From Palmström A.: RMi – a rock mass characterization system for rock engineering purposes. PhD thesis, Oslo University, Norway, 1995, 400 p.

APPENDIX 2

ON FAULTS AND WEAKNESS ZONES

> *"It remains just as necessary today as it ever has been for the engineer to simplify to understand and to visualise the problem. It is only the retention of this ability that enables the engineer to react appropriately when, as ever, he encounters in nature some features unexpected in his original concept."*
> A. M. Muir Wood, 1979

According to ISRM (1978) a fault is *"A discontinuity zone along which there has been recognisable displacement, from a few centimetres to a few kilometres in scale. The walls are often striated and polished (slickensided) resulting from the shear displacement. Frequently rock on both sides of a fault is shattered and altered or weathered, resulting in fillings such as breccia and gouge. Faults may vary from millimetres to hundreds of metres."*

To be characterized as 'fault' it is thus required that there is a proof of movement. Similarly, a gouge is (ISRM, 1978; Dictionary of geological terms, 1962): *"A clay-like material occurring between the walls of a fault as a result of the movements along the fault surfaces."*

Knowledge of the origin or formation of the zone can be helpful in working out the description and evaluation of its composition and structure. But used in rock engineering and construction the features of main interest are connected to the actual properties and behaviour of the zone. Therefore, the more general term 'weakness zone', including also other weaknesses, is used in this work. This term has also been recommended by the Norwegian Rock Mechanics Group (1985) for large structural lineaments in the earth's crust, defined as: *"A weakness zone constitutes a part of the ground in which the mechanical properties are significantly lower than those of the surrounding rock mass."*

Similarly, together with gouge which is related to faults, the more general term *filling* is often used for the finer, often clay-like material occurring between the walls of a seam (filled joint) or a weakness zone.

Although weakness zones basically can be said to be composed of mainly rock(s) in addition to joints and seams with or without filling, a great variety exist. Many of them are formed as a result of tectonic events, while other are related to layers of weak rocks surrounded by stronger rock masses. Common for them all is that they form zones, lenses, veins or layers in almost all types of rocks. Basically, there are two main groups of weakness zones: those which are formed from tectonic events, and those consisting of weak materials formed by other processes. Weathering, hydrothermal activity and alteration are features that may have had a significant impact on the composition and properties of a zone.

Selmer-Olsen (1964, 1971) who has studied many of the weakness zones encountered in more than 2000 km of Norwegian tunnels in crystalline Precambrian and Palaeozoic rocks, has worked out the following division for use in engineering geology:

- Zones of weak materials.
- Fault and fracture zones:
  - tension fracture zones;
  - shear fault and fracture zones (crushed zones);
  - altered faults and fracture zones.
- Weathered and recrystallized zones.

The remaining part of this section is mainly short descriptions of zones based on the division above.

1 ZONES OF WEAK MATERIALS

These types of weakness zones consist mainly of:

- Layers, veins or dykes of soft or weak minerals.
- Zones of weak rocks or of rocks which are heavily jointed.
- Deposits and weathered rocks.

Many of these types of weak materials are only regarded as weakness zones if they are surrounded by other, stronger rock masses. Some of the types here can also sometimes be regarded as crushed zones (see Section 2.5.1 - 2.5.4), but may belong to such weak materials because the brecciation is related solely to the rock in the zone which has a limited extension as a band, layer, lens, vein or zone in the surrounding rock masses.

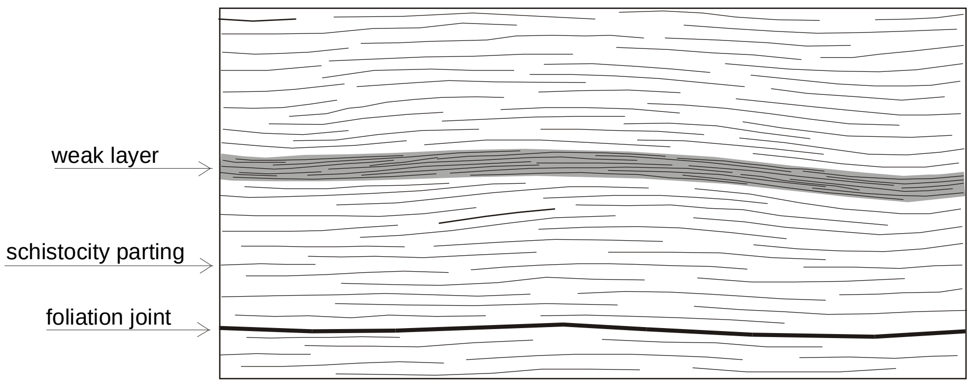


Fig. A2-1 Zone of weak rock, for example chlorite or talc schist in a phyllite.

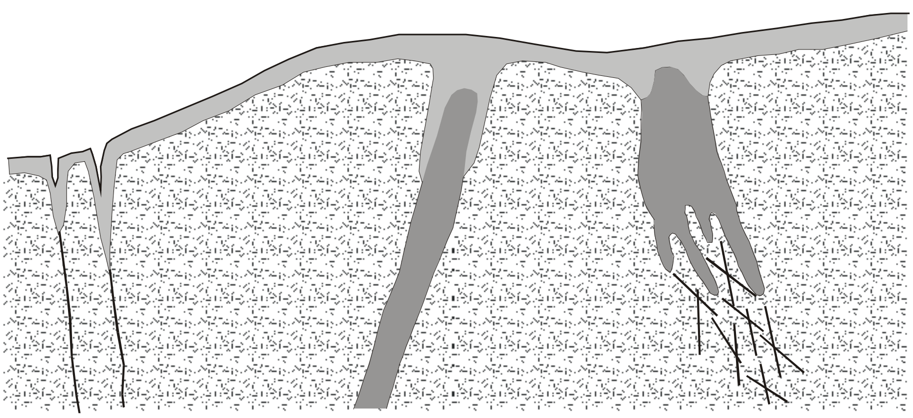


Fig. A2-2 The action of weathering along joints, rock boundaries and crushed zones in and near the surface (from Morfeldt, 1976).

The (weak) material in these zones may consist of clay, pegmatite, mica or chlorite, poorly cemented sedimentary layers (for example tuff layers in basalts), or coal layers (seams). The zone has often a sharp boundary to the adjacent stronger rocks, as shown in Fig. A2-1.

Also weathered surface and near surface occurrences belong to this group. The weathering process has often acted along rock layers, dykes or rock contacts, or along joints, seams, and crushed zones to form zones, layers or pockets of weathering products with low mechanical properties as shown in Fig. A2-2.

2 FAULTS AND FRACTURE ZONES

Large faults are the major rupture zones encountered in the earth's crust. It is important to realize that most of the larger faults and fault zones are the result of numerous ruptures throughout geological time and that their composition and magnitude may vary largely.

Faults and fracture zones are a result from the effects of regional tectonic compression or tensile stresses accompanying uplift or lateral stretching (ISRM, 1978). They can have been formed through failure in extension/tension, in shear, or in more complex failure through a combination of both, see Fig. A2-3. Rupture surfaces from *extension* are characteristically rough and clean with little detritus, while simple surfaces from *shearing* are characteristically smooth with considerable detritus. Because these two main modes, shear and tension, generally result in different structure and composition it is convenient to distinguish between them as has been done in Section 2.4 and 2.5.

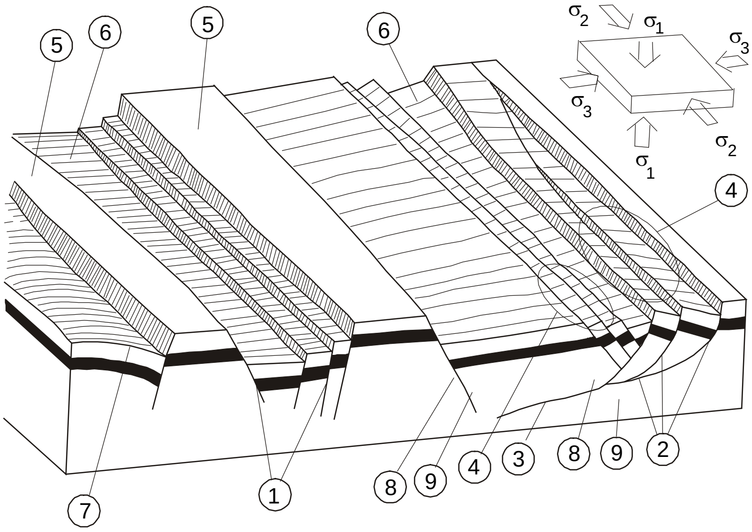
The tunnelling problems associated with a fracture or fault will generally increase with its width. However, this factor should always be assessed in relation to the attitude of the fault and to:
- the frequency, orientation, and character of adjacent joint sets;
- the existence of adjacent seams or faults (if any); and
- the competence of the wall rock type.

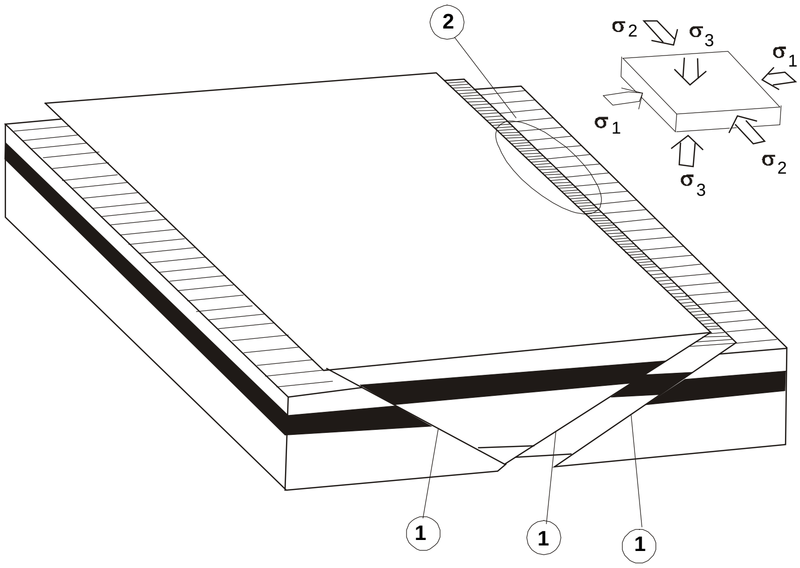
Several severe slides in tunnels have occurred where each individual seam or fault has been of a small width, but where the interplay between several seams and joints has lead to the instability and failure (Brekke and Howard, 1972).
The main type of weakness zones formed from faulting are:

1 *Tension fracture zones*
   - filled zones

2 *Shear fracture and fault zones*
   - coarse-fragmented crushed zone
   - small-fragmented crushed zones
   - sand-rich crushed zones
   - clay-rich crushed zones, such as:
      > simple, clay-rich zones
      > complex, clay-rich zones
      > unilateral, clay-rich zones
   - foliation shears

3 *Altered faults and fractures*
   - altered clay-rich zones
   - altered veins/dykes
   - altered, leached (crushed) zones.





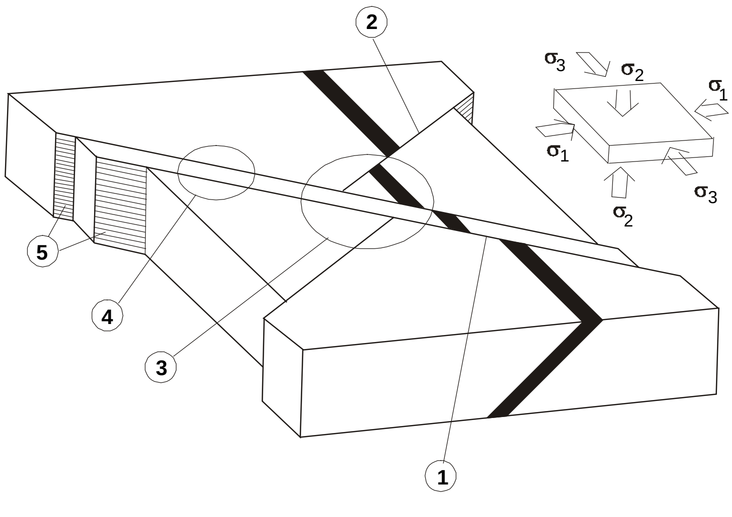


Fig. A2-3 Various types of faults and features related to extension regimes (upper), and compression regimes (middle and lower) (from Nystuen, 1989)

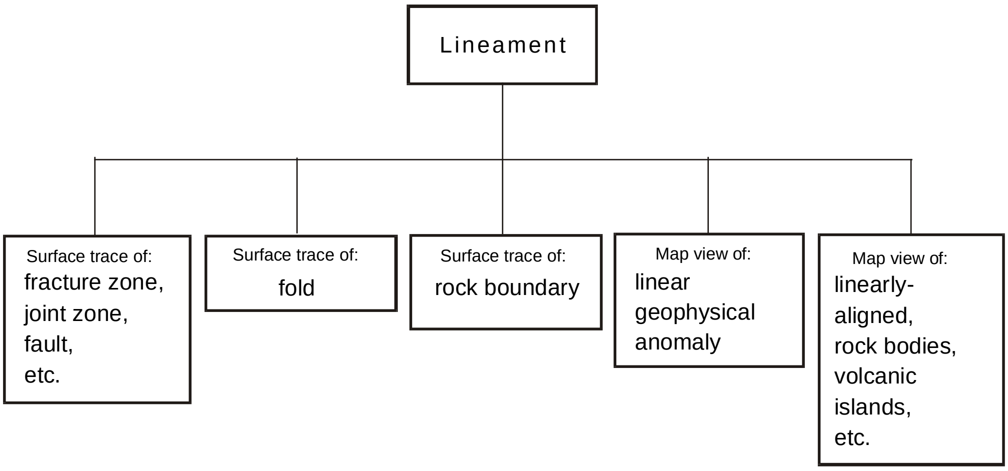


Fig. A2-4 Faults and weakness zones are one group of lineaments, i.e. topographical features reflecting surface traces of various crustal structures (from Nystuen, 1989).

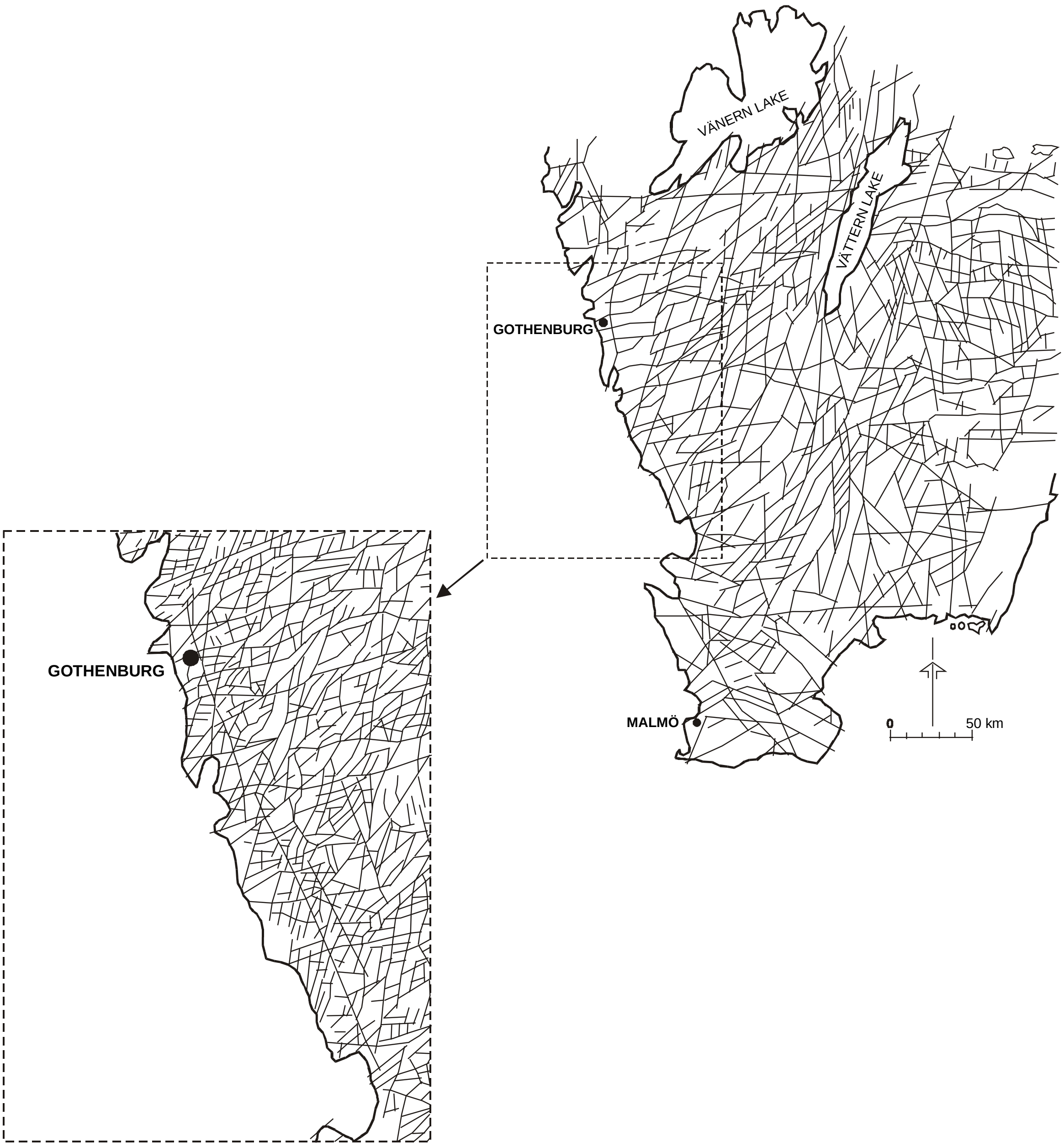


Fig. A2-5 Three dimensions of regional lineament (upper) and fault pattern in southern Sweden (compiled from Tirén and Beckholmen, 1992).

2.1 Occurrence of faults and fractures

The outcropping of large faults and fault zones often form depressions in the topography forming part of the lineaments in the earth's surface, see Fig. A2-4. From surface observations it is, however, seldom possible to observe their composition and size because of overburden and weathering.

Faults constitute characteristic regional patterns in the earth's crust (Fig. A2 -5) consisting of several mutual independent sets or systems (Selmer-Olsen, 1964). The main directions, which mainly were determined by the state of stress, have often the same orientations as the joint sets within the same structural area.

Although the filling material or gouge in a fault may be only some centimetres wide, the overall affected zone with open or altered joints may be some metres wide and the extent of the length of the fault zone may be from hundred metres to more than a kilometre. Fault zones can be found hundreds of meters below surface (Brekke and Selmer-Olsen, 1965). Sometimes clay fillings with a very low degree of consolidation have been encountered.

Nieto (1983) and Gillespie et al. (1992) have observed that the length generally is proportional to the *thickness* of the fault, Fig. A2-6. Thus thick crushed- and gouge-filled faults can be traced for very long distances (kilometres) whereas thin, gouge-filled faults and shears usually extend for only some tens of metres. These trends are most prevalent in igneous and metamorphic terrains. Cowie and Scholz (1992) have shown that the length of a zone can be proportional also to the displacements caused by the ruptures, Fig. A2-6.

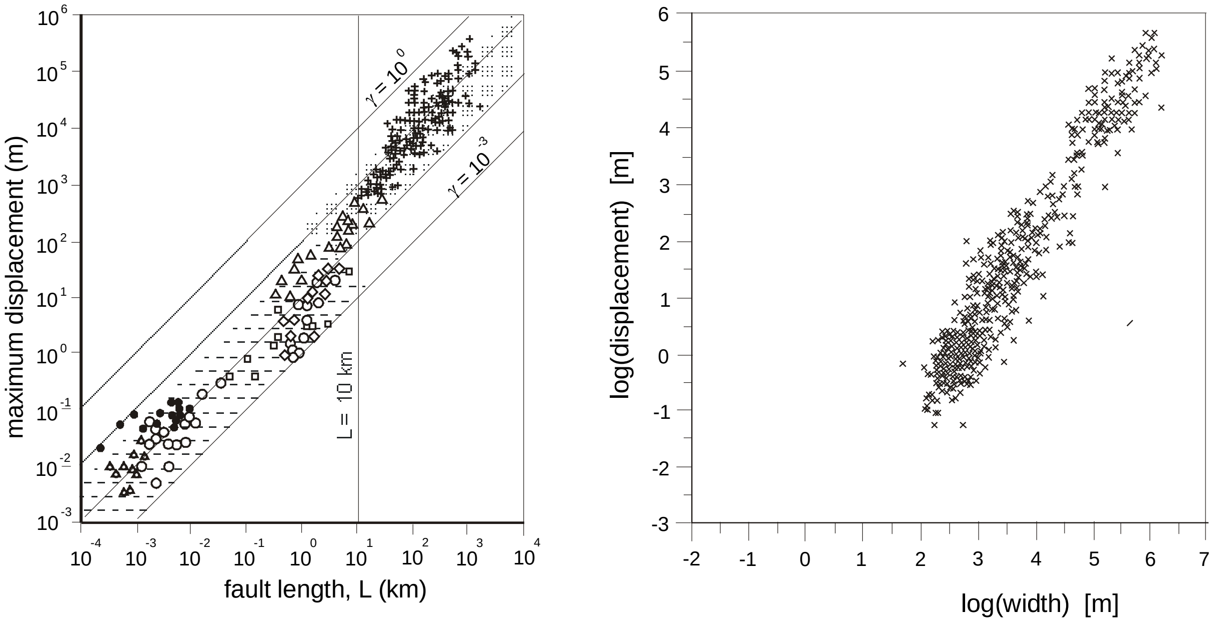


Fig. A2-6 The correlation between displacement and fault length (left: from Cowie and Scholz, 1992) and between displacement and fault width (righ: from Gillespie et al., 1992).

Generally, faults will mostly be developed in the rocks which from a mechanical point of view are the weakest in the area. Where two faults of different orientations meet or cross each other a larger part of the rock masses suffer from increased crushing or jointing, see Fig. A2-7.

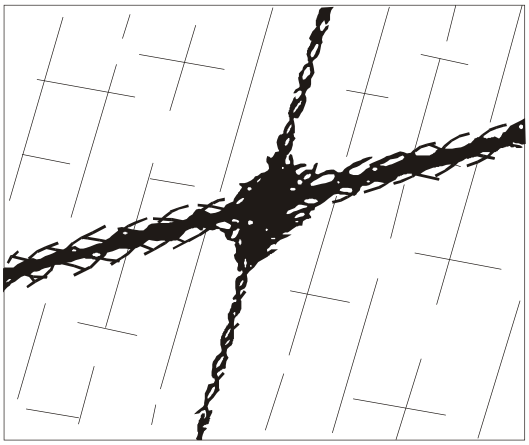


Fig. A2-7 The crossing of two faults (from Selmer-Olsen, 1964)

Nieto (1983) has observed that the strike and dip of fault zones in igneous and high-grade metamorphic terrains can vary sometimes drastically, over relatively short distances. Faults in anisotropic rocks at an acute angle to the schistocity partly follows along the structure of the rock, and partly across it. By this a zigzag course is developed. Selmer-Olsen (1950) reports that the width of such faults are thinner where they follow the rock structure, refer to Fig. A2-8 (A and B). The thickness of a fault is also often reduced when it passes from brittle (granite) into less brittle (dolerite), as seen in Fig. A2-8 (C).

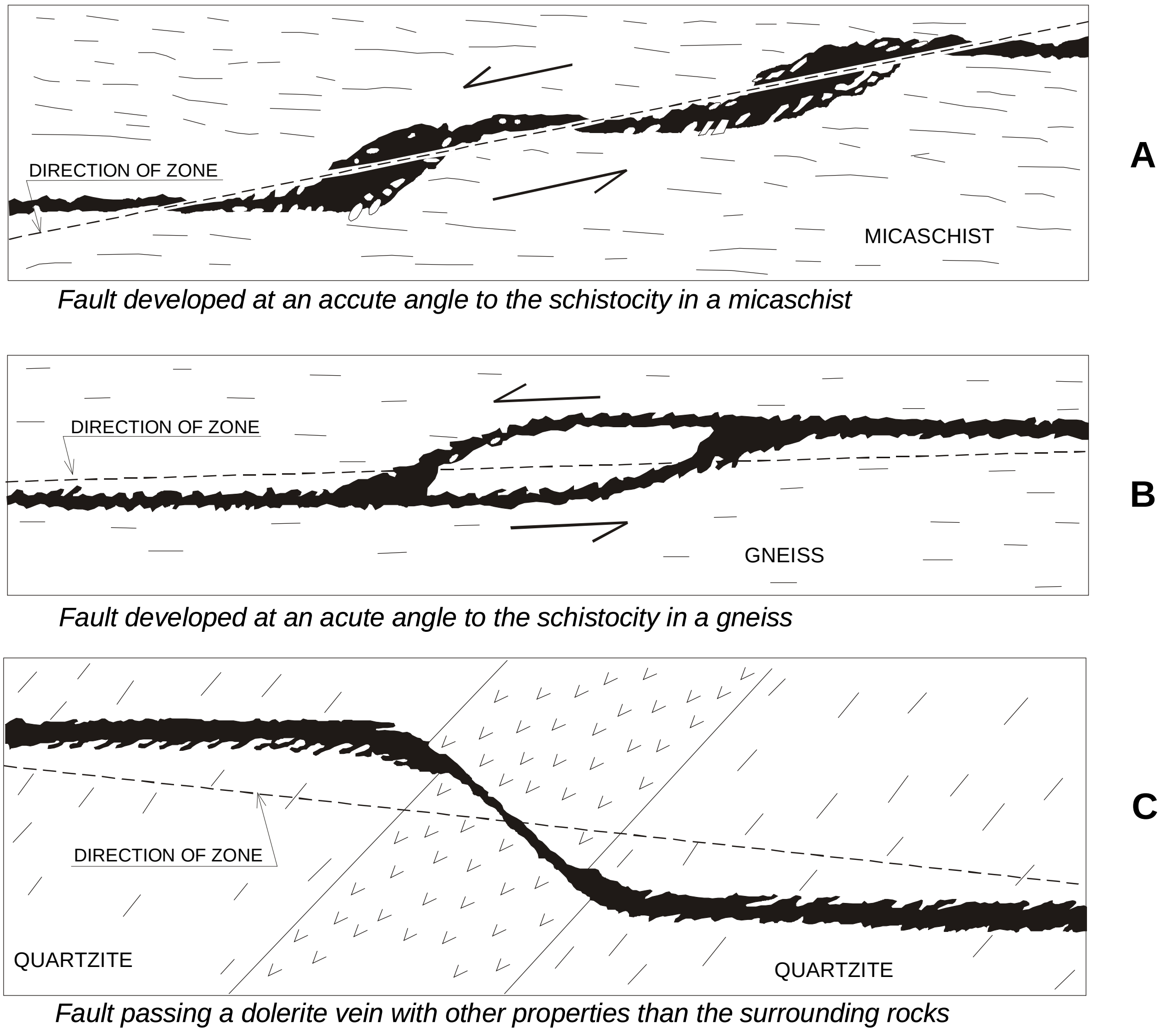


Fig. A2-8 Principles in variation in course, thickness and structure of a fault dependent on the rock (revised from Selmer-Olsen, 1964).

2.2 Composition and structure of faults

Faults and fracture zones can vary in composition from mostly brecciated or crushed material with relatively small amounts of clay to highly weathered or hydrothermally altered, highly plastic, swelling clay gouge. The composition of these pieces can be similar to the adjacent rock, or hydrothermal solutions can have altered the original rock material and/or brought in and deposited new minerals that are not associated with the petrography of the adjacent rock or the wall rock. This is most important since it implies that the mineralization in faults and seams is not necessarily a function of the composition of the 'host' rock (Brekke and Howard, 1972). Therefore, any mineralization may be found in a fault where hydrothermal activity and/or alteration has taken place.

Faults in *brittle rocks* such as granites, quartzites and some sandstones are likely to be developed as relatively wide "crushed zones" from crushing or brecciation into blocky material, consisting of relatively large angular fragments of broken rock surrounded by finer gouge material. Since this type of faulting constitute underground drains (Terzaghi, 1946), they may be invaded by surface waters or by hot solutions coming from below, or by both. Chemical alteration in such zones is likely to be more intense and more varied than in zones containing mainly (impervious) gouge produced by the crushing.

Faults are seldom developed as large crushed zones in *'ductile' rocks* such as shales, many schists, and some of the basic igneous rocks. In these rocks faulting mainly occurs as plastic deformation like flexure and intense folding, resulting in more narrow zones richer in fine-grained material. A large number of shear surfaces and slickensides may be present in the zone.

As mentioned in Section 2.2 in Appendix 1, faults are quite often associated with other parallel discontinuities that decrease in frequency and size in the direction away from the central zone of the fault (Terzaghi, 1946). Thus, as a tunnel approaches a zone of intense crushing, it passes through rock masses which are more and more heavily jointed.

Apart from the sand-like materials, fault gouge itself is normally impervious. Possible high permeability connected to faults can be due to the high jointing density often found adjacent to the fault as in unilateral crushed zones (see Section 2.5.4). High water inflows in tunnels and underground openings encountered after excavating through the impervious gouge is one of the most adverse conditions associated with faults as reported by Brekke and Howard (1972).

Another significant problem in tunnelling through faults may be caused by materials that have been *crushed* to an almost cohesionless (sand-like) material which may run or flow into the tunnel immediately after blasting (see Section 2.5.3 and Chapter 6, Section 4.3).

2.3 Gouge (filling materials) in faults

Brekke and Howard (1972) reports that the character of the gouge material in faults is very seldom uniform. The gouge will sometimes have the character of unaltered crushed rock. *"Blocks, or even plates, of intact rock may 'float' in a basic matrix of soft material. In addition bands or seams of hard material such as quartz or calcite may occur."* Thus, fault gouge constitutes normally a very complex material both in regard to mineralization and in regard to physical properties.

Subsequent possible hydrothermal alteration of the 'original' rock and the gouge material and/or the deposition of hydrothermal products will complicate the mineralogical identification since products not associated with the petrography of the crushed rock or wall rock may be present.

Brekke and Howard (1972) have given an overview of the major types of materials that can be found in weakness zones and faults. This is shown in Table A2-1 together with the potential behaviour of the material in excavations. The basic division is made according to the mineral or material that dominates the properties of the filling. This is not necessarily the most abundant material.

Table A2-1 GROUPING OF FILLING AND GOUGE MATERIALS AND THEIR POTENTIAL BEHAVIOUR (modified after Brekke Howard, 1972).

Dominant material in filling (or gouge)	**Characteristic behaviour**
1. SWELLING CLAY	Swelling, sloughing and squeeze
2. INACTIVE CLAY	Slaking and sloughing caused by squeeze
3. CHLORITE, TALC, GRAPHITE, SERPENTINE	Ravelling
4. POROUS OR FLAKY CALCITE, GYPSUM	May dissolve
5. QUARTZ, EPIDOTE	Durable, high strength
6. CRUSHED ROCK FRAGMENTS (gravel size) OR SAND-LIKE FILLING	Ravelling or running.
7. FILLING OF OTHER ROCKS	

The often complex composition and structure of the gouge in a given fault may well overlap several of these classes. Fault gouge and filling materials are normally impervious, with the major exception for sand and gravel-like compositions (Brekke and Howard, 1972).

The third group listed in Table A2-1 is intended to cover blocky gouge material that is heavily interwoven with slickensided seams and joints filled or coated with the minerals listed (Brekke and Howard, 1972). The characteristic property of such gouge is low shear strength, in particular when wet.

In zones with swelling clays (smectite) the initial and later change of water content can be important for the mobilized swelling pressures. In addition, swelling clays have both a low shearing strength. Several authors (Piteau, 1970; Brekke and Selmer-Olsen, 1965; Selmer-Olsen and Palmström, 1989,1990) describe stability problems with rock falls, slides, and in some cases, collapses caused by the swelling of clays in joint fillings and faults.

2.4 Tension fracture zones

These zones are often developed with a filling of soft minerals between parallel walls having a low degree of jointing. The filling material can be chlorite, (swelling) clay, porous calcite, silt etc., and the zone can be named according to the dominant filling; for example clay-filled zone, or calcite-filled zone. Feather or pinnate zones ("fiederspalten") belong to this group. There is generally a sharp boundary to the adjacent rocks in tension fault zones. These types of zones may sometimes also be classified as zones of weak materials described in Section 1; this depends whether the characterization is based on the formation of the zone or from its material.

2.5 Shear fault and fracture zones

Shear faults and shear fault zones are formed as a result from shear strain which causes the rock mass to be crushed and brecciated by many intersecting joints and/or seams, as in Fig. A2-9. Their central part may sometimes be weathered or completely altered to clay. Faults formed in shear are in general much more susceptible to alteration than are those formed in extension. Normally, such alteration leads to a lowering of the strength and to other disadvantageous conditions for construction.[1]

Shear zones can vary in width from a few centimetres to several metres, and may be termed *crushed zone* in the case of hard rock. In the case of metamorphic rocks shear zones may occur parallel with the foliation, typically along weak mica-rich rocks. In such cases they are often termed *foliation shear zones*.

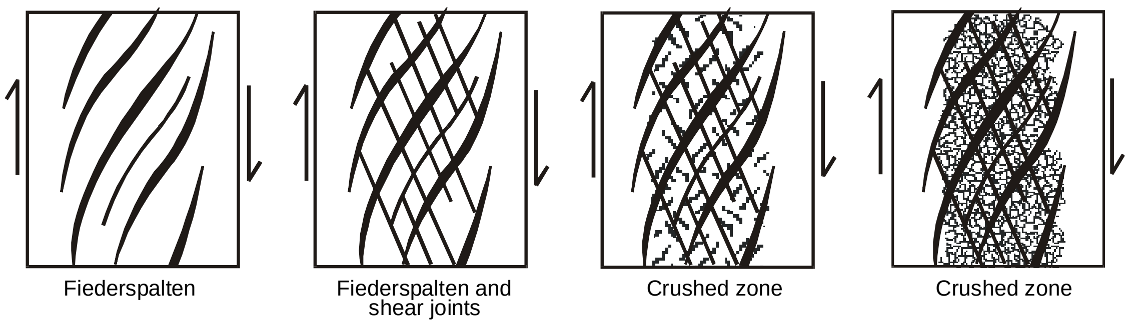


Fig. A2-9 Principles in the development of crushed zones (from Selmer-Olsen, 1964).

The main parts of a typical shear zone may consist of:

- The central part. This is where the main movements mainly have taken place, which have resulted in intense jointing or crushing of the rock, with possible hydrothermal activity and deposition of minerals and/or alteration.
- The transition part, i.e. the area disturbed by the movements with a higher degree of jointing than in the adjacent rocks where also alteration can have taken place.
- The surrounding rock masses which have been little influenced by the movements, but sometimes penetrated by seams and minor faults that branch out from the zone.

The main elements (both in the central and the transition part) of the zone are:

- Blocks and/or fragments.
- Filling (or gouge) of clay-like or sandy material. Thicker fillings are generally restricted to the central part. Also the transition part often contain joints and seams but in a lesser amount than in the central part.
- Coating or slickensides on joint surfaces.
- Alteration of blocks/particles both in the central and the transition part.

[1] In the case of bedding plane slip caused by folding or basin formation, shear zones may develop in, for example, interbedded layers of over-consolidated clay, with the formation of lenses and slickensided shear surfaces. In both cases the relative shear displacement of the discontinuity walls is insufficient for the zone to be characterized as a fault.

There is seldom a uniform composition of the central part; sometimes there are two or more central parts with transition areas between them as is the case in complex zones described in later in this section, see Table A2-2. Brekke and Howard (1972) mention that the blocky gouge material may be heavily interwoven with slickensided seams and joints filled or coated with clay, mica, chlorite etc.

Crushed zones are most commonly found in hard rock provinces. They are often pervasive and relatively planar seen along a distance of some hundred metres. Crushed zones have most often a gradually reduced degree of jointing from their central part to the surrounding rock masses. There are numerous types of crushed zones of which the main are listed below. Consequently, there are many intermediate occurrences between these.

Caine and Foster (1993) have developed the scheme shown in Fig. A2-10 for permeability structures in fault zones. The four end members in this classification scheme are based on the content of subsidiary structures (i.e. joints, veins, seams) and gouge (i.e. filling materi-als) are the variables used for the main groups.

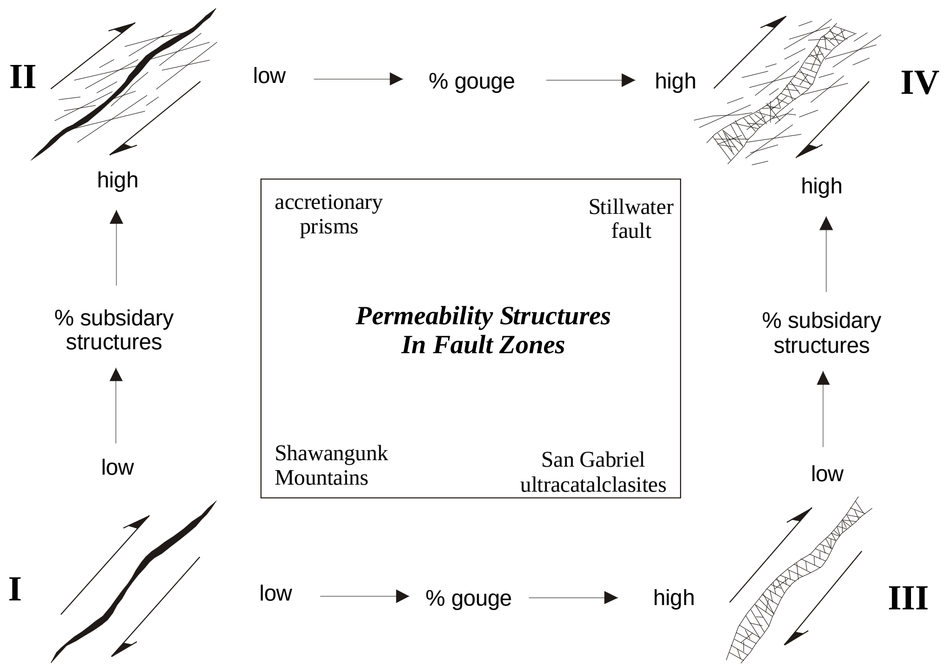


Fig. A2-10 The main groups of fault zones with respect to permeability based on the content of joints, and gouge (from Caine and Foster (1993).

End member I includes faults free of both gouge and subsidiary structures, which means single discontinuities which in the field often are termed large joints. End member II and III are cases where either gouge or subsidiary structures are absent, while group IV con-sists of a well developed central gouge zone in addition to replete subsidiary structures. Most of the various types of shear faults described in the following can be correlated to group II, III or IV.

2.5.1 Coarse-fragmented crushed zones

These zones, shown in Fig. A2-11 (left), have blocks over the entire width, often with larger blocks towards the adjacent rock masses, and belong generally to end member II in Fig. A2-10. The blocks are often slickensided with or without clay coatings, and the individual blocks have often rhombohedral shape.

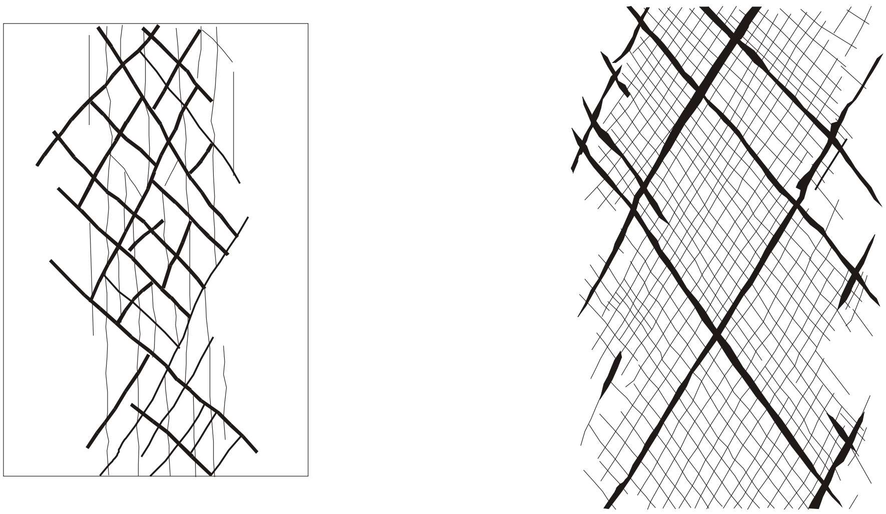


Fig. A2-11 Left: Coarse-fragmented crushed zone.
Right: Small-fragmented crushed zone (from Rokoengen, 1973).

2.5.2 Small-fragmented crushed zones

Such zones have a central zone with fragments of gravel size. There are generally few seams or clay filled joints but lots of small slickensided fissures, Fig. A2-11 right. A gradual transition to larger blocks in the surrounding rock masses is common. This type of crushed zone can be classified as end member II in Fig. A2-10.

2.5.3 Sand-rich crushed zones

If brittle rocks are subjected to intense deformation, they may fracture to such an extent that *"the fragments may even be reduced to powder as if it had passed a crushing machine"* (Terzaghi, 1946). In such cases the rock is completely crushed or decomposed to contain rock fragments of gravel or sand size, i.e. materials with a typical cohesionless behaviour.

Sand-rich crushed zones may cause major excavation problems having very short stand-up time where typical earth tunnelling conditions may be encountered. As further described in Chapter 6, Sections 2 and 4.3 running or flowing ground may occur in connection with such zones (Brekke and Howard, 1972). Ward (1978) mentions examples from the Alps and Himalayas where wide thrust zones contain a dense pulverized mass, or a highly slickensided mylonite with typical earth tunnelling conditions.

2.5.4 Clay-rich crushed zones

Clay-rich zones show wide variations in composition and structure. They have often a central clay-rich zone in addition to more scattered clay-filled joints in the less crushed transition zone to the adjacent rock masses, and they can therefore be classified as end member IV in Fig. A2-10. The main types are:

i *Simple, clay-rich, crushed zones* with blocky composition. The joints have generally a spacing of 0.05 - 0.5 m and cut through the foliation of the rock. Sometime they occur as long, smooth and planar joints or seams extending several tens of metres out from the zone, see Fig. A2-12 left.

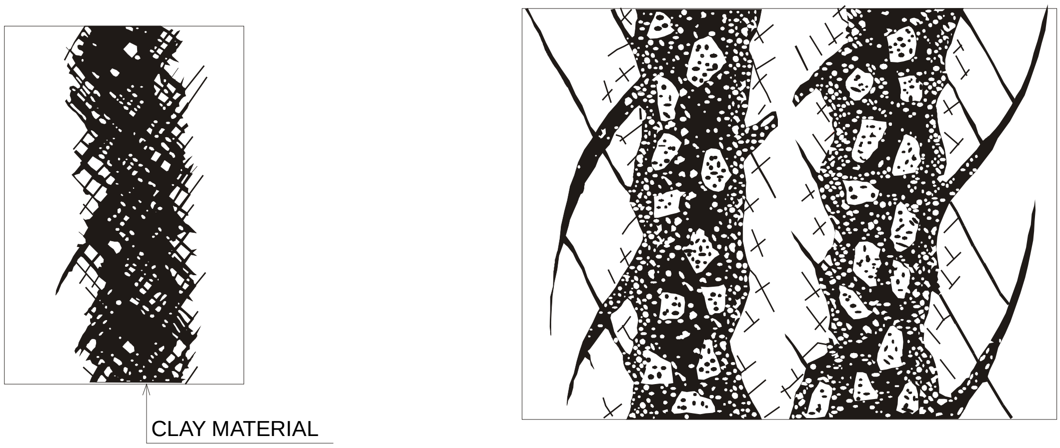


Fig. A2-12 Left: Simple clay-rich, crushed zone.
Right: Complex clay-rich, crushed zone. (from Selmer-Olsen, 1971).

ii *Complex clay-rich crushed zones*, which in the central part show several clay-rich zones or seams, often with crushed rocks between them (Fig. A2-12 right). Two or more close crushed zones should be regarded as one complex crushed zone in tunnel stability evaluations, provided that the distance between their central crushed part is less than about 1.5 times the span of the tunnel/cavern.
Also small-fragmented and coarse-fragmented crushed zones can occur as complex zones.

iii *Unilateral clay-rich crushed zones* are zones where the seams, shears or filled joints are concentrated in one side of the zone with a sharp boundary to the surrounding rock masses.. Such zones may contain highly permeable brecciated rocks adjacent to highly impermeable clay gouge with strongly anisotropic water conducting flow parallel to the plane of the fault. Tunnelling from the impermeable side in a large zone of this type may, as mentioned, cause considerable excavation problems as low stability and water inflow may occur at the same time.

2.5.5 Foliation shear zones

Foliation shear zones or "foliation shears" occur in metamorphic rocks as thin sheared zones along the foliation of metamorphic rocks, often in mica-rich schists (Patton and Deere, 1970; Deere 1971). Such mica-rich rocks are reported in thick schist sequences but, more importantly, also as thin interbeds in massive metamorphic gneisses and quartzites. *"The shears trend parallel, or in some instances subparallel, to the foliation. Locally the shears may cut across the foliation where they flatten or roll. Typically, the shears will thicken and thin somewhat".* They belong to end member III or between II and III in Fig. A2-10.

In addition to the clayey filling which may be only some centimetres wide, the overall affected zone with partially crushed, sheared and slickensided rock may be some metres wide, Fig. A2-13. The extent of the zone along its trend may be from hundred metres to more than a kilometre (Deere, 1971). Differential slippage along weak micaceous interbeds during folding or stress relief probably accounts for the origin of most of them.

The joints in the hard rock adjacent mica-rich schist containing the shear zone, may be somewhat disturbed with some loosening, slickensiding, and chemical alteration (thin clay or chlorite coating on the joint surface). Thinner foliation shears may occur parallel or sub-parallel to the main one at distance of some meters.

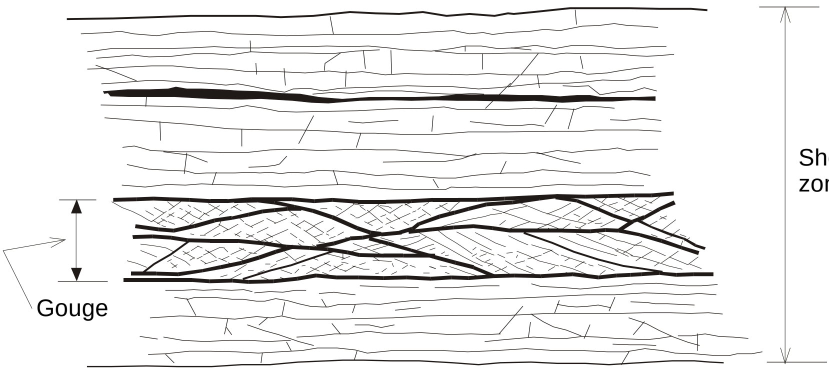


Fig. A2-13 Typical foliation shear zone (from Cording and Mahar, 1974).

2.6 Altered faults

Alteration of faults may take place in most types of the weakness zones described above. The alteration processes may occur during the formation of the zone and/or later.

2.6.1 Altered clay-rich zones

These zones are characterized by alteration to clay of feldspar in the zone and in the adjacent rocks. The (hydrothermal) alteration is mainly related to crushed zones, sometimes also to seams and clay-filled joints and zones. Compared to many other crushed zones this type of altered weakness zones is often highly consolidated and almost impervious. The clay has often high swelling properties (Brekke and Howard, 1972).

Fig. A2-14 Altered, clay-rich zone (from Selmer-Olsen, 1971)

2.6.2 Altered, leached (crushed) zones

These are normally smaller coarse-fragmented or small-fragmented crushed zones where the rocks in the transition zone have been dissolved to form permeable materials. The minerals removed are generally quartz and feldspar or carbonate.

As mentioned earlier, a real hazard exists where large quantities of water in a permeable rock mass are released when an impervious fault gouge is punctured through excavation. In this instance, large quantities of gouge and rock can then be released.

3 RECRYSTALLIZED AND CEMENTED/WELDED ZONES

Recrystallization may cause significant changes to the composition, properties and behaviour of a weakness zone. These types, which probably earlier have been coarse-fragmented or complex, crushed zones, are still geologically named faults or thrust zones. Still they often have some slickensided and clay filled joints, with secondary formed minerals of epidote, quartz, feldspar, calcite siderite and/or chlorite which have "welded" the blocks and 'reinforced' the zone.

4 DESCRIPTION OF WEAKNESS ZONES

Larger faults and weakness zones should be described and mapped as structural regions of their own in connection with rock construction (Bieniawski, 1984). Core drilling from the surface or probing ahead from an advancing heading are the most effective means of collecting information of a zone before it is penetrated. It can, however, be difficult to obtain enough data to fully describe its structure, especially in case of core loss.

After the zone has been encountered in the excavation its composition and structure can be studied. However, only a small part of it is 'opened'. It is therefore difficult to observe and measure other features of a weakness zone than its orientation, and local thickness, composition and structure. An adequate description of these features is very important for the decision of excavation procedure(s) and for the various analyses included in the design for appropriate rock support. Where time is available the description can be backed up by laboratory tests to measure the properties of important features.
A description of a weakness zone would consequently consist of:

- Size, measured as total thickness, formed by
  - the thickness of the central part, and
  - the thickness of the transition part.
- Composition and structure (arrangement) of the zone, in
  - the central part, made up of either
    - mainly blocks, or
    - blocks and fillings (gouge), or
    - mainly fillings (gouge);
  - the transition part to the adjacent rocks, being either
    - sharp or gradual.
- Possible alteration different from that of the surrounding rocks) in
  - the central part, and
  - the transition part.

In the case of important weakness zones it is helpful to make idealized sketches showing the estimates of the principal dimensions (ISRM, 1978). A verbal description of these features should always be given so that extent and character of the discontinuity is communicated (ISRM, 1975).

Hints on description of weakness zones are also given in Appendix 3, Section 5.

Many weakness zones do not have a well defined thickness, but show a gradual transition from the central part to the surrounding rock masses. The description of a zone should pay attention to this. Also, the conditions of the surrounding rock masses may be of importance for the rock mass behaviour in connection with the weakness zone. Of special importance is the occurrence of nearby weakness zones, as well as seams, shears or small faults connected to the main zone.

The following is an example of a description of a 10 m wide weakness zone encountered in the 25 m^2 headrace tunnel at the Haukrei power plant in Norway:

> *The zone has an orientation strike/dip = N 45^{o}E/90^o related to the tunnel. It consists of a partly chloritized diabase. It is formed by several parts having different composition as described in Table A2-2.*
> *The surrounding rocks consist of Precambrian gneiss and granitic gneiss with strike/dip = N 20-30^{o}E/70-80^o with 1 - 5 m long rough and undulating foliation joints spaced 0.5 - 2 m. Some random joints occur.*

TABLE A2-2 COMPOSITION OF THE WEAKNESS ZONE AT HAUKREI POWER PLANT

FEATURE	adjacent rock	**thickness of individual parts of the central part (m)**							**adjacent rock**
		0.5 - 1	**1 - 2**	**2**	**1 - 2**	**1 -2**	**0.4 - 0.5**	**0.5 -1**	
Joint spacing (m), set 1	0.5 - 2	0.01-0.05	0.1-0.5	0.05-0.2	0.02-0.1	0.01-0.05	a zone	0.2-0.3	0.5-2
set 2					0.3-1		mainly of		
Joint length (m), set 1	1-5	0.1-0.5	0.5-3	0.3-3	0.3-2	0.1-1	chloritic	0.5-2	1-5
set 2					0.01-0.1		clay		
Joint smoothness	rough	smooth	smooth	smooth	smooth	smooth		rough	rough
Joint waviness	undul.	undul.	undul.	undul.	undul.	undul.		planar	undul.
Joint alteration or coating	fresh	chlorite	chlorite	chlorite	chlorite	chlorite			
Random joints	a few							a few	a few
Block volume, min.	0.3 m^3	2 cm^3	10	5 dm^3	1 dm^3	2 cm^3		0.02 m^3	0.3m^3
max.	3 m^3	50 cm^3	100 dm^3	50 dm^3	10 dm^3	100 cm^3		0.1 m^3	3 m^3
Block shape	flat	long	flat	flat	flat	long (rhomb.)		flat	flat
Rocks	granitic gneiss	slightly altered diabase with chlorite coating on most joint planes							granitic gneiss

This zone is also described in Appendix 7, Section 1.3 in connection with the description of ground condition and applied rock support used in Chapter 6.

5 SUMMARY

Faults and fractures are often complex features where several factors have influenced upon development and the final result found today. However, some few general trends are:

- Crushing and brecciation occur mainly in brittle rocks.
- Where faults exhibit zigzag course in schistose rocks: they are thinner along than across schistocity.
- Where two or more faults intersect, larger volumes of rocks are involved (increased thickness of zones).
- There is often increased jointing in rock masses adjacent to a major fault.

TABLE A2-3 SUMMARY OF WEAKNESS ZONE CHARACTERISTICS

TYPE OF WEAKNESS ZONE	Swelling clay	Inactive clay	Chlorite, talc, graphite, serpentine, or mica	Crushed rock fragments (gravel- or sand size)	Porous or flaky calcite, or gypsum	Possible other materials
Zones of weak materials						coal
Layers or lenses of soft or weak minerals			x			
Zones of rocks, sometimes fractured, such as:						
- some dolerite dykes *	x		x	x		altered rock
- some pegmatites (broken)				x		
Weathered near surface occurrences	x	x	x	x		weathered rock
Faults and fault zones						
Tension fault zones						
- filled zones	x	x	x		x	
Shear fault zones						
- coarse-fragmented crushed zones ***	c	c	c			
- small-fragmented crushed zones ***	x	x	x	x	x	
- sand-rich crushed zones				x		
- clay-rich crushed zones *, such as:						
> simple, clay-rich zones	x	x	x		x	
> complex, clay-rich zones **	x	x	x		x	
> unilateral, clay-rich zones	x	x	x		x	
- foliation shears		x	x			
Altered faults						
- altered clay-rich zones	x	x	x	x		
- altered veins/dykes	x	x	x			
- altered, leached (crushed) zones				x		
Recrystallized and cemented zones			x		x	epidote, quartz

* May also occur as altered and as weathered zones where the adjacent rock may be affected
** May occur as recrystallized/cemented zones
*** May occur as 'leached' zones
c Occur mainly as coating or thin filling

Faults show very wide variations in dimensions, structure, composition, occurrence of gouge, as well as in the character of the transition zone to the adjacent rock masses. A division of faults for rock mechanics, rock engineering and rock construction purposes can consist of:

1. Tension fault zones, which sometimes are developed as feather joints containing filling of soft minerals. They consist mainly of infilling or secondary materials with a sharp boundary to the adjacent rocks.
2. Compression faults, mostly developed as crushed zones believed to be formed by shear movements. They can vary from "dry" fragmented zones to zones mainly consisting of soft, clayey materials. Many of these faults show a transition zone with a gradually reduced jointing quantity from the central part to the surrounding bedrocks.

3. Altered faults, which are characterized by alteration to clay of feldspar in the zone and in the adjacent rocks. Alteration may have caused that minerals have been dissolved to form a permeable materials. A summing up main characteristics in weakness zones is presented in Table A2-3, and assumed RMi or JP values in Table A2-4.

TABLE A2-4 ASSUMED RANGE OF JP AND/OR RMi VALUES FOR THE MAIN TYPES OF WEAKNESS ZONES. THE VALUES DO NOT INCLUDE THE EFFECT OF SWELLING.

TYPE OF WEAKNESS ZONE	Jointing parameter **JP**	Rock mass index **RMi**	Assumed values of input parameters		
			σ_c (MPa)	**Vb** (10^{-3} m^3)	**jC**
Zones of weak materials					
• Layers of soft or weak minerals, such as:					
- clay materials [1]		**0.01 - 0.05**	0.025 - 0.1	**	-
- mica, talc, or chlorite layers and lenses [2]		**0.05 - 5**	0.1 - 10	**	-
- coal seams	**0.04 - 0.1**	0.6 - 3	15 - 25	10 - 100	1 - 2
• Zones of weak rocks or brecciated rocks, such as:					
- some dolerite dykes [3]	**0.005 - 0.05**		*	0.1 - 10	1 - 2
- some pegmatites, often heavily jointed	**0.005 - 0.05**		*	0.1 - 10	1 - 2
- some brecciated zones and layers which have not been "healed"	**0.005 - 0.05**		*	0.1 - 10	1 - 2
• Weathered surface or near surface deposits	0.005 - 0.05	**0.05 - 3**	1 - 10	1 - 100	0.2 - 0.5
Faults and fault zones					
• Tension fault zones					
- feather joints and filled zones, such as:					
> clay-filled zones [1]		**0.01 - 0.05**	0.025 - 0.1	**	-
> calcite-filled zones [2]		**0.5 - 5**	0.1 - 10	**	-
• Shear fault zones					
- coarse-fragmented, crushed zones	**0.01 - 0.1**		*	1 - 100	0.5 - 1
- small-fragmented, crushed zones	**0.001 - 0.02**		*	0.01 - 1	0.4 - 0.8
- sand-rich crushed zones	**0.0005-0.005**	0.0005-0.005	1	0.001 - 0.1	0.5 - 1
- clay-rich, crushed zones, such as:					
> simple, clay-rich zones	**0.001 - 0.015**		*	0.1 - 10	0.2 - 0.5
> complex, clay-rich zones	**0.0005 - 0.01**		*	0.01 - 10	0.2 - 0.4
> unilateral, clay-rich zones	**0.002 - 0.02**		*	0.1 - 10	0.3 - 0.6
- foliation shears [4]					
• Altered faults					
- altered, clay-rich zones	0.005 - 0.05	**0.006 - 3.5**	0.1 - 10	1 - 100	0.2 - 0.5
- altered, leached (crushed) zones	0.002 - 0.02	**0.003 - 2**	0.1 - 10	0.1 - 10	0.3 - 0.6
- altered veins/dykes	0.01 - 0.1	**0.0003 - 0.3**	0.01 - 0.5	10 - 1000	0.2 - 0.5
Recrystallized and cemented/welded zones	It is difficult to indicate numerical values for these types of zones				

* Varies with the type of rock
** Massive rock is assumed (a scale factor of 0.5 has been applied for the compressive strength of rock)
1) The clay is assumed as very soft - firm
2) No strength data have been found. The values given are, therefore, assumed
3) It is assumed that the joints are without clay
4) When occurring alone, the foliation shear is probably a singularity; else probably a simple or complex clay-rich zone

In addition to the orientation and thickness the following features may be applied in description of faults:

- joint and seam characteristics;
- filling or gouge type and properties;
- block sizes and shapes; and
- the types of rocks or minerals and their possible alteration.
- the composition of the rock masses in the transition zone between the zone and the adjacent rocks.