surrounding rock. In other words, it is a planar zone of concentrated (dominantly simple shear) deformation which by itself, or in association with other zones, helps to accommodate, or wholly accommodates an imposed regional or local, strain rate beyond the strength of the country rock. Shear zones are typically planar to gently curved, but some of them show complex geometries.

[+] Invited Tutorial

These are typically produced when volumes of rock, metamorphosed or intruded at high temperatures, are reworked under lower temperature conditions. Traditionally, only ductile shear zones were only described as shear zones to distinguish them from clean-cut faults. In modern terminology, the term shear zone encompasses both clean-cut faults and ductile shear zones (Ramsay, 1980). The shear zones range in scale from microscopic or grain scale to the scale of a few hundred kilometers in length and a few kilometers in width, as reported from the Precambrian gneisses of Greenland (Bak et al., 1975). They exist at all scales: microscopic or grain scale; a few hundred kms in length and a few kms in width. They are long relative to their width, generally 5:1. They can extend up to mantle depths. Shear zones can occur as intersecting and anastomosing pattern, depending on the nature: Compressional (Thrust), extensional (Normal or Lag), Strike-Slip or Oblique Slip (Wrench).

Traditionally, shear zones are believed not to show any loss of coherence, between the wall rock and the shear zone itself. A marker layer, though deflected in the shear zone, should not be broken at the contact. Therefore, a ductile shear zone cannot be regarded as a fault in the ordinary sense of the term. However, the distinction is difficult, if not impossible, for most field examples especially when the tangential displacement is very large in comparison with the width of the ductile zone. In such shear zones marker units may undergo extensive boudinage and the continuity of the markers may be unrecognizable in the mylonite belt. Following Ramsay (1980), we can designate this entire class of structures as shear zones, with faults and ductile shear zones as the end members. It also depends on the scale we are looking at these structures. A line, for instance, on a million-scale map represents nearly 1 km width on the ground, which indicates that it is a zone of planar elements or crushed material. Even on outcrop scale, although we find it as a line in the field, if we project the same on to a microscopic scale, it invariably becomes a zone. So, it is justified to refer the entire spectrum of faults as shear zones.

4. Recognition of shear zones

Identification of shear zones is not simple. Field geologist's perspective is, in general, limited to out crop scale. The shear zones are invariably marked by heterogeneous strain and in association with the common occurrence of less deformed areas of different sizes. Misidentification of mylonites, pseudotachylites, schists is also a common feature among geologists. It may be noted that large shear zones can be identified easily on maps of regional scale particularly through satellite images. However, it is cautioned that shear zones with steep to moderate dips are distinctly visible while the flat lying shear zones, which are common, would not be easily recognisable on the image. It is observed that the concept based approach in mapping shear zones has become more successful. First, identify the shear zones in the form of lineaments on the image and start looking for evidences in the field. Identification of shear zones is crucial. If not, one may be misled totally in their interpretation be it in structural geology, P-T-t history, geochemical signatures, isotopic systematics or geophysical anomalies.

It may be noted that shear zones may act as both closed and open geochemical systems, irrespective of their size. The geometry of individual shear zones is dependent on both the degree of pre-existing anisotropy and the orientation of the new anisotropy with respect to strain field. It is also recognized that apparent multiple deformation events occur within a shear zone arising from single progressive deformation event.

"Several areas have been revisited, changed earlier thinking and reinterpreted."

5. Classification of shear zones

The shear zones can be classified into three classes (Figure 1).

(i) Faults / Brittle shear zones – are a special variety of shear zones, where a clear discontinuity exists between the sides of the zone and the shear zone walls are almost unstrained or perhaps brecciated. Gouges and cataclasites are produced. As a rule of thumb, brittle shear zones form in the upper crust at temperatures below about 300^{o} C.

(ii) Brittle-ductile shear zones – are associated with some ductile deformation in the walls, which show permanent strain for a distance of up to 10 meters on either side of the fault break. There is a possibility that the ductile part of the deformation history formed at a different time from that of the fault discontinuity. Another type of brittle-ductile shear zone is the extension failure. The deformation zone shows an en-echelon array of extension openings, usually filled with fibrous crystalline material. The openings usually make angle of 45^{0} or more with the shear zone and some times shearing in a sigmoidal form.

(iii) Ductile shear zones – are those in that the deformation and differential displacement of the walls is accomplished entirely by ductile flow. No discontinuities can be observed on the scale of the rock outcrop. Marker layers in the country rock can be traced through the shear zone; they are deflected and may change in their thickness, but mostly they remain unbroken. Ductile shear zones are extremely common in deformed crystalline basement rocks (granites, gabbros, gneisses, etc.) of all grades of metamorphism. Crystal plastic deformation processes, e.g: pressure solution, dislocation creep, grain boundary sliding and diffusion, along with recrystallization and neomineralization, dominate to make mylonites; which are characteristics of ductile shear zones. Field examples of all the varieties are provided in Figure 2.

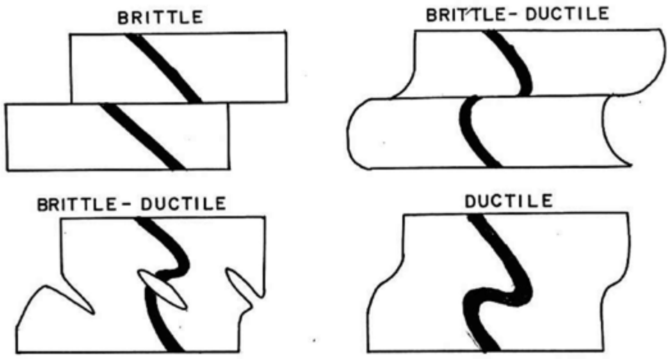


Figure 1. Diagrammatic classification of shear zones.

Figure 2. Field examples of shear zones in granitic rocks around Hyderabad: (a) Brittle shear zone; (b) Brittle-ductile shear zone; and (c) Ductile shear zone

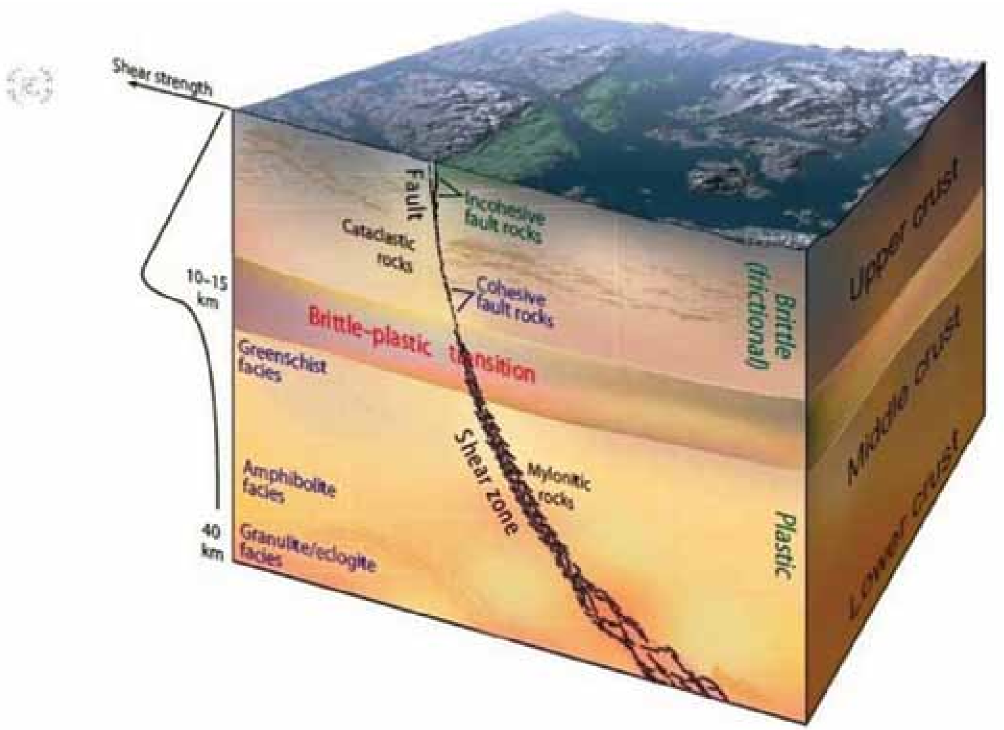


Figure 3. Simplified model of the connection between faults, which normally form in the upper crust, and the classic ductile shear zones. The transition is gradual and known as the brittle–plastic transition.The depth depends on the temperature gradient and the mineralogy of the crust. For granitic rocks it normally occurs in the range of 10–15 km (source: Fossen, 2010).

In general, ductile – and brittle-ductile varieties are the deep level counterparts of brittle shear zones and faults at higher levels in the crust. These shear zones may range in scale from the microscopic or grain scale to the scale of few 100 km in length and a few metres or a few tens of kilometers in width, eg. Precambrian gneisses of Greenland (Bak et al., 1975) and crustal shear zones in Africa (Daly, 1986). Ductile shear zones can be further classified into two types: (a) discrete shear zones which cut across rocks, otherwise undeformed by the particular phase of deformation; and (b) shear zones located at the margins of mobile belts or at the margins of sub zones within the belts (Coward, 1980). The former are unrelated to the local tectonics and the later develop necessarily to maintain compatibility between zones of different intensities of deformation. Ductile shear zones are formed at mid-crustal levels of around 15-20 km depth as indicated by the high metamorphic grade of the associated fabrics. There is increasing evidence from deep seismic reflection surveys and theoretical considerations of crustal rheology that major detachment horizons of this kind exist within middle and lower crust. It should be borne in mind that faults and shear zones are closely related structures. In fact, the general perception of shear zones as the deep counterpart or extension of faults is well illustrated in Figure 3. The depth depends on the temperature gradient and the mineralogy of the crust. For granitic rocks it normally occurs in the range of 10–15 km. Both shear zones and faults are strain localization structures. Both involve displacement parallel to the walls, and both tend to grow in width and length during displacement accumulation.

6. General characteristics of Shear Zones

Typically, the shear zones are characterized by the development of mylonitic fabric – in granitic material for instance, the closely spaced foliation is defined by alternating layers of recrystallized quartz grains, milky ribbons of fine grained, recrystallized feldspar and fine platy biotite. The following are the common characteristics in shear zone rocks: (a) The foliation surfaces contain a very strong lineation (stretching lineation) defined by the elongation (and / or boudinage) of minerals like hornblende, micas, quartz, feldspar, etc. as well as mineral aggregates, (b) S-C mylonites are very common, indicating non-coaxial deformation history, (c) The amount of strain is highly variable resulting in the occurrence of mylonitic series (Proto- to ultramylonite), (d) Grain size reduction is typical, (e) Retrogression is usual, (f) Development of new grain-growth, particularly biotite, kyanite, staurolite and muscovite, (g) The shear zones occur as intersection and anastomosing patterns, (h) Generally, they are associated with large geophysical anomalies, and (i) Association with igneous intrusions is a common feature. The typical

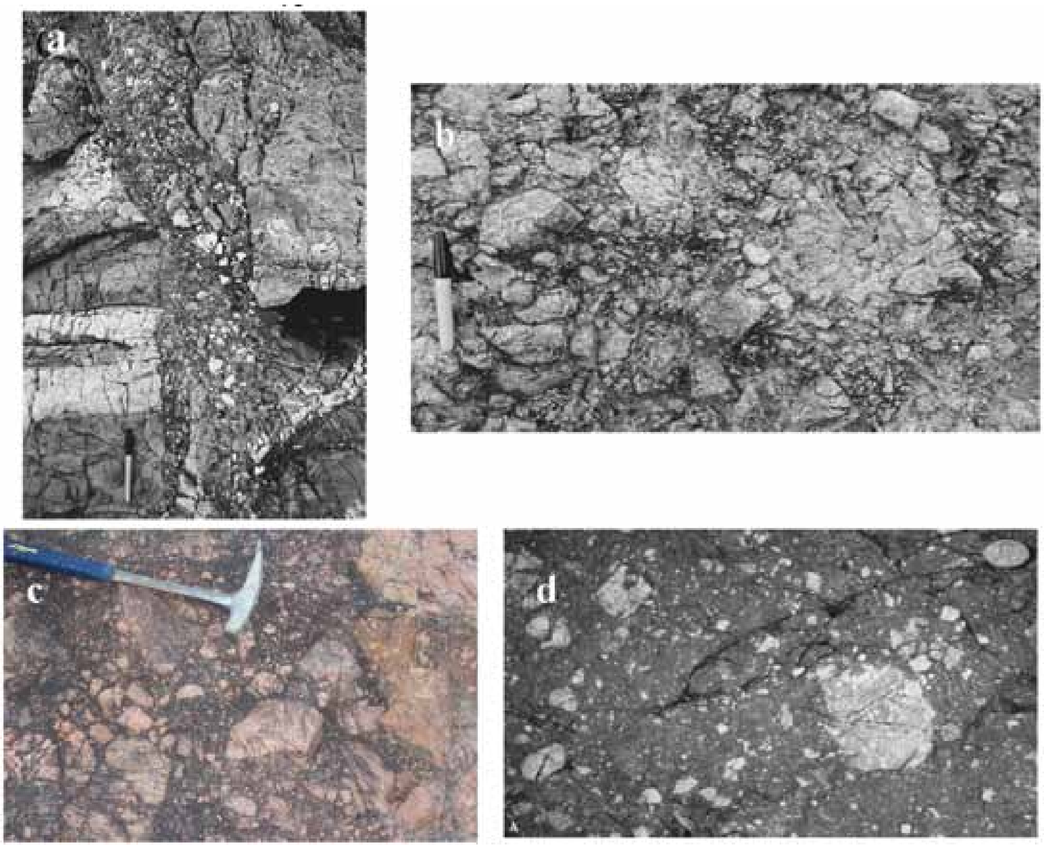


Figure 4. (a) Brittle shear zone cutting across the layered sequence, (b) Brecciated granite, (c) Fault gouge, (d) Cataclasite.

features associated with different types of shear zones are illustrated below.

6.1 Brittle Shear Zones

Brittle shear zones form in the shallow parts of the crust, generally within 5-10 km of the Earth's surface, where deformation is dominated by brittle mechanisms, such as fracturing and faulting. Brittle deformation is also favoured by the relatively rapid strain rates that occur during seismic events (many earthquakes occur within the upper 10-15 km of the crust). Accordingly, and shear fractures, and brecciation. Brittle shear zones can also be termed as fault zones and are characterized by closely spaced faults, numerous joints marked by fault gouge and other breccia series (Figure 4).

Breccia

Brecciated rock is composed of angular fragments of host rock greater than about 1 mm, and as much as several meters across and is noncohesive. Creation of a random array of nonsystematic mesoscopic fractures that surround angular blocks of rock creates fault breccia. In general, breccias have random fabrics, implying that they do not contain a distinctive foliation. Continued displacement across the fault zone may crush and further fragment breccia, and/or may break off microscopic asperities protruding from slip surfaces in the fault zone, thereby creating a fine-grained rock flour described as fault gouge. Gouge and (micro) breccia are noncohesive fault rocks, meaning that they easily fall apart when collected at a fault zone or hit with a hammer.

Gouge

Gouge is incohesive fault rock that result from shallow level movements in a zone. Sometimes, they have a weak foliation. They tend to be limited to narrow zones often within wider mylonitic or cataclastic zones. Gouge is a rock composed of material, whose grain size has been mechanically reduced by pulverization. Grains in fault gouge are less than about 1 mm in diameter. Like breccia, gouge is noncohesive. Shearing of gouge along a fault surface during progressive movement may often create foliation within the gouge. Clay formed by alteration of silicate minerals in fault zones may be difficult to distinguish from true gouge.

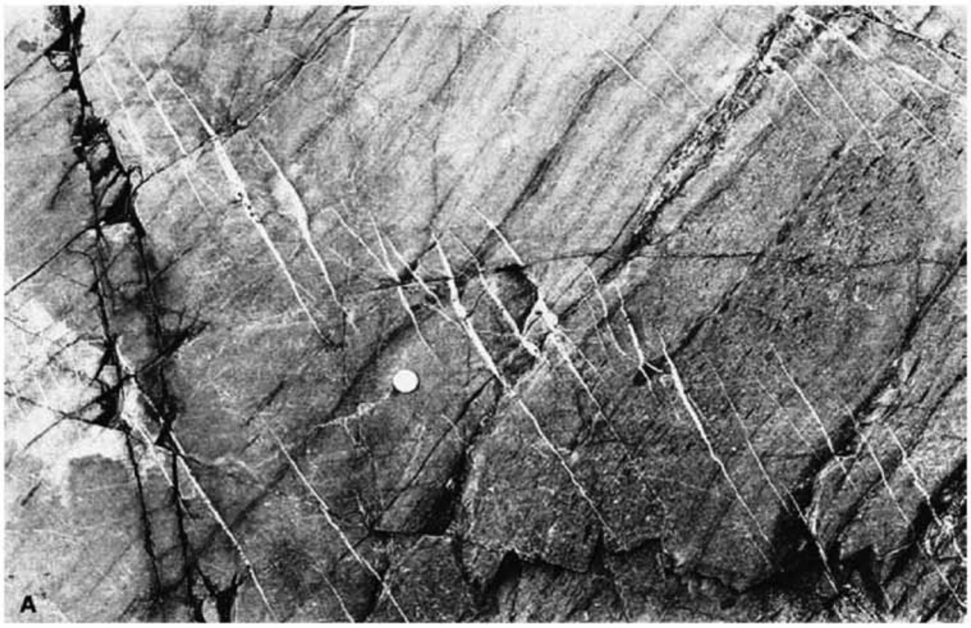


Figure 5. Brittle-ductile shear zones in the field defined by en echelon quartz veins. A single set of veins defining a shear zone crossing diagonally across the photograph.

Cataclasite

Cataclasite is a cohesive brittle fault rock that differs from gouge or breccia in that the fragments interlock, allowing the fragmented rock to remain coherent even without cementation. Cataclasites generally have random fabrics (i.e., no strong foliation or lineation). A cataclasite lacks a foliation and has angular clasts in a fine-grained matrix which consists of newly developed minerals, mainly white mica, chlorite and/or calcite. A similar classification to that used in mylonites is also applied to cataclasites, based on the proportion of matrix in the rock. In protocataclasite, 10–50% of the rock is matrix; in cataclasite (*sensu stricto*) 50–90% is matrix; and in ultracataclasite, 90–100% is matrix. This can also grade into mylonite after initial cataclasis. Unlike breccia, it is a solid rock that does not disintegrate when struck with a hammer.

Pseudotachylites

Pseudotachylites result from melting along sliding planes during an earthquake event. It requires dry rock and is limited to the seismogenic zone. The melt is ejected from the generating planes into adjacent rocks. Consequently, these appear as small, cross cutting black veins of igneous material in the shear zone.

6.2 Brittle-ductile shear zones

Brittle-ductile shear zones (Figure 5) form when (i) the physical conditions permit brittle and ductile deformation to occur at the same time, (ii) different parts of a rock have different mechanical properties, (iii) a shear zone "strain hardens," (iv) a short-term change in physical conditions, such as in strain rate, causes the rock to switch from ductile to brittle mechanisms or vice versa, (v) physical conditions change systematically during deformation.

6.3 Ductile Shear Zones

Ductile shear zones are formed by shearing under ductile conditions, generally in the middle to lower crust (10 – 20km) and in the asthenosphere. For the most common crustal rocks (e.g., granite), brittle deformation at shallow crustal levels gives way downward into ductile deformation at the brittle-ductile transition. Most ductile shear zones form under metamorphic conditions, and the resulting sheared rocks are metamorphic in character, typically possessing foliation and metamorphic minerals. Rocks within a ductile shear zone may be so changed by the intense shear, by metamorphism, and by fluids passing through the shear zone that it becomes very difficult, if not impossible, to decipher the original rock—the protolith.

Mylonites are the most commonly encountered rocks in ductile shear zones and also the one most likely to be misidentified as schist. There is one additional fault rock, a pseudotachylite which is a frictional melt generated during the earthquake rupture of strong dry rocks in the upper crust. Moine Thrust belt is the classic area from where much of the structural geology has come while studying this belt a century back – a famous geologist by name Lapworth (1885) has come across a peculiar rock type lying mostly along the thrust plane. Lapworth describes the rocks in the following way. "The most intense mechanical metamorphism occurs along the grand disloction (thrust planes), where the gneisses and pegmatites resting on those planes are crushed, dragged and ground out into a finely laminated schist, composed of shattered fragments of the original crystals of the rock set in a cement of secondary quartz, the lamination being defined by minute inosculating lines (fluxion lines) of Kaolin or chloritic material and secondary crystals of mica". Then he has coined the term "Mylonite" for such rock type and defined it, for the first time, as "Mylonites are the schist-like products of dominantly ductile reworking of the country rock within a shear zone". Depending on the size of the zone, mylonites can vary in width from centimeters to tens of kilometers. They are further subdivided into three broad classes, depending on the degree of reworking. They are, with increasing shear strain: Protomylonite, mylonite and ultramylonite. The boundary between each class is set by the percentage of reworked matrix, relative to clasts of parent country rock minerals. In a protomylonite, the matrix makes up less than 25%, a mylonite between 25% and 90% and ultramylonite more than 90%. The term ultramylonite does not necessarily mean an ultrafine grain size always. It is simply the degree of reworking. Thus ultramylonites mark the most highly strained areas within a shear zone.

The classical ideas about the process of development of mylonites have been greatly modified subsequently and were demonstrated that the dominant process of grain refinement in mylonites is by syntectonic recrystallisation and neomineralization. The well-known mortar structure of mylonites develops by syntectonic recrystallisation and not by cataclastic processes. Typically, a mylonite consists of elongated and drawn out clasts (augen) in a fine-grained matrix. It is the matrix that flows by crystal processes. The clasts tend to be the stronger minerals, for example in the granite gneiss, the stronger K-feldspar clasts form the augen and the softer phases, quartz and phyllosilicates form the matrix. The phyllosilicate orientation and the elongation of the matrix quartz causes the mylonitic foliation. At low temperatures, e.g. greenschist facies, the feldspar clasts, both plagioclase and K-feldspar, elongate by fracturing and the fragments retrogress to a white mica, chlorite, quartz assemblage which is incorporated into the matrix. As the change from mylonite to ultramylonite is effected, the granite gneiss changes into a finely laminated phyllosilicate quartz assemblage which may resemble a slate and which deforms ductile environment. The effect of retrogression is to change the brittle feldspar into a weaker and consequently ductile mineral assemblage. At higher temperatures, the feldspar deforms ductilely, plastically elongate and undergo grain refinement by recrystallisation, rather than by fracturing and neomineralization. Quartz grains always refine by recrystallisation under all mylonite conditions. In a quartzite or quartz bands the harder grains of quartz may remain as elongate augens and the softest as ribbons.

The diagnostic features of mylonites include intrafolial folds, rotated clasts, internal shear bands forming a second foliation and oblique grain growth, all of which have a constant sense of symmetry related to the direction of shearing. Also, mylonites have another feature viz., a stretching lineation, which is absent in schists. Two lineations are encountered in mylonites, one unique to mylonites, the stretching lineation, and the other, an intersection lineation, which is found in both mylonites and schists. The later results from the intersection of one foliation on the plane of another. This lineation has no kinematic significance. The stretching lineation indicates the direction of flow in a mylonite. This can be distinguished from an intersecting lineation as it is marked by elongate minerals such as hornblende or by elongated or pulled out clasts such as feldspars, quartz and calcite.

7. Depth of shear zones

The brittle to ductile shear zone rock sequence: gouge-cataclasite-mylonite forms a depth sequence (Figure 6). Gouge forms at shallow crustal depths where temperatures are so low that clay mineral growth in the matrix and precipitation from fluids is not sufficient to "weld" the fault rock together. This is likely to be favoured by temperatures lower than 100-150°C. At higher temperatures, welding occurs and a cataclasite would be developed. The cataclastic / mylonite boundary is taken as the temperature at which the ductile / brittle transition occurs in a granite type mineral assemblage. This was first noted by Sibson (1977) and the transition ranges between 250-300°C. This implies that the earthquakes, which are a manifestation of catastrophic brittle failure, occur at temperatures lower than the transition range. This is confirmed by later seismic studies.

Considering the above, the depth of shear zones becomes a controversial issue, especially for strike slip zones which cannot be directly imaged by reflection seismics. However, the depth can be worked out indirectly from the depth of normal and thrust movements, but in general, all strike slip zones are coupled with them. The depth to which individual normal and thrust faults, can reasonably be estimated. For example, the faults cutting through the upper mantle are rare, many of them decouple along the Moho and many others within the crust. Therefore, few strike slip zones cut into the mantle, more end at the Moho and most end within the midcrust. From these considerations, three possible main orders can be outlined: (a) First order – major strike slip mobile zones coupled to entire thrust and extensional (basin)

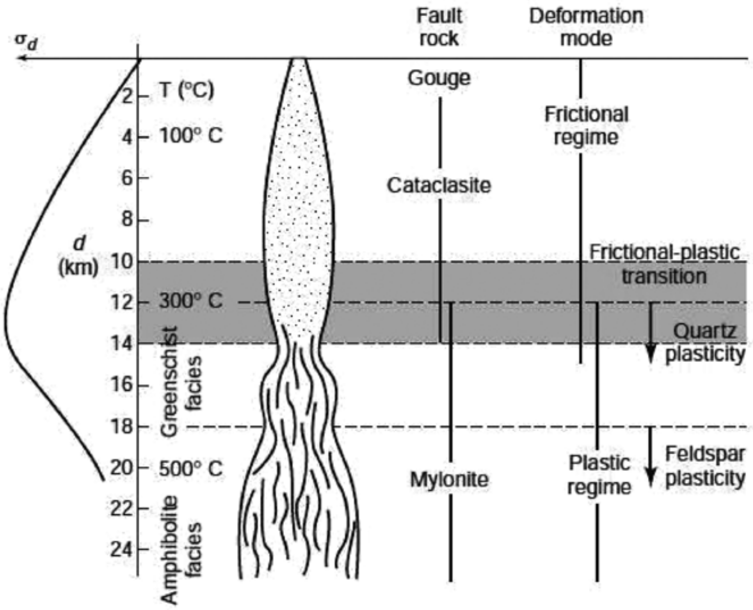


Figure 6. Integrated model for a displacement zone that cuts deep into the crust, showing the frictional and plastic regimes, the frictional–plastic transition, and crustal strength (σd)*; this is sometimes* called the Sibson-Scholz fault model. Fault rocks typically found at crustal levels are indicated.

belts (orogenic belts) and the coupling of which effectively divides the continental lithosphere into platelets, (b) Second order – main strike slip shear zones occur within a thrust or extensional belt and terminate at the Moho, and (c) Third order – minor, shorter zones within these belts that terminate at shallower depths. They are the most abundant. The variation in depth will influence magma generation within a strike slip zone and also the source of deep fluids entering an individual zone or an array. It will also have a bearing on reactivation tectonics.

The model for depth variation in shear zones was formalized by Sibson (1977), who shows that a shear zone broadens with depth (Figure 6). The reason for the broadening, especially a ductile one, could be due to relative differences in strength (viscosity) between fault rocks and the enveloping rock with depth. This is based on experimental as well as from the field evidences. For instance, the shear zones in the Moine Thrust in N.W. Scotland, are typically less than 10 m wide in shallow zones, while the deeper shear zones extend over 100 m in width.

If a major, deep shear zone has a vertical component of movement, it will exhume itself during movement and bring up the deeper part of the zone. The prime example for this is the Alpine Fault in New Zealand. However, there is insufficient data to formalize a depth-width relationship. The fault rock profile across the Alpine fault shows a temperature increase into the hanging wall. Uplift has concentrated on the footwall and parts of the zone are progressively accreted on to the hanging wall as uplift progresses. Consequently the lateral sequence cataclasite-augen-mylonite-green, mylonite-schistose, mylonite-early schist is a depth sequence arising from the accretion. The zone is approximately 200 m wide in cataclastic field widening to 700 m at the ductile / brittle transition as indicated by the augen and green mylonites and finally widening to 1 km at the temperature at which the early schists developed (Johnson and White, 1982). However, there is insufficient data to formalize a depth-width relationship.

8. Development of folds in shear zones

Flow within a shear/mylonite zone is extremely inhomogeneous because of variations in the competency of individual bands that may reflect variations in grain size – fine grained bands of quartz concentrate deformation to a greater extent than coarse grained ones. The result of this is to develop local dilatant and compressive zones in a mylonite. The former may concentrate fluids and the latter will initiate intrafolial folds as shown in Figure 7.

The folds develop in shear zones as simple buckles with their axes perpendicular to the movement direction, i.e. perpendicular to the stretching lineation, which they fold. The axial plane of these folds rotates from an inclined position at about 45° to the foliation into parallelism with it as shear strain increases. The short limb is progressively thinned during the rotation and may shear out to leave isolated fold hinges.

In addition to inhomogeneous flow between bands, there is also inhomogeneity along the plane of a band.

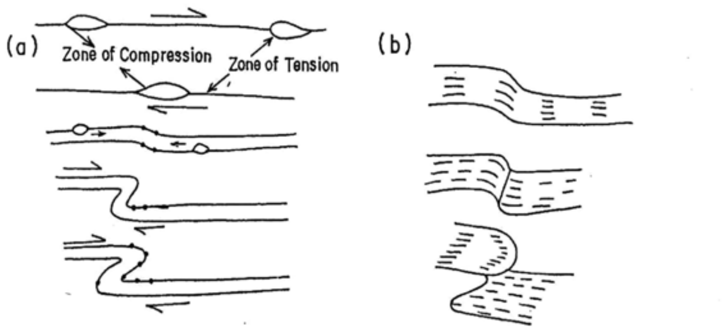


Fig.7(a) The development of intrafolial folds due to local stress notches along the mylonite foliation due to differential shearing along the foliation (after Rhodes and Gayer, 1978).

(b) Progressive tonguing out of the intrafolial fold to form a sheath fold (Minnigh, 1979).

Figure 7. Concentration of deformation along the shear zones and the development of folds.

This causes bowing of the axial plane and the folds become grossly non-cylindrical. The combination of both inhomogeneities is to tongue out the folds in the flow direction, i.e. parallel to the stretching lineation. Carreras et al. (1977) termed them as "sheath folds" because they resembled a knife sheath in profile. If sectioned perpendicular to the stretching lineation, they have an eye appearance, sometimes known as "eye folds". The "eye" like cross section is similar to Type I interference pattern that results from the superimposition of two fold events (Ramsay, 1967) and have often been interpreted as such. Sheath folds are not the product of fold super imposition.

The size of a sheath fold depends upon the size of a shear zone. They may range from the microscopic scale in ultramylonite bands up to the kilometric scale (a km in width and several kms long) in major shear zones, e.g., mobile belts (orogens), which have great thickness of mylonite. The amount by which a shear zone tongues (length: width ratio) is a measure of shear strain (Cobbold and Quinquin, 1980). The effect of the tonguing process is to rotate the axial plane from being perpendicular to the stretching lineation; to having large segments parallel and small segments oblique to the stretching lineation depending on the amount of tonguing. Any folds in the country rocks will also be rotated towards parallelism with the stretching lineation.

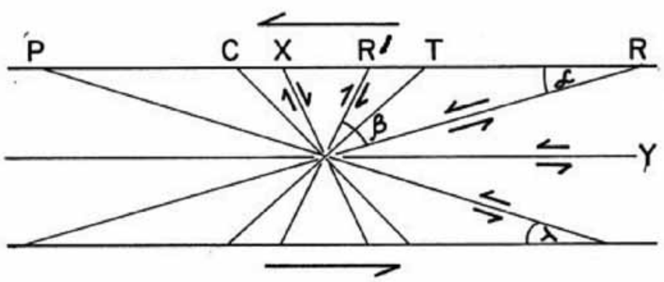
Once sheath folds tongue out they effectively become a part of the mylonite again but are a heterogeneity in the zone. Consequently, they tend to nucleate another intrafolial fold, which is initially perpendicular to the stretching lineation and consequently "refolds" the sheath fold and in turn becomes tongued itself and is then "refolded" and the process repeated again and again. Quite complex fold pile-ups result from this refolding process and all during a single deformation.

"The concentration of fold axes perpendicular and parallel to the stretching lineation with the former folding the lineation and the later having an apparent superimposition appearance, formerly always and now often, led geologists to conclude that there had been at least two distinct periods of folding post dating the initial development of the mylonite foliation, which is not correct. This is well evident from the history of Moine Thrust studies (Evans and White, 1984), where the previously postulated first three deformation events were found to be due to a single event of progressive deformation."

9. Apparent multiple deformation events arising from single shearing event

The shear band structures rotate the mylonite foliations and also rotate intrafolial folds and present pseudo appearance that all folding is post deformational. Consequently in a classical interpretation of geometrical analysis, such folds are taken to represent four multiple deformation events. But in reality, all these structures are produced from a single shearing event. Thus, if a mylonite is misidentified as a schist, the following four regional deformation events are thought to have occurred: D1- development of the schistose foliation, D2- folding of this and development of the lineation, as a b-lineation, parallel to the fold axis, D3- refolding of the above folds and lineation about a perpendicular axis with local development of an axial planar foliation, D4- large scale regional folding (because they are not seen) to form the shear band foliation, whose constant asymmetry is used to deduce the position of the large scale invisible folds.

"The above analysis of apparent multiple deformation events shows that an entire mess can be made of the regional structural geology if major mylonite belts (shear or mobile zones) are misidentified as schist belts arising through regional shortening."



8 Geometrical relationships between individual shears in a sinistral array.

Y - shears; parallel to the shear zone edge.
P - Pressure shears; 20-30° to the D-shears (measuring clockwise from the slip sense of the zone).
R - Riedel shears; 150-160° to Y shears.
X - Shears; 70-80° to Y shears.
R1 - Riedel shears; 110-120° to Y shears.
T - Tensional shears

Figure 8. Strike slip arrays in a major shear zone and their geometrical relationships.

10. Three dimensional geometry of shear zone arrays

Shear zones are commonly arranged in networks or sets composed of a number of individual shear zones. They may occur in subparallel sets, may deflect toward one another and link up in an anastomosing pattern, or may crosscut and displace one another. Some shear zones have a curviplanar or folded geometry. Such geometry may indicate that an originally planar shear zone was folded or warped by subsequent deformation. Alternatively, many shear zones form with an original curviplanar geometry, encompassing and wrapping around more rigid, less deformed rocks.

In nature, most individual shear zones are members of an array or of a set in a larger array. Therefore, it is important to consider the fault arrangements in strike slip, extensional and thrust arrays with particular reference to fluid flow and / mineralization and then turn to the depth to which the shear zones cut the lithosphere and in turn will affect the fluid compositions.

Strike slip arrays

There will be individual strike slip zones in the arrays and have a similar sense of movement. Similar geometrical features are produced in experiments of the simple shear of clay blocks. That shows, the same geometrical relationship exists within strike slip zones, irrespective of scale from the mega scale down to the microscale. The relationship is shown in Figure 8.

The arrays consist of normal faults, extensional zones, tensional fractures, 135° to the Y-shears. Reverse faults, fold axes; 45° to Y-shears. The above angles show only slight variations with increasing strain. Y-, P-, R- shears all have the same sense of displacements as that of major shear zone, i.e. in sinistral, while X and R^1 shears have the opposite sense of shear. Each of the individual shear zones have the same internal structures as described earlier. Thus each, in a shear/mylonite zone, has its own uniquely oriented intrafolial folds, shear bands etc. If it is a cataclastic zone, it will have within its own Y-, R-, R^1- and P shears and extensional zones, i.e. shears within shears develop. An example can be from Abitibi greenstone belt where Y-, R-, and R^1 shears are described by Dimroh et al., (1983).

Zone of maximum dilatancy occur where a Y-shear transfers across another Y-through a R-shear and especially where the terminations of two Y-shears are cross-linked by a normal fault (a large extensional or dilational jog) (Figure 9). In cataclastic environments, the R- segments are characterised by extensive veining. In ductile shear zones, they display greater veining and replacement than that of normal faults. The transfer of displacement between two Y-shears also takes place through a P-shear with complete stresses on the P-segment. If there is cataclastic environments in such transitional zone, intense crushing and veining is produced. The most concentrated zones for enhanced fluid flow are the extensional jogs. As will be seen small jogs can give rise to "breccia pipes" and large ones which form the pull apart basins will run into normal faults and extensive fracturing at depth.

"From an exploration viewpoint, extensional jogs offer the best potential for mineralisation, especially vein mineralisation, then R and P shears. The last is more likely to have dispersed mineralisation. The depth to which veins develop especially in the transitional zone depends on the pore fluid pressures and can be calculated."

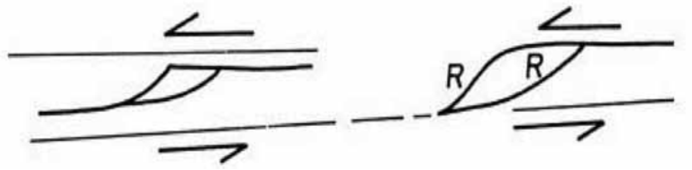


Figure 9. Development of large extensional or dilational jogs when two Y-shears are cross-linked by a normal fault.

Reverse / Thrust Zones

The structure of shear zones in the basement rocks are only considered here but not the ones in cover sediments. The reader is referred to an excellent review by Boyer and Elliot (1982) for the geometrical arrangement of faults in cover sequences.

Shear zone arrangements in thrusted basement are well studied in the South Arunta block on the Alice Springs on 1: 100,000 Geological sheets. They consist of steeply north dipping zones together with some back thrusts dipping to the south and which again have an anastomosing pattern but lack the regularity that appears in strike slip arrays. Cross cutting faults occur more or less, at right angles to the general trend of the anastomosing reverse faults and have a vertical dip. These are transfer or transform strike slip shear zones that accommodate lateral variations in regional shortening (they are also referred to as lateral or sidewall ramps in the thrust literature). The reverse faults show down dip stretching lineations and all internal structures, e.g. sheath folds, shear bands etc. that reflect thrusting. However, in the transfer zones, the lineation is oblique, being parallel to that in the reverse shear zones and again all structures within the zone reflect the oblique shearing. Also of importance, are the transfer faults as they are vertical structures and are the shortest path length for fluids. Once recognized, they can be prospected as straightforward slip zones.

The nature of normal fault arrays in the basement rock is not clearly understood. Much information is available from the oil industry on the structure of normal faults in basins. Deep structures show that they exhibit a similar geometry as that of thrust terrains. There are also transfer strike slip zones accommodating differential extension and as in thrust terrain, they should also be prospected as strike slip shear zones for any mineralization. Andersonian analysis indicates that the vertical segments of the listric normal faults are the most dilatant and are known sites for extensive veining. However, exploration along detachment zones of extensional terrains shows that dispersal mineralization can occur in the flat detachment zone as a result of dilatancy, associated with cataclasis and veining in mylonites.

Extensional faults also propagate into the footwall during continued extension and as a result of maximum thinning and inversion (uplift) towards the basin axis, i.e. into the hanging wall direction of the main listric faults. Metamorphic grade also increases in this direction. This metamorphism differs from that in compressional terrains (thrust) it is of the low pressure regional facies and often confused with contact metamorphism.

Coupled Zones

The transfer faults in the above extensional and thrust terrains are examples of coupling where the strike slip zones are needed to accommodate differential horizontal movements. Coupling does not only aid Andersonian analysis and this, in turn can be used to identify coupling on a regional scale. The best example of coupled shear zones has been reported from Broken Hill of Australia. Another example is from South Africa where the coupling of strike slip zones joins a series of thrust belts.

11. Kinematic indicators in Shear zones

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 structures that show monoclinic (low) symmetry, exhibiting asymmetric structures. The asymmetry is related to the rotational component or non-coaxiality of the deformation.

The monoclinic structures that give information about the sense of displacement or sense of shear represent crucial kinematic indicators. Some of the key kinematic indicators include: (i) Deflected markers (Foliations and other marker horizons), (ii) S-C structures, (iii) Porphyroclast systems, (iv) Grain-tail complexes, (v) Foliation fish and foliation boudinage, (vi) Crystallographic orientation, and (vii) Fibres and veins.

(i) Deflected markers

It is well observed that the pre-existing markers (linear or planar) become rotated into shear zones during shearing. Even if the shear zone margins are not seen, rotation of planar markers (foliation/marker horizon) from an area of low strain to an area of high strain, provides a

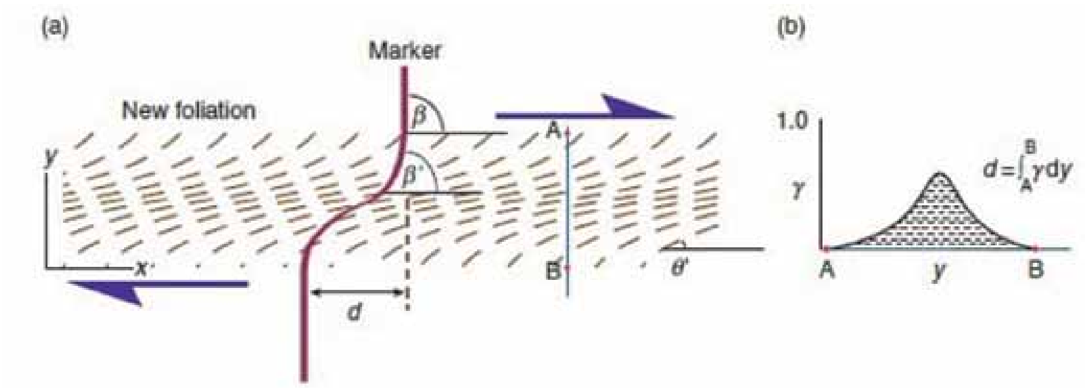


Figure 10. (a) Shear zone with genetically related foliation. The foliation makes 45^0 with the shear zone along the margins. This angle is reduced as strain increases toward the centre of the zone. Y^0 is the angle between the shear zone and the foliation, (b) The displacement can be found by measuring or calculating the area under a shear strain profile across the zone if the deformation is simple shear (source: Fossen, 2010).

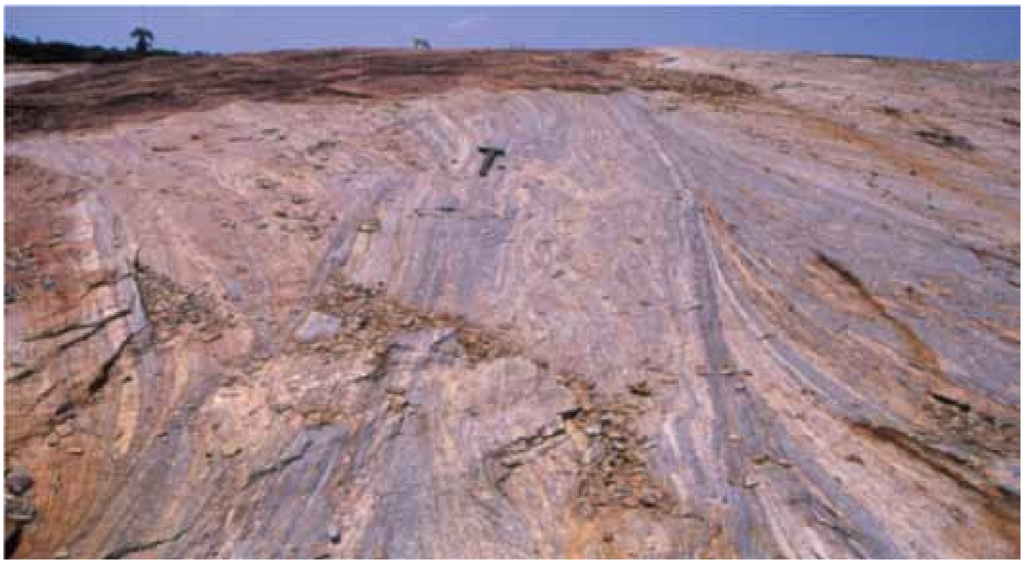


Figure 11. A field example of high grade gneissic rocks in southern Granulite terrane, exhibiting a 1m wide shear zone with deflected gneissic foliation (S-C fabrics).

very reliable criterion for sense of shear determination (Figure 10). Existing country rock foliations rotate into a shear zone and if shearing is homogeneous continue to rotate so that at high shear strains they become parallel to the shear zone edges and through reworking become mylonite foliation (Figure 11). In isotropic country rocks such as granite, a foliation first develops parallel to the flattening plane of the regional strain ellipsoid and then rotates into parallelism with the zone edge as above. However, deformation is seldom homogeneous especially in a zone with a width greater than a meter or so. Small-scale shears marking narrow zones of more intense deformation and strain localization develop at the edges, often described as C-planes and they coalesce to form the braided internal structure of the shear zone and enclose the pods of country rock. The enclosed pods will have a foliation, S, oblique to the mylonite foliation, which should be recognized during mapping as less deformed pods and consequently their internal foliation should cause no difficulties in a regional synthesis.

(ii) C-S and C-C′ Structures

Most mylonites show at least one well-developed foliation that is generally at a low angle to the boundary of the shear zone. Previously, this foliation was called the mylonitic foliation, and it is otherwise known as the S-foliation; S is derived from the French word for foliation, "schistosité." Its angle with the shear zone boundary may be as little as a few degrees, at which point, it is hard to distinguish from a

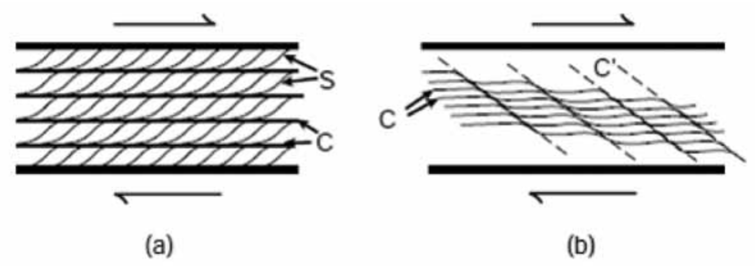


Figure 12. Characteristic geometry of (a) C-S and (b) C-C′ structures in a dextral shear zone.

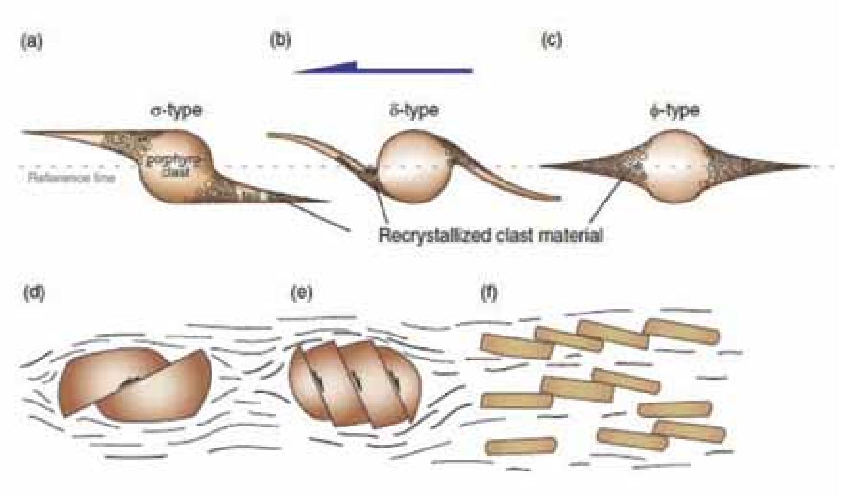


Figure 13. (a) and (b) show monoclinic symmetry (with the rotation axis being perpendicular to the page). (c) The tail is symmetric about the reference line due to coaxial deformation, (d) Fractured porphyroclast with synthetic fracture, (e) Antithetic shear fractures, (f) Tiling (imbrication) of porphyroclasts. All structures (except (c) are consistent with sinistral shear (source: Fossen, 2010).

foliation that parallels the shear zone boundary, called the C-foliation (Figure 12); C comes from "cisaillement," which is French for shear. Often, a third foliation is also developed showing discrete shear displacements that is oblique to the shear zone boundary is called the C′-foliation. The C-surface is parallel to the shear zone boundary and is a surface of shear accumulation (i.e., not parallel to a plane of principal finite strain). The S-foliation is oblique to the shear-zone boundary and may approximate the *XY-plane of the finite strain ellipsoid.* The C′-foliation in (b) displaces an earlier foliation (C or composite C/S).

(iii) Porphyroclasts

Porphyroclasts of feldspar, quartz, mica or other minerals can develop a mantle of recrystallized material that also forms tails, as illustrated in (Figure 13a–c). Coaxial deformations produce tail geometries that are symmetric with respect to the general mylonitic foliation (see Figure 13c). Porphyroclasts with recrystallized tails show sigma-type where the tails do not cross the reference line (Figure 13a) and the tails cross in delta-type (Figure 13b).

(iv) Foliation within mylonites

Two foliations may develop within the mylonites: a localized foliation, axial planar to the intrafolial folds and a more penetrative foliation, that is due to oblique shearing in the zone and has nothing to do with folding. The former is a typical fold related foliation due to local shortening, associated with the intrafolial folds and rotate towards the mylonite foliation as the axial plane of the intrafolial fold rotates into parallelism with the mylonite foliation. The second oblique foliation is commonly encountered in mylonites especially in phyllonites. The foliation is due to localized, internal oblique shearing with the same sense of movement as the main zone, and which leads to extension in the zone in the direction of overall flow. The relationship between this foliation, the mylonite foliation and the movement direction can be referred to as a shear band foliation (White et al., 1986). It further develops along the direction of Riedel shear (R-shear), which is a high shear strain phenomenon, forming well after the mylonite development. The shear bands back rotate with increasing strain and cause the mylonite foliation

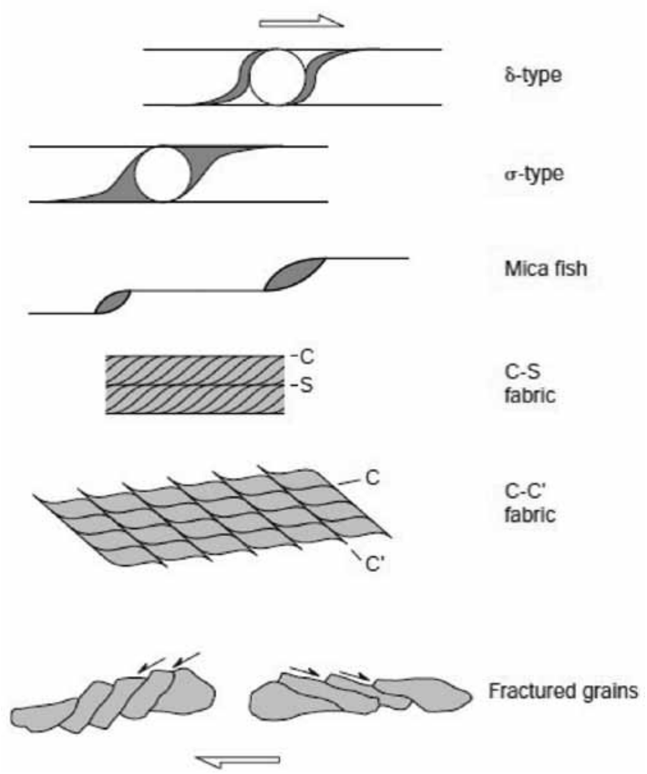


Figure 14. Summary diagram of shear-sense indicators in a dextral shear zone. A copy of this figure on a transparency (for left- and right-lateral shear) makes a handy inclusion in your field notebook (source: Pluijm et al., 2004).

to become oblique to the shear zone edge. The mylonite foliation increasingly steepens as the shear bands back rotate. It is not uncommon for a second set of shear bands to cut a back-rotated earlier set.

(v) Pods or less deformed clasts

In a shear zone with a braided internal morphology, shear strain gradients develop around the pods of enclosed country rock of intended igneous rocks. The result is to develop large shear stresses around these which depending upon the shape will tend to cause dilation at their ends, if they have a low length/width ratio, or pull the pods apart if the length/width ratio is high. The pods tend to break into halves and then quarters and so on later subsequently with increasing shear strain. Often, they develop boudin structures and internal fractures and are perpendicular to the trend of the zone.

With rounded pods extensional fractures or dilatant zones develop at the edges perpendicular to the flow direction with fracturing or dilatancy preferentially occurring at the largest pods. These effects should be remembered when exploring large zones, which contain well preserved pods of country rock or of intruded igneous rocks. A similar behavior is displayed by hard clasts, e.g. feldspars in mylonites at lower temperatures.

Of all kinematic indicators, C-S and δ-clasts are most readily interpretable. For more details of other kinematic indicators such as Grain-tail complexes, Foliation fish and foliation boudinage, Crystallographic orientation, and Fibres and veins and their significance the reader is referred to a book by Passchier, and Trouw (2005). Shear sense in ductile shear zones can be reliably determined when two or more different indicators give a consistent sense of displacement. The summary diagram (Figure 14) shows shear-sense indicators that are commonly encountered in a ductile shear zone.

"Always consider as many sense-of-shear indicators as possible to establish the shearsense."

12. Geometry and Nature of shear zones

Shear zones are commonly arranged in networks or sets composed of a number of individual shear zones. They may occur in subparallel sets, may deflect toward one another and link up in an anastomosing pattern, or may crosscut and displace one another (Figure 15). Some shear zones have a curviplanar or folded geometry. Such geometry may indicate that an originally planar shear zone was folded or warped by subsequent deformation alternatively, many shear zones form with an original curviplanar geometry, encompassing and wrapping around more rigid, less deformed rocks.

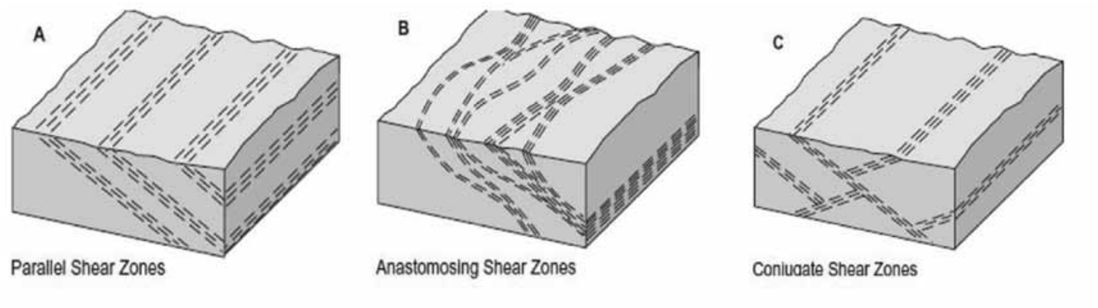


Figure 15. Regional geometry of shear zones.

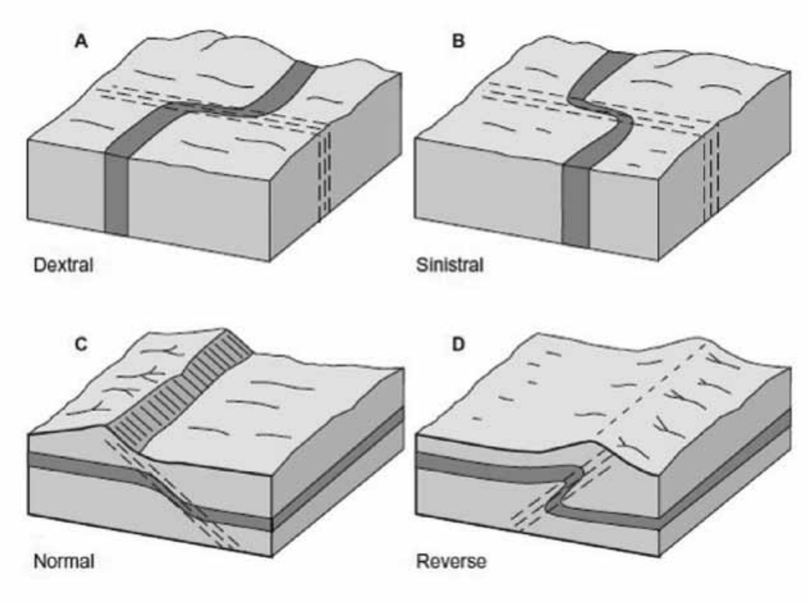


Figure 16. Deflection and offset across shear zones: (A) right-handed or dextral, (B) left-handed or sinistral, (C) normal, (D) reverse. Oblique shear zones have components of both strike-slip and dip-slip (source: Davis et al., 2012).

Determination of relative displacement of rocks on opposite sides of a shear zone reveals the sense of shear within the zone. Similar to fault terminology, shear zones can also be strike-slip, normal, reverse, and oblique-slip (Figure 16). Strike-slip shear zones may be right-handed (dextral) or left-handed (sinistral). Normal-slip shear zones are marked by hanging wall displacement downward relative to the footwall. Reverse- and thrust-slip shear zones are marked by hanging wall displacement upward relative to the foot wall. Oblique shear zones have components of both strike-slip and dip-slip.

13. Reactivation tectonics

In many cases, the brittle-ductile character of a shear zone indicates either that the physical conditions systematically changed during deformation or that the shear zone formed under one set of conditions and was later reactivated under much different conditions. Reactivation tectonics can be easily recognisable when conditions change from ductile to brittle environment. The brittle structures, such as fractures, will overprint an earlier ductile fabric in the shear zone and are easily identifiable. It is more difficult recognizing a shear zone formed during a change from brittle to ductile conditions, because early, brittle structures may be totally overprinted and "healed" by later ductile fabric and metamorphic minerals.

14. Shear zones at Plate Boundaries

Shear zones form in a wide variety of tectonic settings (Figure 17), including plate boundaries of all types. They are undoubtedly forming at depth today in any region with abundant earthquake activity or other manifestations of active deformation (Davis et al., 2012). For example, shear zones are present along seismically active strike-slip zones, such as the San Andreas Fault of California, the Alpine fault of New Zealand, and the numerous strike-slip faults that dissect China and Tibet north of the India-Asia continental collision. Shear zones also mark the sites of past strike-slip zones, such as the South Armorican shear zone of western France and the Great Glen fault of Scotland.

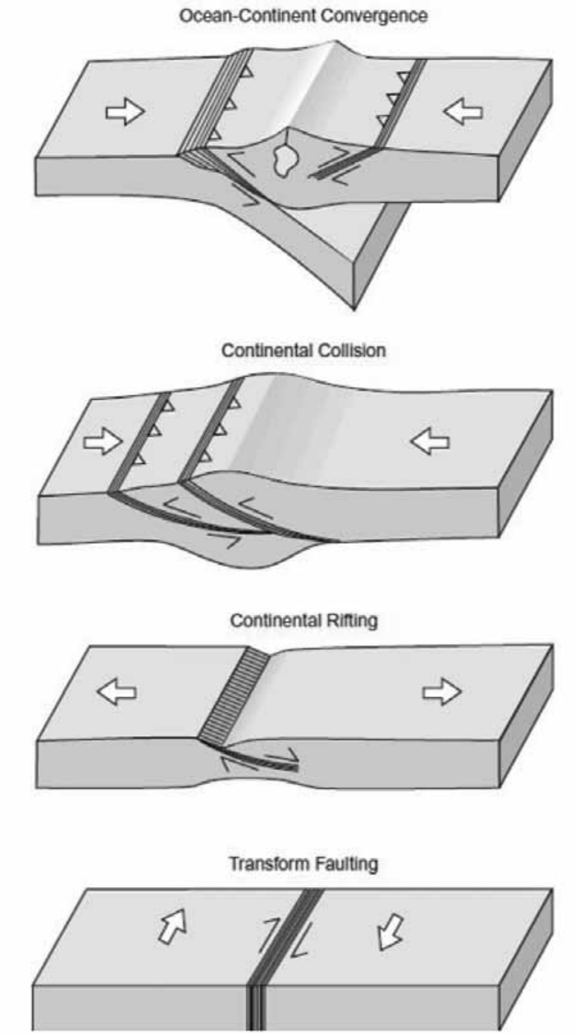


Figure 17. Shear zones occurring in a wide variety of tectonic settings, particularly at plate boundaries of all types.

Shear zones that develop during plate convergence and crustal shortening commonly have thrust displacements that typically bring older, deeper rock up against younger and higher level rock sequence. The best examples are large and spectacular thrust shear zones that occupy nearly the entire length of the Alpine Zagros, Himalayan belt, derived from the collision of Africa and India with the southern flank of Europe and Asia. On the other hand, shear zones that accommodate crustal extension place high-level rock in the hanging wall down against deeper rocks of the footwall. Extensional shear zones are interpreted as forming at depth in regions of active continental rifting, such as the African rift, Greece, and the Basin and Range province of western United States.

15. Controls on fault and shear zone development

Three sets of controls on fault and shear zone development exist: lithospheric-scale, network geometry-scale, and grain-scale. Each scale range tends to be the focus of different research communities, e.g. geodynamicists, structural geologists and microstructural geologists, respectively. However, in order to gain a complete understanding of fault and shear zone processes and their controls, it is necessary to consider the relationships and interactions of processes across all scales.Field-based studies

The fault rock sequence gouge - cataclasite - mylonite forms a depth sequence. Gouge forms at shallow crustal depths where temperatures are so low that clay mineral growth in the matrix and precipitation from fluids is not sufficient to "weld" the fault rock together. This is likely to be favoured by temperatures lower than 100-150°C. At higher temperatures welding occurs and a cataclasite results. The cataclastic / mylonite boundary is taken as the temperature at which the ductile / brittle transition occurs in a granite type mineral assemblage. This was first noted by Sibson (1977). According to him, the transition ranges at around 250-300°C. This implies that the earthquakes which are a manifestation of catastrophic brittle failure, occur at temperatures lower than the transition range. This is confirmed by later seismic studies.

Many shear zones are simple and well-defined structures, yet our knowledge and understanding of how they form and develop, is far from complete. For simplicity, it is often assumed that they form in homogeneous rocks such as granite. In practice, shear zones form at the weakest point or along the weakest layer in the rock, such as micaceous layers, partly molten zones, veins, fractures, fine-grained layers, dikes etc. This will have to be addressed separately for each shear zone.

Shear zones can develop quite differently, depending on rock properties, fluids, deformation mechanisms and metamorphic reactions, but generally go through an early phase of widening. For further advanced studies on shear zones, the reader is recommended for an excellent review (Fossen and Cavalcante, 2017), published recently, that provides the most useful and fundamental aspects of shear zones, their evolution from incipient to large structures, and discuss challenges that need to be studied in the future.

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I am thankful to Dr. O. P. Pandey, Editor, Journal of Indian Geophysical Union for his invitation to contribute this article. I must also submit here that this article is not exhaustive, but provides only important elements related to shear zones. I am hopeful that this would be of some help for many students, teachers, researchers and other professionals in their scientific pursuits and applications.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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