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# Arbeitsbericht NAB 19-12

## Structural Analysis Manual

February 2019

A. Ebert & K. Decker

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KEYWORDS

Structural Geology, Manual, TBO, drill cores, Northern Switzerland, Sediments

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**Please note:**
This manual was originally produced as a Nagra Internal Report. It has been revised based on the experience and feedback of the contractor's workshop in December 2018. The present report constitutes the final manual and reference document for structural geology, to be used for internal and external reporting in the framework of Nagra's drilling campaign.

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# 1 Introduction

This manual is intended to provide background information for recording and describing deformation structures in drill cores from Nagra's drilling projects. The purpose of this instructional manual and the associated factsheets shall ensure consistency for core descriptions of different individuals. The documents include a concise list of structures to be used. Names of structures are based on accepted definitions published in peer-reviewed literature (see chapter 10). This manual, however, is not intended to inform geologists regarding the geotechnical core inspection, but rather provide field personnel with a brief overview of the different deformation structures in drill cores and definitions of structure types to be used during core inspection for Nagra. All parameters necessary with regard to a standard procedure for core inspection are characterised.

In particular, this manual focuses on brittle deformation structures in sedimentary rocks such as mudstone, marl and limestone of the Swiss Jura Mountains. The drill cores may also contain a limited suite of ductile structures such as shear bands and pressure solution surfaces. These ductile structures are briefly described. However, this manual is not meant to be applied to structures developed by ductile deformation.

This manual outlines a standard procedure for describing structural records on newly recovered core material. A flowchart (see appendix A) helps to distinguish clearly between the different deformation structure types.

# 2 Overview: Discontinuities and deformation mechanisms

Discontinuities are fabrics within a rock that interrupt or disconnect the homogeneous rock mass. Mechanical discontinuities are defects, flaws or planes of weakness as well as abrupt material variations in the rock mass, regardless of their origin. The most familiar discontinuities are bedding, compositional layering, foliation, and different types of fractures. Structures of interest that should be identified and described during the structural core analyses are those originating from brittle or ductile deformation. Discontinuities in rocks which do not result from mechanical deformation processes, termed integral discontinuities (e.g. sedimentary structures such as bedding, cross-bedding, slumps, fossils) are not discussed.

Different kinds of stress applied to rock mass may lead to its deformation, either by brittle (frictional plastic) or ductile (viscous) processes. Deformation (i.e. changes in the shape, position and/or orientation of a rock mass) is termed strain. Whether the deformation is brittle or ductile depends on various parameters, such as temperature, deformation rate, stress, rock composition and the presence of fluids.

Brittle deformation leads to the failure of rock by fracturing and loss of cohesion. *It breaks*. Mohr-Coulomb type brittle deformation processes are independent of strain rate and temperature. The resulting features are faults, fault zones, joints or veins (Section 3.2).

Viscous deformation leads to permanent changes in the shape of rocks without loss of cohesion. *It flows.* In viscous deformation, rock strength depends on both temperature and strain rate. For example, the calcite-bearing sedimentary rocks of the Swiss Jura, which are the subject of Nagra's investigations, did not reach temperatures necessary for penetrative viscous deformation. However, some viscous structures such as stylolites, stylolitic fault rocks, and shear bands may occur (Section 3.6).

Depending on the type and degree of deformation, strain and rock rheology, different types of structural discontinuities can develop. The structures can be divided into 5 main groups of discontinuities (see Fig. 2-1): fractures with and without shear or slip indications caused by brittle deformation, structures caused by dissolution, fabrics caused by ductile deformation, and man-made artificial fractures induced by drilling, coring and core handling. Detailed definitions of structural discontinuities are given in the following chapters and enclosed factsheets.

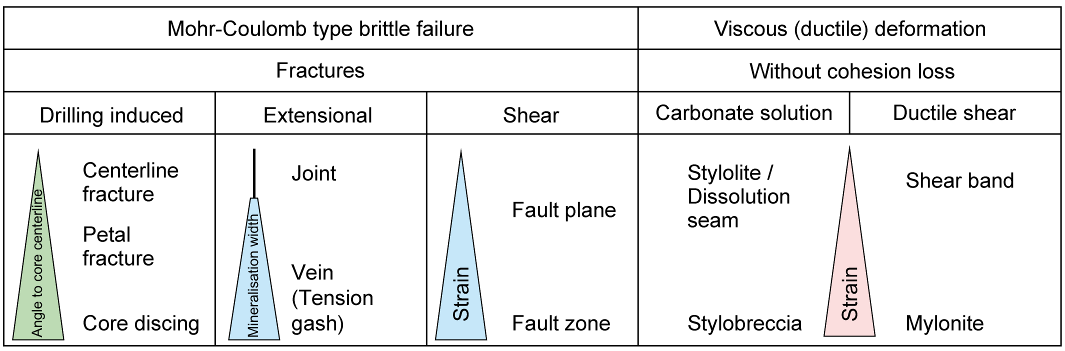



Fig. 2-1: Five types of structural discontinuities

5 main groups of discontinuities are distinguished: drilling-induced fractures, brittle fractures with and without shear, fabrics resulting from carbonate dissolution, and fabrics resulting from ductile shear.

Discontinuities can be one-, two- or three-dimensional (Fig. 2-2 and chapter 6). Lineation is a strain-induced one-dimensional fabric element on a two-dimensional foliation plane or an intersection line of two intersecting planar structures. Fault striation is another typical example of a one-dimensional discontinuity. Planar structures are two-dimensional discontinuities such as joints, faults or foliation. Fault zones or volumes of fault rocks are three-dimensional fabric elements.

Planar structures can be separated into sharp and tabular discontinuities (Fig 2-2). Sharp discontinuities show no, or only narrow, aperture/thickness of the structure (up to a few mm; e.g. joints, tension gashes, fault planes). All of the rock mass adjacent to the fracture plane has undergone the same displacement. Sharp discontinuities are typical for brittle fracturing. In contrast, tabular discontinuities represent shear zones, where displacement occurs within a zone with significant width, such as brittle fault zones or shear bands. Fault zones may consist of a fault core with fault rocks and/or multiple fault planes and adjacent damage zones (also termed process zones).

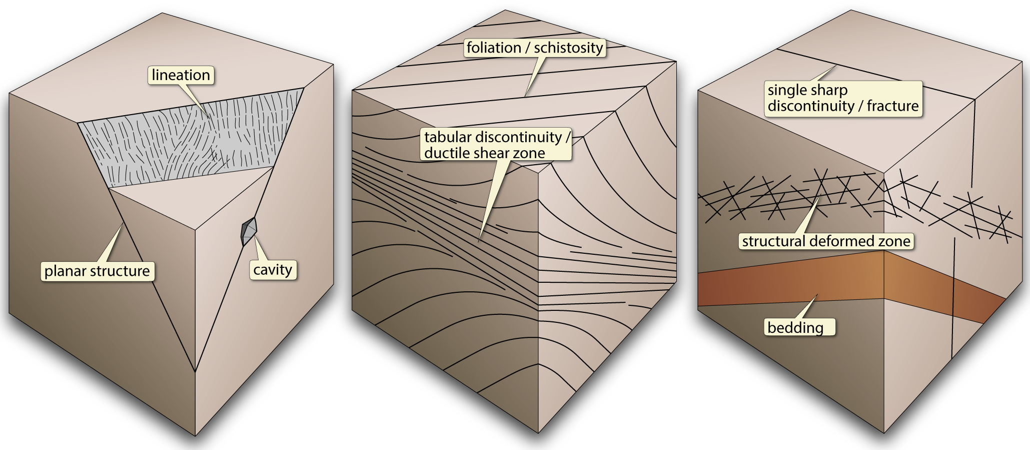



Fig. 2-2: Fabric elements and geometries of discontinuities

Striation on fracture surface and cavity within planar structure (left image); fabric of tabular discontinuity, where foliation, schistosity, or bedding bends into the shear zone with increasing strain towards the centre of the shear zone (centre image); difference between single fracture, deformation zone and bedding (right image).

# 3 Definition of discontinuities

## 3.1 Sedimentary discontinuities

**Sedimentary structures** are structures formed during or shortly after deposition of sediments. For example, bedding, channels or ripple marks are typical sedimentary structures, and represent changes in the deposited material (e.g. mineral composition or grain size, Fig. 3.1-1).

**Soft-sediment deformation** can cause discontinuities and characteristic rock types similar to brittle structures in hard rocks as mentioned in Section 3.2. Soft-sediment deformation is any deformation other than sediment compaction. It is caused by rearrangement of sediment particles by grain-boundary sliding. In contrast to deformation in hard rocks, particles do not internally deform and interstitial cement, as well as striation or slickenfibres, are usually lacking. Another criterion that indicates soft-sediment deformation is the overprinting of deformation structures by sedimentary or organic structures, e.g. trace fossils, sediment-filled dykes or dewatering structures that cross-cut deformation contacts.

Possible triggering examples for soft-sediment deformation are (a) slumps or debris flows in deposition areas with steep slopes and corresponding synsedimentary faults and folds, (b) earthquakes and related cracks filled with thixotropic mobilised sediments or convolute bedding (complex and chaotic folding) in unconsolidated sediments, or (c) current-induced reworking of unlithified sediments resulting in synsedimentary breccias (Fig. 3.1-2). At the observation scales of drill cores, such breccias may resemble fault rock. In Northern Switzerland, sedimentary breccias are particularly known from the Keuper (Upper Triassic) of Lausen.

**Fossils and trace fossils** are also sedimentary structures (Fig. 3.1-3). For example, if the rock sample is small, large recrystallised shells can be misinterpreted as veins.


Fig. 3.1-1: Bedding

Layers with varying clay content. The competent, orange layers with low clay percentage react differently to stress. They show a dense network of joints (marls and quartzites, Bretagne).

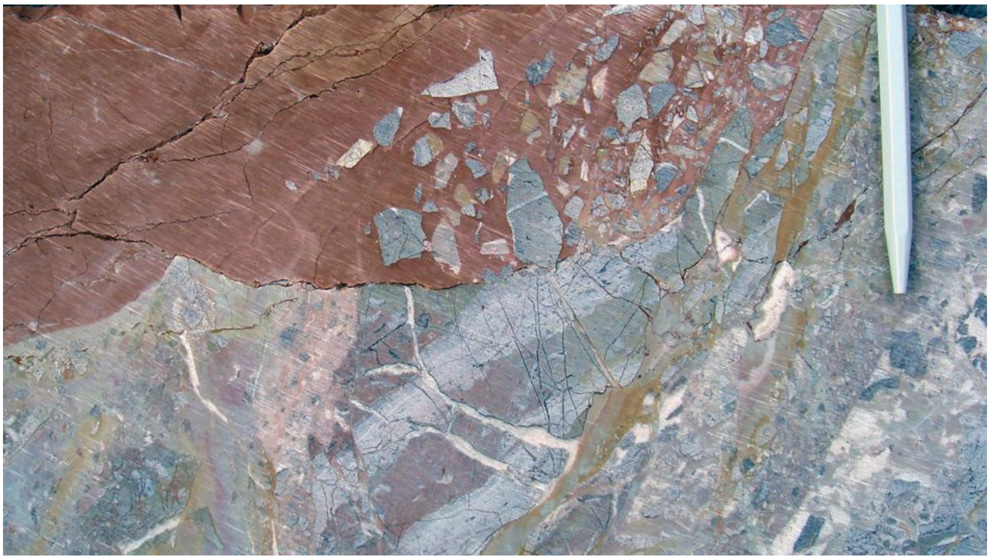


Fig. 3.1-2: Synsedimentary breccia

Sedimentary breccia due to reworking, Broccatello d'Arzo.


Fig. 3.1-3: Trace fossils

If not properly analysed, large recrystallised shells or trace fossils as on the image can be misinterpreted as fracture discontinuities (marl, Bretagne).

## 3.2 Planar brittle discontinuities

Brittle fracturing may result in extension or shear, with fracture planes orientated differently to the principal stresses. Fracturing generally results in mechanical defects or planes of weakness in a rock mass where the rock has lost its continuity and cohesion (Fig. 2-2). For the work on Nagra's drill cores, the following definitions apply:

- **Fracture** is used as a general term for a structure without preserved evidence regarding the mode of fracturing. The term is therefore applicable to structures formed by both extension or shear. According to Peacock et al. (2017), fractures can include approximately planar discontinuities such as dykes, faults, joints and veins. The word fracture is therefore an umbrella term for faults, veins, and joints.

- **Joints** are single planar fractures which, by definition, are closed and display no measurable slip or dilatation at the scale of observation (Hancock, 1985; Fig. 3.2-1). A joint is a fracture where there has been no displacement.

  Joints may be decorated with plumose structures and hackle marks. Plumose structures form a relief pattern on the fracture surface similar to a feather, indicating the growth direction of the crack. Growth starts in the centre of the plumose structure and propagates radially outwards in the direction of the feather lines (Fig. 3.2-2). Hackle marks may occur along the tip line of the fracture (Fig. 3.2-3).

- **Veins (tension gashes)** are brittle extensional fractures that are filled by secondary minerals (Fig. 3.2-4, Fig. 3.2-5). The term vein also applies to sharp and straight fractures with a thin coating of cement on the fracture surface (<< 1 mm in width) that formerly may have been termed "sealed joint" or "Ader".

  Tension gashes may open in the direction perpendicular to the fracture surface, or in directions oblique to its plane. In many cases, the opening direction can be identified from the orientation of elongated crystals growing in the gash fracture.

- **Faults** are single discrete fracture planes with displacement (Peacock et al. 2017). Fault planes show characteristic kinematic indicators such as slickensides, striation, shear sense indicators and (possibly) displaced markers. In contrast to faults, **fault zones** are more complex, forming a volume with discontinuities and numerous brittle structures (see Section 3.5).

  Fault surfaces are typically decorated by striations resulting from scratching or directional mineral growth. In calcareous sediments, grooves on polished fault surfaces (Fig. 3.2-6), stylolites ("slickoliths") and calcite slickenfibres are the most common types of striation (Fig. 3.2-7). These striations represent the direction of relative movement of the adjacent fault blocks and may also allow identification of the shear sense (see Sections 6.1 and 6.2). In clay-rich rocks, the fracture surface commonly becomes polished by frictional movement of opposite rock bodies.


Fig. 3.2-1: Joints, cm to dm scale
Joints in a marl (Bretagne).

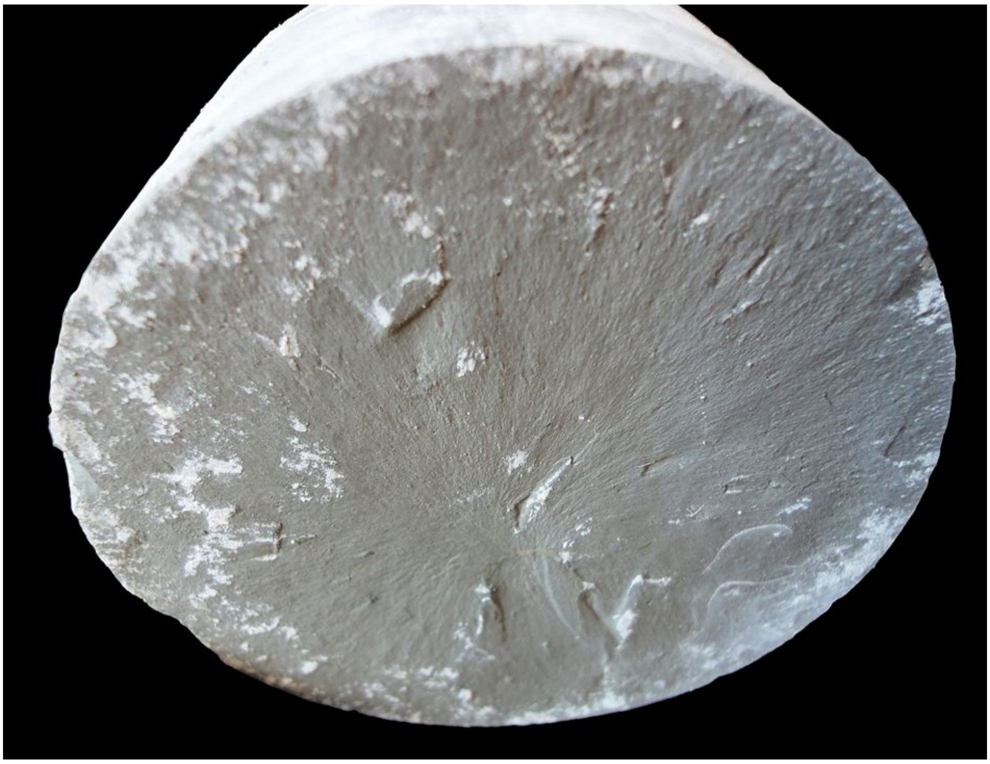


Fig. 3.2-2: Plumose structure
Radial feather-like structure on a joint formed by core discing. The point of crack origin is in the lower centre of the core, from where the plumose morphology fans out (Gösgen borehole).

Fig. 3.2-3: Hackle marks
Short overstepping fractures along the margin of an elliptical joint are called hackle marks.

Fig. 3.2-4: Tension gashes (veins)
Veins in a marl (Dents du Midi).

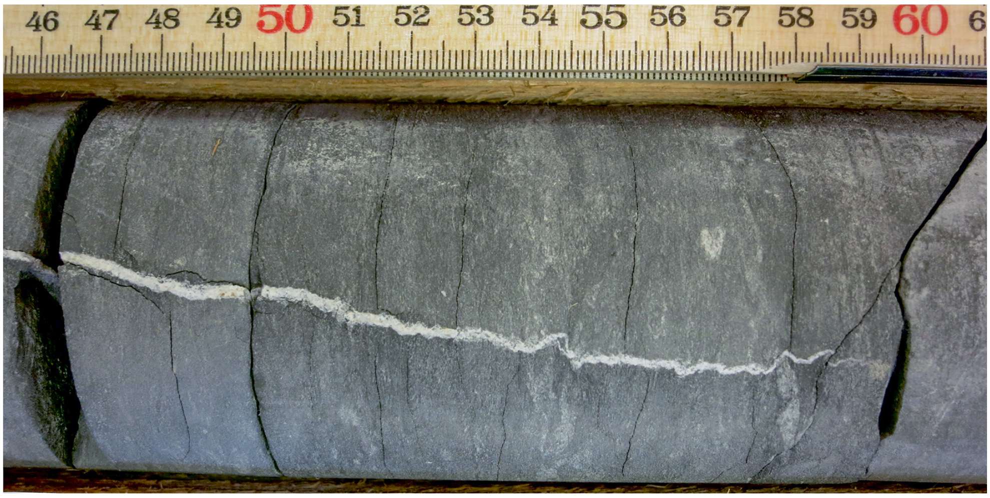



Fig. 3.2-5: Tension gash (vein)

Calcite-filled tension gash in marly limestone. Note ptygmatic folding of the vein due to compaction.


Fig. 3.2-6: Fault: polished mirror-like slip surface

Fig. 3.2-7: Fault plane with synkinematic fibrous calcite

## 3.3 Cavities and druses

Cavities associated with tectonic structures typically result from incomplete cementation of tension gashes/veins and faults (e.g. at releasing fault bends). Fractures which include open volume shall be characterised as "open" when the open void or gash extends all along the fracture or through the core, or "partly open" when fracture planes include only patches of open space (Fig. 3.3-1 and Fig. 3.3-2). Such patches may or may not be connected to each other along the fracture plane.

Open and partly open fractures are normally filled with newly formed crystals (druse; Fig. 3.3-3). Such idiomorphic crystals can only form when growing into open space. Coatings of idiomorphic crystals are therefore prime indicators for open fractures, even in cases where cores are broken or fully dismembered by drilling/core handling.

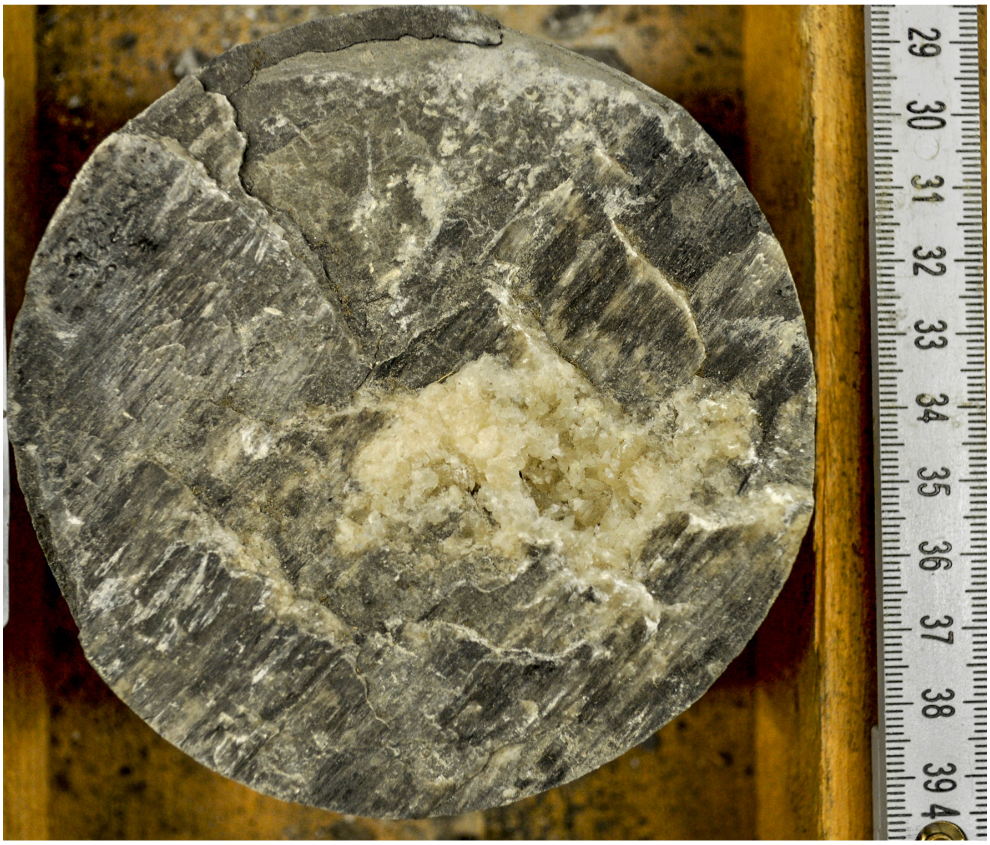


Fig. 3.3-1: Partly open fault plane gash with isolated open void in marly limestone

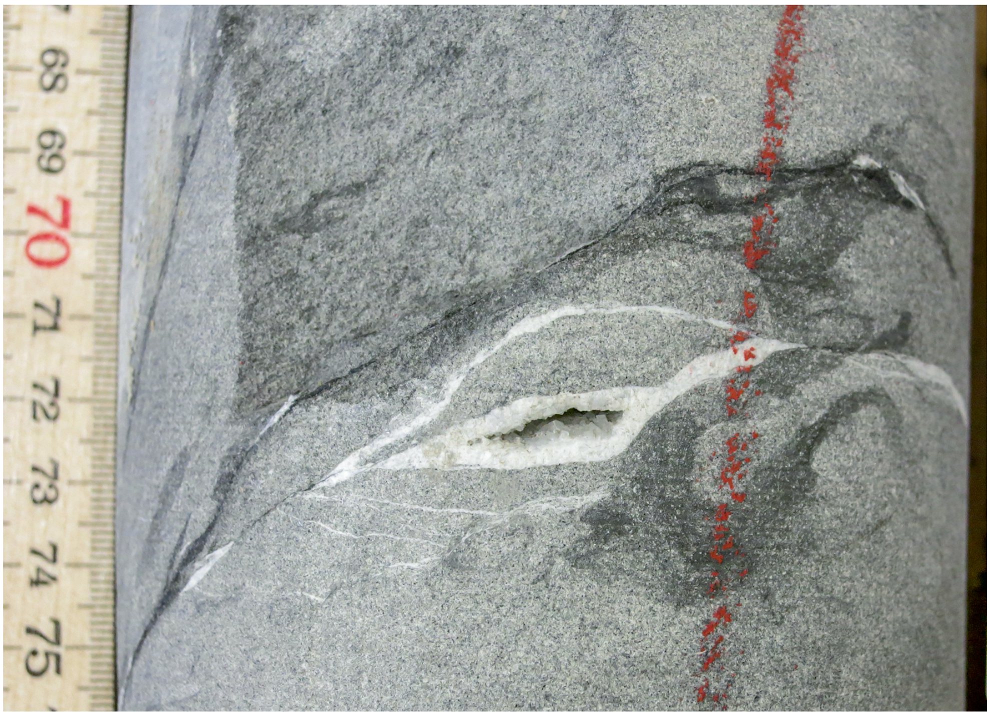


Fig. 3.3-2: Partly open tension gash with isolated open void in marly limestone

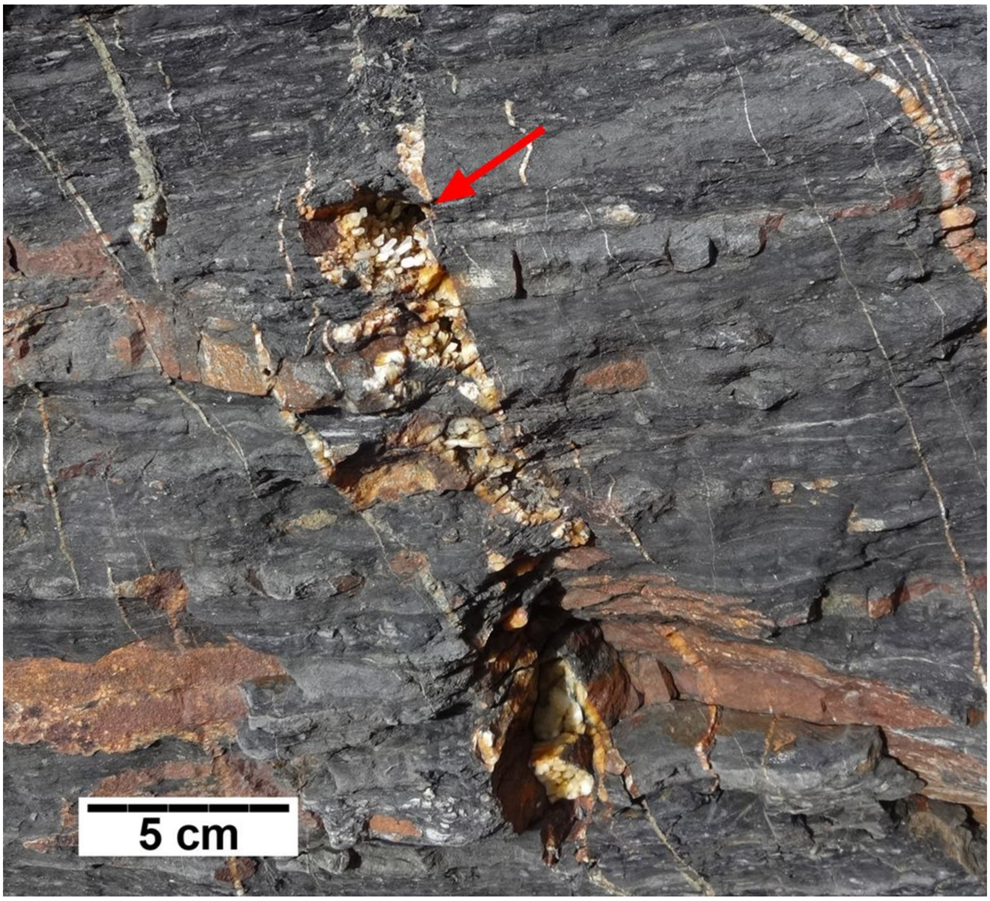



Fig. 3.3-3: Cavity within fault
Fault-related cavity partly filled with crystals (druse), Bretagne.

## 3.4 Dissolution surfaces (stylolites)

Stylolites are formed under pressure-dissolution of calcareous rock that produces irregular, jagged dissolution surfaces that may truncate components, sedimentary layers or other structures (see also appended factsheets).

Rock material which cannot be dissolved becomes enriched along the residual stylolitic seams along serrated (Fig. 3.4-1) or smooth surfaces (Fig. 3.4-3). Insoluble residues typically consist of clay minerals and iron oxide. The dissolved material may re-precipitate in the near proximity or in a different part of the rock mass, e.g. as vein material in opening fractures.

Stylolites often occur in marly limestone. They are frequently non-planar and discontinuous and may form connected networks of dissolution surfaces, which result in a "brecciated" appearance of the sedimentary rock (Fig. 3.4-2). Stylolites can therefore frequently not be described on a structure-by-structure basis. In such cases, core description should denote the abundance and character of stylolites (including average length and spacing of individual structures) and the length of the core interval characterised by the description.

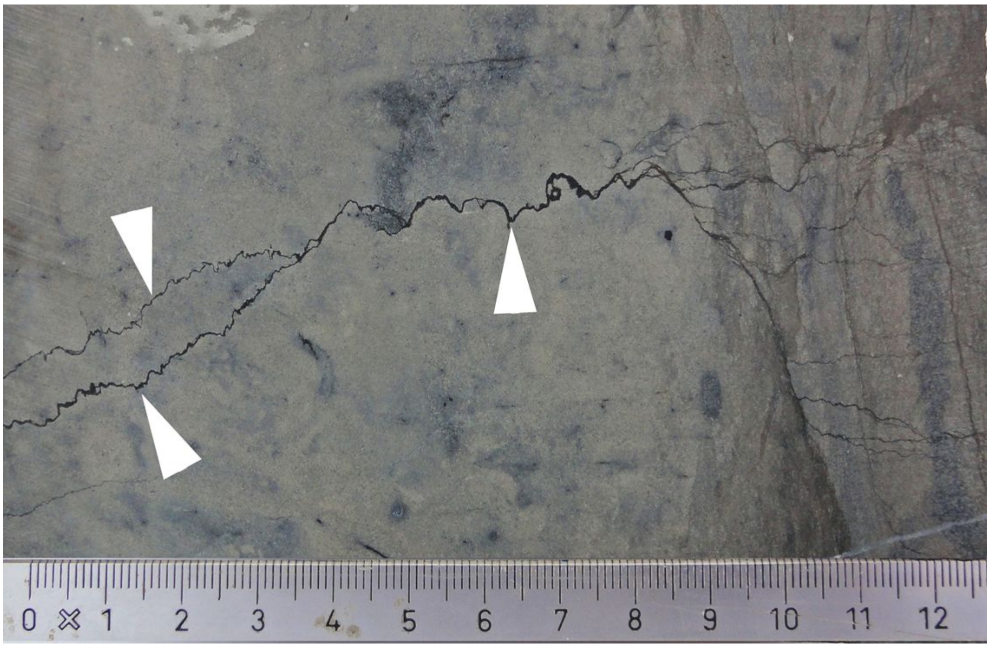



Fig. 3.4-1: Stylolites with serrated head seams
Stylolites as a result of pressure solution in a limestone (Malm, Weiach borehole).

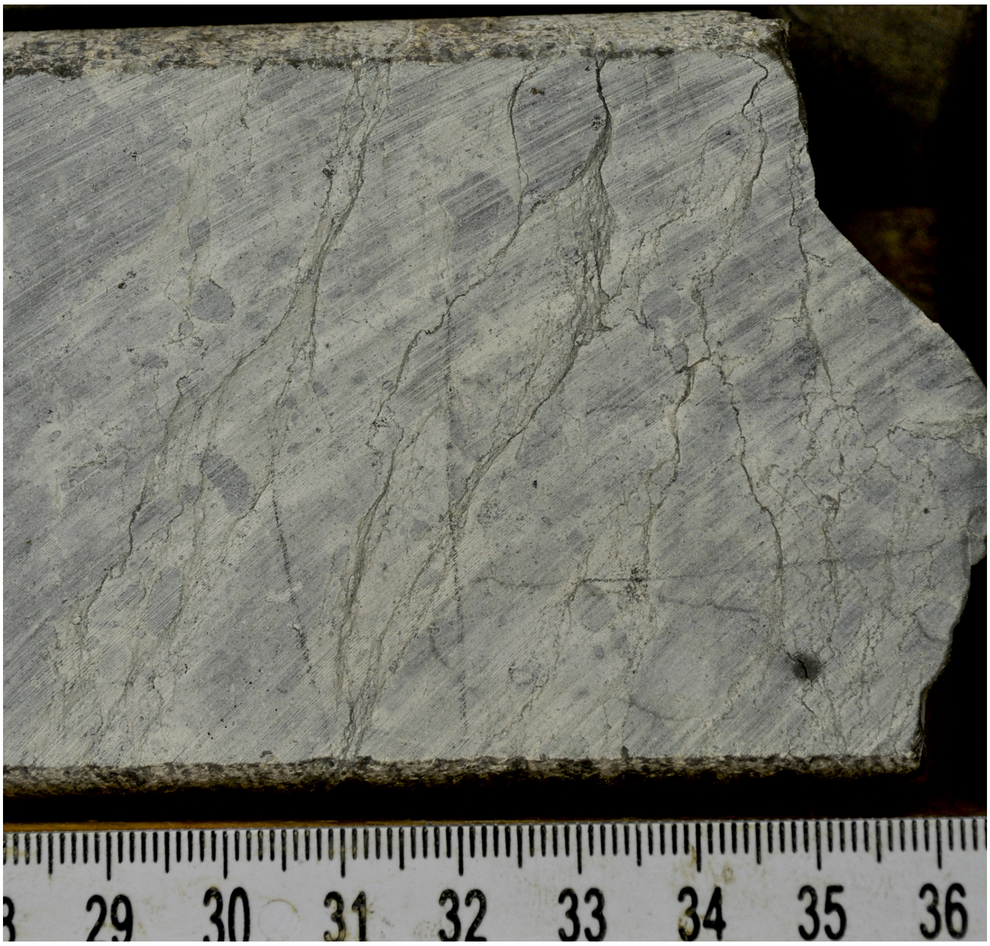



Fig. 3.4-2: Stylolites forming an anastomosing network in Jurassic marly limestone


Fig. 3.4-3: Stylolites forming smooth dissolution surfaces

Note that the stylolite at 3.5 cm is decorated with several mm thick clay. Jurassic marly limestone.

## 3.5 Fault zones

**Fault zones** consist of a dense arrangement of different brittle discontinuities forming a fault-parallel (tabular) rock volume of significant width. This volume may include interacting fault segments in densely fractured rock and/or fault rocks (Peacock et al. 2017).

Fault zones may contain a fault core and damage zones adjacent to one or both sides of the fault core (Fig. 3.5-1). Outcrop studies show that the delimitation of fault cores and damage zones is not straightforward and open to some subjectivity (Bauer et al. 2016). The following characterisation may be helpful for structural drill core analysis:

- Fault cores are characterised by volumes of newly formed fault rocks typically bounded by sub-parallel margins or fault planes and/or extremely dense networks of kinematically compatible faults (e.g. sub-parallel faults with similar slip direction and identical shear sense).
- Damage zones form by the initiation, propagation, interaction and build-up of slip along faults, creating a volume of deformed wall rock around a fault (Peacock et al. 2017). Damage zones are frequently characterised by a gradual decrease in deformation with distance from the master fault/fault core. In drill cores, damage zones may contain faults which are kinematically compatible with the structures in the fault core (e.g. faults sub-parallel to the master fault; syn- and antithetic Riedel shears and/or en-echelon tension gashes) or fractured rock with fracture intensity decreasing with distance from the master fault/fault core.

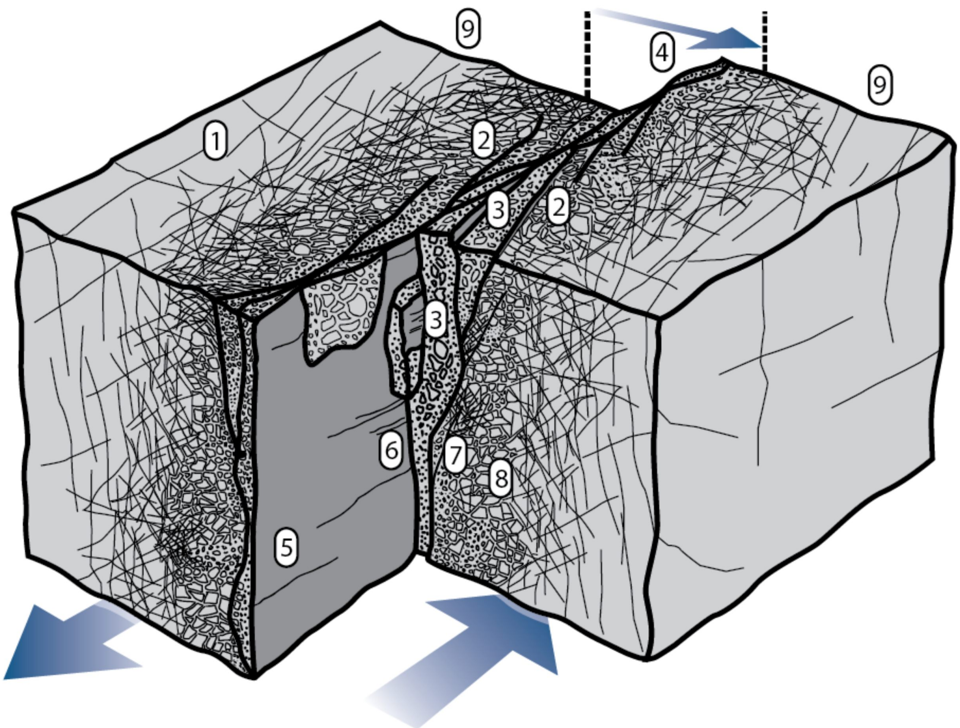



Fig. 3.5-1: Schematic sketch of fault zone with fault core and damage zone

1, 9. damage zones with fractured host rock; 2. Riedel shears; 4. fault core including main slip surface (5, 6), cataclasite (3, 7) dilation breccia (8) (from Schröckenfuchs et al. 2015)

Fault zones and their architecture are extremely important for the hydrogeological and mechanical assessment of rock mass. Core descriptions should therefore characterise fault zones on a structure-by-structure basis as far as reasonably practical. A core log listing the orientation and properties of individual structures in a fault zone is preferred over a notation such as *"1 m thick fault zone with abundant fault planes"*. On the other hand, core descriptions should clearly denote a listed number of individual structures belonging to a single fault zone, or to its damage zone.

Examples of fault zones are shown below (Fig. 3.5-2). The structures are arranged in distances of mm and are often similarly orientated. Such zones typically occur in strongly deformed clay-rich rocks, where slickensides on a fault plane are the most common structures (e.g. Opalinus Clay). In contrast, the fault plane may be coated by different types of discontinuities, such as different veins and faults (Fig. 3.5-3).

In the case of such a fault zone with one predominant structure type, it is not feasible to define each discontinuity. In this case, it is recommended to (a) define the structure type, (b) estimate the number of structures per core length, (c) determine the significant orientation and dip and (d) characterise parameters such as mineralisation, shear indicators, etc.

Fig. 3.5-2: Fault core – damage zone

Cataclasite (below red pencil) in the core of a fault zone of the Inntal Fault with a damage zone consisting of heavily fractured carbonates (Fracture Density Classes FDC 3 and FDC 4).

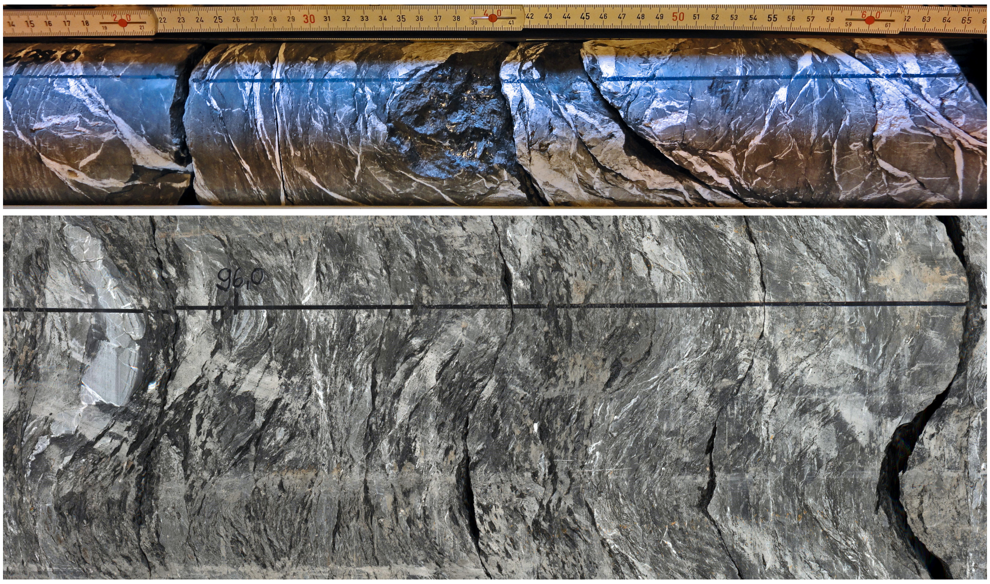


Fig. 3.5-3: Fault zones in marl and shale

Top: fault zone with a complex fabric consisting of fault planes, dissolution surfaces (stylolites) and calcite-filled tension gashes, Oftringen borehole.

Bottom: fault zone in Opalinus Clay (Bözberg B2/13 borehole) with countless sub-parallel fault planes per metre core.

## 3.6 Ductile discontinuities

In contrast to brittle fracturing, ductile deformation localises under elevated temperatures or confining pressure in ductile shear zones. The ductile shear zones represent a tabular fabric, i.e. they define a volume and exhibit a strain and displacement gradient across the shear zone.

**Shear bands** are narrow zones of relatively intense deformation in which progressive deformation is non-coaxial (i.e. mostly simple shear; Passchier & Trouw 1996). Such structures may form in shaly and marly sedimentary rocks at low temperatures. The following types of shear bands should be identified in core analysis:

- **SC-type shear bands:** The term refers to minor shear zones with fabrics consisting of C-type shear band cleavage and S-planes. S-planes define a foliation that is cut by C-type shear band cleavage or C-planes (Fig. 3.6-1 and Fig 3.6-3; Passchier & Trouw 1996). C-planes are decorated by slickenlines, which are oriented perpendicular to the intersection line between S- and C-planes (Fig 3.6-4).
- **SCC'-type shear bands:** These are minor shear zones containing two planar fabrics that can be divided into a sigmoidal penetrative foliation (S-planes), and discrete planar shears that displace the foliation (Fig. 3.6-2 and Fig 3.6-5; C and C' surfaces; Blenkinsop & Treloar 1995). C- and C'-planes are decorated by slickenlines, which are oriented in the direction perpendicular to the intersection line between S- and C-planes.

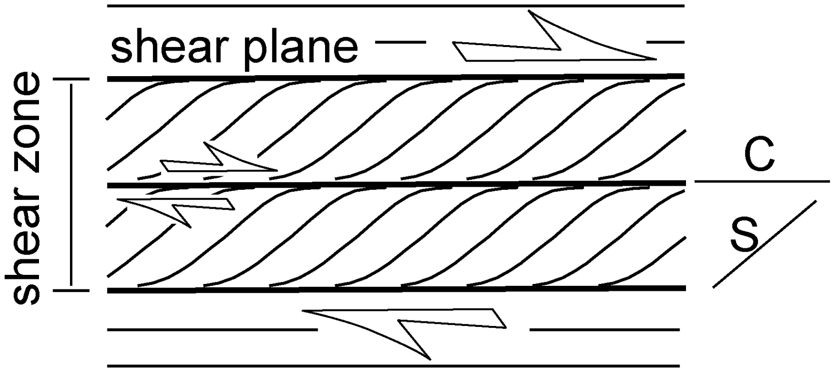



Fig. 3.6-1: SC-type shear band
adapated from Redrawn from Blenkinsop & Treloar (1995)

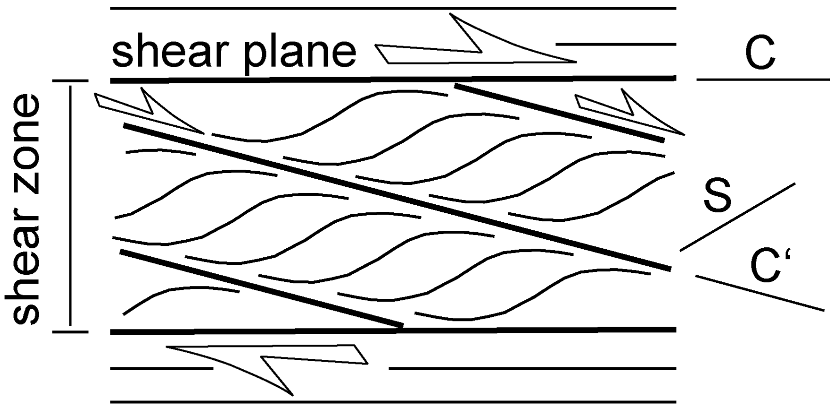



Fig. 3.6-2: SCC'-type shear band
adapted from Blenkinsop & Treloar (1995)

The calcite-bearing sedimentary rocks of the Swiss Jura, which are the subject of Nagra's investigations, did not reach temperatures necessary for penetrative viscous deformation. Ductile structures such as mylonitic fabrics, foliation, narrow/isoclinal folding, elongated and recrystallised grains, porphyroclasts and fault rocks such as mylonites are therefore not described.

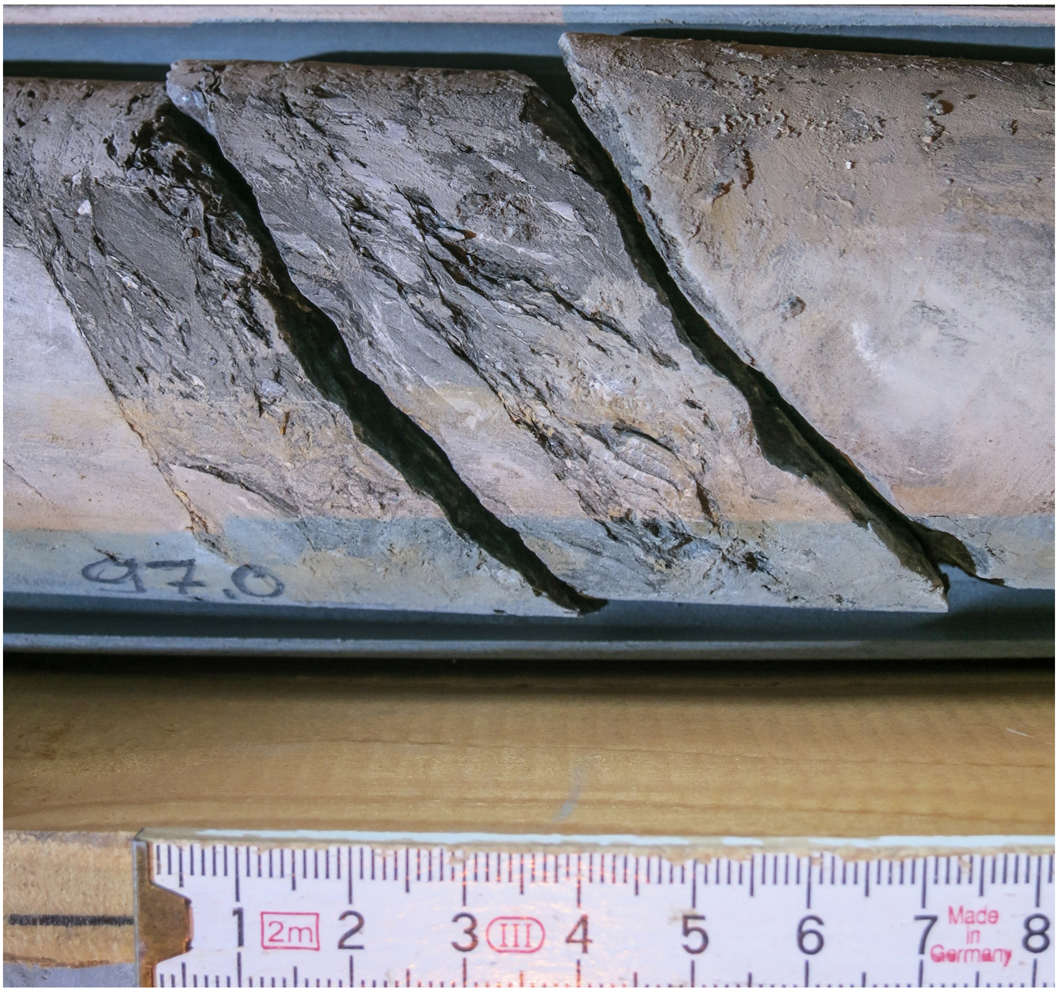



Fig. 3.6-3: SC-type shear band in "mélange"
between Opalinus Clay and Malm carbonates. C-planes dip 45° to the left, S-planes dip 60° to the left; shear sense is reverse (thrust), Bözberg B2/13 borehole, 97.05 m.


Fig. 3.6-4: C-plane of SC-type shear band "mélange"
between Opalinus Clay and Malm carbonates. C-plane of the shear band depicted in Fig. 3.6-1. Note that the plane is decorated with slickenlines, Bözberg B2/13 borehole, 97.05 m.

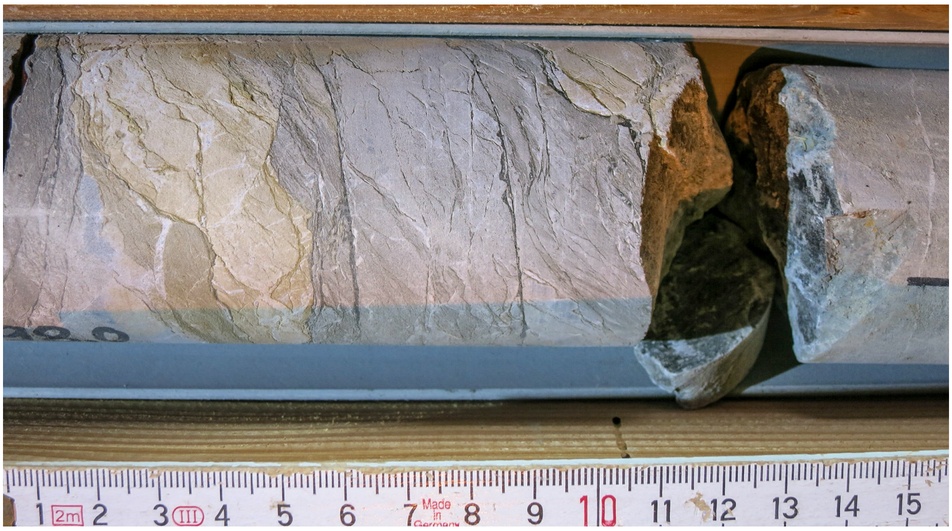



Fig. 3.6-5: SC- and SCC'-type shear bands in "mélange"
between Opalinus Clay and Malm carbonates. SC-type fabrics between cm 7 and 11, SCC'-type fabric between cm 2 and 6, Bözberg B2/13 borehole, 97.05 m.

# 4 Fracture architecture, fracture density and RQD

## 4.1 Fracture architecture

Depending on the orientation, type and origin of the structures, fractures can occur as:

- a single element
- a set of structures with similar orientation (Fig. 4.1-1)
- a network of fractures Fig. (4.1-2)

Fig. 4.1-1: Set of sub-parallel calcite-filled tension gashes
Morcles nappe (image width = 10 cm).

Fracture architecture can be described by the number of fracture sets observed in a rock mass, or by the observation that fractures occur at random (or apparently random) orientation (Fig. 4.1-3). The assessment of the number of fracture sets is based exclusively on fracture orientation without considering different classifications of fractures, meaning that:

- sub-parallel joints and fault planes are counted as one set of fractures
- conjugate fault planes or joints are counted as two sets
- fracture networks that lack parallelism are described as "random"

The number of fracture sets is used to determine the joint set number (Jn) and parameters for rock mass classification which are based on that number.

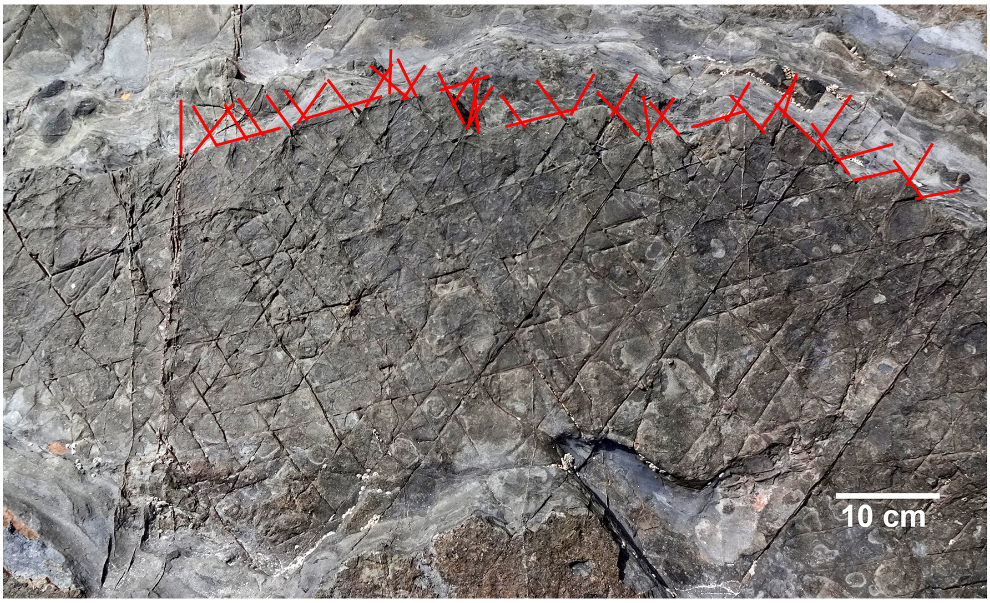



Fig. 4.1-2: Fracture network

Network of at least three joint sets in a competent layer (red lines indicate orientation). More clay-rich and consequently less competent layers above and below this layer reveal less joints (marl, Bretagne).

## 4.2 Fracture density

Fracture density (or fracture intensity) is expressed by a numerical value that reflects a quantitative measure of the abundance of fractures in a rock mass.

Measures of fracture density (intensity) further account for the following dimensions of fracture measure:

- Fracture count (n) (number of fractures encountered)
- Fracture length (L) (length of intersection lines of fractures with a plane of observation, e.g. a bedding plane)
- Fracture area (A)
- Fracture volume (v) (given as the product of fracture area and average fracture aperture)

Measures of fracture density are based on whether measurements are done:

- Along a one-dimensional scanline or borehole ($P_{11}$). Such measurements are denoted with subscript 1. The one-dimensional fracture intensity or fracture density (or linear fracture frequency), $P_{11}$, is defined by the average number of fracture intersections per unit length (e.g. core axis).

  In one-dimensional fracture analysis, the apparent number of fractures (n) encountered along a scanline of known length (L) is measured. Note that the number depends on the orientation of the fracture set and the scanline direction (except when fractures are isotropic and normal to the scanline). $P_{11}$ is therefore not regarded as a reliable characterisation of fracture intensity.

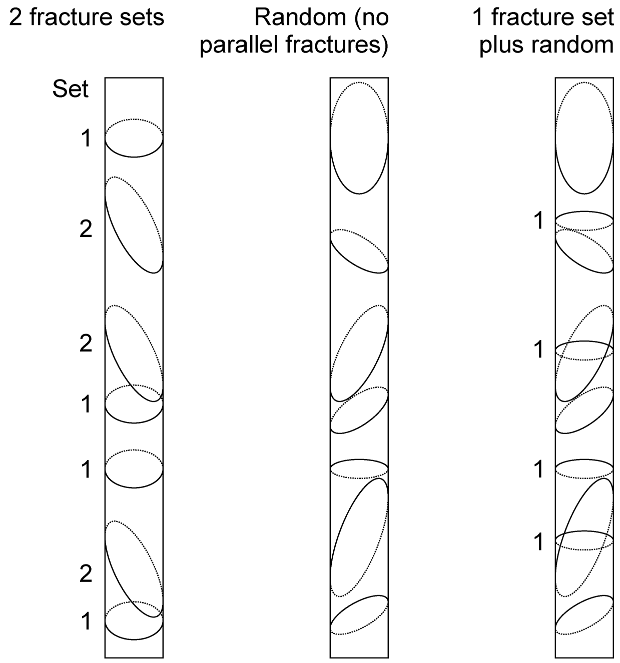



Fig. 4.1-3 Definition of the number of fracture sets

1 and 2 denote different sets of sub-parallel fractures

- On a two-dimensional scan plane (e.g. outcrop or bedding plane); denoted with subscript 2. The number of fractures per area ($P_{21}$) or the total trace length of fractures ($P_{22}$) is calculated from the individual lengths of single fractures measured in each scan plane (area, A). By their nature, such analyses are not applicable to drill cores.
- In a three-dimensional volume of rock (rock mass); denoted with subscript 3. Possible counts are the number of fractures per volume ($P_{31}$), the area of fractures per volume of rock ($P_{32}$) and the fracture volume per volume of rock ($P_{33}$).

  $P_{31}$ and $P_{32}$ are easily calculated from quantitative structural core analyses, while $P_{33}$ requires data on the opening width of all fractures.

  Three-dimensional fracture density $P_{32}$ can be calculated for all cores irrespective of knowing their true orientation. The value is measured as the total fracture area per unit rock volume ($m^2/m^3$) given by the total area of fractures (A) within the core interval divided by the volume of the rock mass (V) of that interval (Fig. 4.2-1).

  The calculation of $P_{32}$ is based solely on the intersection angle between the individual fractures and the borehole axis as shown in Fig. 4.2-1.

  The described procedure reveals sufficiently accurate values for fractures with dips up to about 70°, i.e. fractures that include angles of less than 20° with the core axis in vertical boreholes. The areas of steeply dipping fractures with inclinations of less than 20° with respect to the core axis should be calculated from the borehole diameter (d) and the measured length of the major axis (D) of the intersection ellipse. The same procedure should be applied to fractures which do not cut the entire core diameter to derive reasonably accurate values for $P_{32}$.

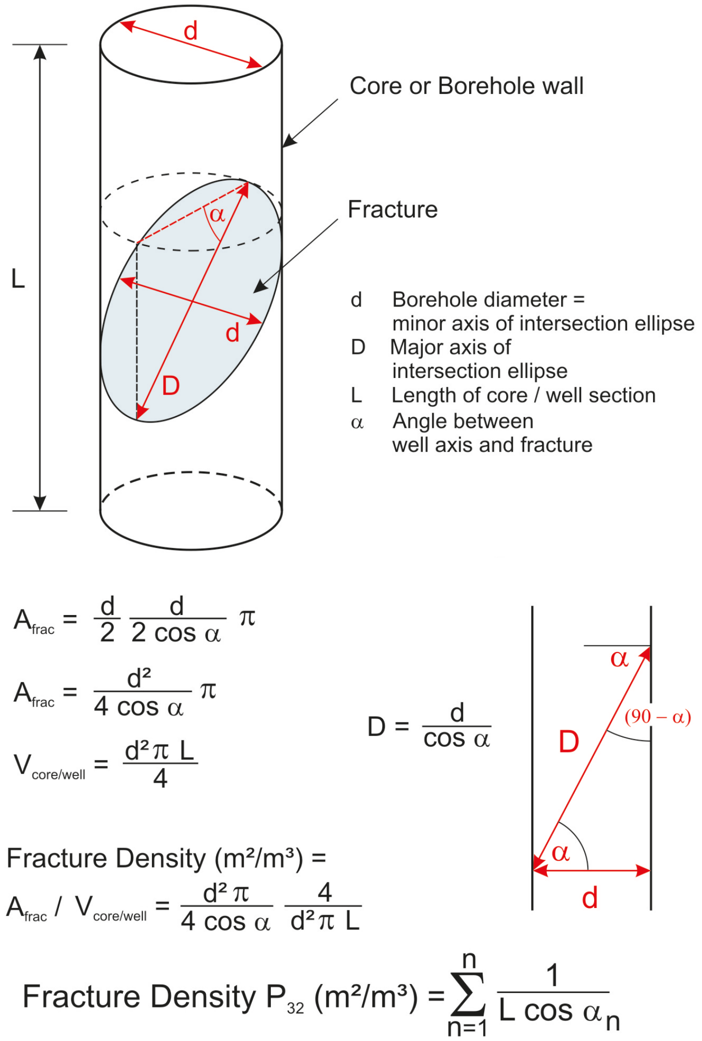



Fig. 4.2-1: Calculation of the fracture density $P_{32}$

## 4.3 Fracture density classes

Fracture density cannot be quantified for cores or parts of a core which are heavily disintegrated. For such core intervals, fracture density should be estimated using a classification scheme distinguishing between 4 classes of rocks with distinct fracture density using Fracture Density Classes (FDC) 1 to 4 characterising rocks with increasing fracturing. The classification was originally developed for outcrop analyses (Bauer et al. 2016) but can be applied to disintegrated cores as well. Fracture densities corresponding to FDC 1 (slightly to moderately fractured with average fracture spacing > 10 cm) are not expected to result in disintegrated cores.

FDC 2 to FDC 4 are defined as follows:

- **Fracture Density Class 2:** Closely fractured (Fig. 4.3-1). Refers to closely fractured rock characterised by three or more fracture sets with average spacing of sub-parallel fractures of about 5 to 10 centimetres. The sizes of multifaceted core fragments vary between about 5 to 10 cm. Estimated fracture densities ($P_{32}$) for FDC 2 range from about 20 to 60 m²/m³.

- **Fracture Density Class 3:** Very closely fractured rock (Fig. 4.3-2 and Fig. 4.3-4). Fracture sets are difficult to recognise or appear at random orientation. Close spacing of intersecting fractures at distances of about 1 to 5 centimetres results in multifaceted rock fragments with maximum diameters of a few centimetres (Fig. 4). Estimated fracture densities ($P_{32}$) for FDC 3 are about 60 – 200 $m^2/m^3$.
- **Fracture Density Class 4:** Extremely fractured rock (Fig. 4.3-3 and Fig. 4.3-5). FDC 4 is assigned to extremely fractured rock with randomly closely oriented fractures. Joints and microfractures spaced at distances of 1 centimetre and less result in multifaceted rock fragments with diameters of 1 centimetre or less (Fig. 4.3-5). Sedimentary features are not recognised due to the heavy fracturing. Such heavily fractured rocks typically appear in damage zones of faults. Estimated fracture densities ($P_{32}$) for FDC 4 are higher than about 200 $m^2/m^3$.

When assessing FDCs, it should be ensured that core disintegration results from natural fractures and not from drilling action or core handling. Arguments for tectonic origin of fracturing may derive from the observation of striations, fillings or stylolites on many or most of the fractures delimiting multifaceted core fragments. Arguments for drilling-induced core destruction may be found in drilling reports.

Fig. 4.3-1: Fracture Density Class 2 (FDC 2)

Closely jointed dolostone with 3 well-defined joint sets and joint spacings between 3 and 15 cm. Hauptdolomit Fm., Eastern Alps.

Fig. 4.3-2: Fracture Density Class 3 (FDC 3)

Very closely jointed dolostone with numerous fracture sets with fractures spaced at distances between about 1 and 4 cm. Hauptdolomit Fm., Eastern Alps.

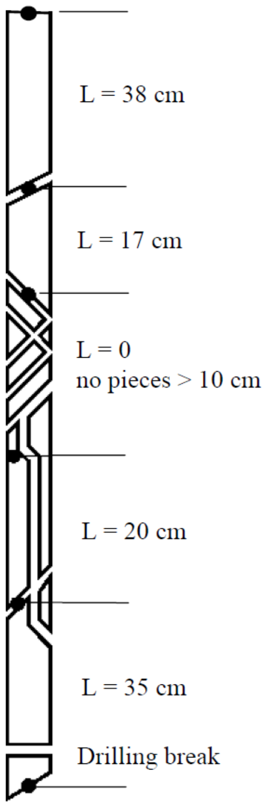
Fig. 4.3-3: Fracture Density Class 4 (FDC 4)

Extremely fractured dolomite with randomly oriented fractures spaced at distances of several millimetres. The spacing of joints results in multi-faceted rock fragments smaller than 1 cm. Hauptdolomit Fm., Eastern Alps.


Fig. 4.3-4: Disintegrated core assigned to Fracture Density Class 3 (FDC 3)

Note that virtually all rock fragments are delimited by polished slickensides ensuring the tectonic origin of fractures, Bözberg B2/13 borehole, 181.90 m.


Fig. 4.3-5: Disintegrated core assigned to Fracture Density Class 4 (FDC 4)
Note that virtually all rock fragments are delimited by slickensides ensuring the tectonic origin of fractures, Bözberg B2/13 borehole, 199.80 m.




Total length of core run = 200 cms

$$RQD = \frac{\sum \text{Length of core pieces} > 10 \text{ cm length}}{\text{Total length of core run}} \times 100$$

$$RQD = \frac{38 + 17 + 20 + 35}{200} \times 100 = 55\ \%$$

Fig. 4.3-6: Definition of Rock Quality Designation (RQD) after Deere (1989)

The **Rock Quality Designation** (RQD) is a standard parameter in drill core logging and is frequently used as a proxy to estimate the relative abundance of fractures in a cored interval (Deer & Miller 1966). It is defined as the percentage of intact core pieces longer than 100 millimetres in the total length of one core section (see Figure 4.3-6). Drilling-induced fractures are also considered in the calculation of the RQD.

Since the RQD value is easily and rapidly estimated, it should be noted by the wellsite geologist to have a quantitative record of the condition of the core straight after its recovery. The procedure for measurement of the length of core pieces and the calculation of RQD are summarised in Fig. 4.3-6.

# 5 Fault rocks

Fault rocks are newly formed rock types which result from the deformation of the wall rock in the core of a fault zone or adjacent to a fault plane. The hydrogeological and geotechnical properties of fault rocks are typically distinct from the properties of the adjacent wall rock, making fault rocks important for the assessment of the hydrogeological (porosity, permeability) and identifying mechanical properties of the rock mass.

Fault rocks are traditionally classified by texture, with most classifications outlined by Sibson (1977). The defining factors for the classification by Sibson (1977) are rock cohesion (at the time of faulting) and the presence/absence of foliation. Accordingly, fault gouge is defined as an incohesive rock composed of < 30 % visible fragments with a randomly orientated fabric.

Woodcock & Mort (2008) provided a revised version of this classification, which is widely used (Fig. 5-1). They outline clast size as a primary criteria along with matrix proportion as secondary criteria for classification (Woodcock & Mort 2008). Fault gouge is classified as a rock which incohesive at present-day outcrop, composed of < 30 % large clasts (> 2 mm in size) and may be non-foliated (random fabric orientation) or foliated. The term incohesive is defined as: *"capable of being broken into component granules with fingers or with the aid of a pen-knife*".

<table>
<tr><th></th><th colspan="2"></th><th colspan="2">non-foliated</th><th>foliated</th></tr>
<tr><td rowspan="3">>30% large clasts >2 mm</td><td colspan="2">75-100% large clasts (>2 mm)</td><td rowspan="3">fault breccia</td><td rowspan="3">dilation breccia (if associated with volume increase)</td><td>crackle breccia</td></tr>
<tr><td colspan="2">60-75% large clasts (>2 mm)</td><td>mosaic breccia</td></tr>
<tr><td colspan="2">30-60% large clasts (>2 mm)</td><td>chaotic breccia</td></tr>
<tr><td rowspan="7"><30% large clasts >2 mm</td><td colspan="2">incohesive at present outcrop</td><td colspan="3">fault gouge</td></tr>
<tr><td rowspan="6">cohesive</td><td>glass</td><td colspan="2">pseudotachylite</td><td></td></tr>
<tr><td>0-50% matrix (<0.,1 mm)</td><td colspan="2">protocataclasite</td><td>protomylonite</td></tr>
<tr><td>50-90% matrix (<0.,1 mm)</td><td colspan="2">(meso)cataclasite</td><td>(meso)mylonite</td></tr>
<tr><td>90-100% matrix (<0.,1 mm)</td><td colspan="2">ultracataclasite</td><td>ultramylonite</td></tr>
<tr><td>pronounced grain growth</td><td colspan="2"></td><td>blastomylonite</td></tr>
</table>

viscous (ductile) deformation

Fig. 5-1: Fault rock classification
adpated from Woodcock & Mort (2008)

In the case of ductile deformation, the fault rock is termed **mylonite**. Mylonites are foliated, highly strained fault rocks produced in viscous shear zones, usually with lineation, shear bands and isoclinal folding. Mylonites are more fine-grained than their host rock resulting in microscale fabrics of dynamic recrystallisation are subgrains, elongated crystals, and a fine-grained matrix with bulged grain boundaries. Mylonites do not appear in the sedimentary rock series of the Jura mountain belt. They are more typical if the deformation temperature is > 250°C, e.g. in the basal thrust zones of the different Helvetic nappes and may be encountered in the crystalline basement underlying the Jura fold-thrust belt. Using the proportion of recrystallised fine-grained crystal matrix, proto- and ultramylonites with matrix contents of < 50 % and > 90 %, respectively, can be defined.

If faulting is seismic and rapid frictional sliding provokes localised melting, the resulting fault rock is termed *pseudotachylite.* It is often characterised by injected veins into the sidewalls and sharp boundaries of the host rock. The pseudotachylite occurs within mm- to cm-wide fault zones consisting of dark glass or microcrystalline and dense material. Such rocks typically form in crustal depths at the brittle-ductile transition (i.e. 10-15 km depth). Pseudotachylite is not expected to occur in the Jura fold-thrust belt.

While the cited classification schemes of Sibson (1977) and Woodcock & Mort (2008) are standards in structural geology, they are not sufficient for describing the variability of fault rocks that result from the deformation of calcareous rocks, marls and shale. Calcareous and shaly fault rocks may be produced by a large variety of distinct mechanisms that result in rock types with distinct hydrogeological and mechanical properties. Processes involved in the formation of calcareous and shaly fault rocks include:

- Rock pulverisation: the process results in strong in-situ grain size reduction and preserves the internal mesoscopic structure of the protolith. Pulverisation appears as an important process in the early stages of calcareous fault rock formation prior to „cataclasis" (Schröckenfuchs et al. 2015).
- Cataclasis: cataclastic flow, which is broadly defined as a deformation in which fracturing forms clasts that frictionally slide past each other and possibly rotate. The clasts progressively decrease in size as cataclasis continues and a foliation sub-parallel to the shear zone boundary may develop in the matrix.
- Hydraulic fracturing: excess pore fluid pressures may lead to the formation of a connected network of tension gashes cutting the host rock and increasing its original volume.
- Dissolution-precipitation creep (DP) deformation: rock deforms by a combination of carbonate solution at pressure solution seams/stylolites and re-precipitation of carbonate in veins and tension gashes. DP deformation is a viscous process not related to fracturing.
- Intracrystalline deformation: viscous (ductile) deformation of calcite may occur at temperatures < 150°, i.e. at temperatures which are commonly associated with the brittle regime (Bauer et al. 2018).

**Fault rock classification.** The complexity of the different processes that may interact during the formation of calcareous and shaly fault rock require a nomenclature that is more detailed than the classifications by Sibson (1977) and Woodcock & Mort (2008). For the description of Nagra's drill cores, the following types of fault rocks should be distinguished:

- **Cataclasite:** Fault rock resulting from cataclasis, i.e. brittle fragmentation of minerals or grains, with rotation of grain fragments, grain boundary sliding, grain flaking and fracturing, grain size reduction, and commonly volume change (Sibson 1977; Peacock et al. 2017) (Fig. 5-2 and Fig. 5-3).
- **Dilation breccia:** Fragmented rock in which there has been a net volume increase during formation; fault rock with angular wall rock fragments surrounded by calcite-filled tension gashes of various orientation and fine-grained matrix consisting of wall rock fragments and calcite cement, frequently showing jigsaw puzzle texture (fitted fabric) (Tarasewicz et al. 2005) (Fig. 5-4 and Fig. 5-5).

- **Fault breccia:** Fault rock composed of fragments of the host rock > 2 mm and 0-10 % matrix composed of fine-grained rock fragments and/or cement (Sibson 1977).
- **Stylolitic breccia:** Fault rock characterised by abundant pressure solution surfaces (stylolites) and the absence of mineralised tension gashes leading to a net volume decrease during formation (Fig. 5-6).
- **Dissolution-precipitation (DP) fault rock**: Fault rock resulting from the combination of carbonate dissolution by pressure solution at stylolitic surfaces and nearby re-precipitation of the dissolved carbonate in tension gashes and fibrous calcite (Fig. 5-7).
- **Layered dissolution-precipitation fault rock:** Fault rock with closely spaced calcite-filled gashes and fibrous slickensides occurring together with stylolitic slip surfaces and clay seams resulting from pressure solution (Fig. 5-8).
- **Gouge, clay gouge:** Fine-grained incohesive (*"capable of being broken into component granules with fingers or with the aid of a pen-knife"*) fault rock mostly consisting of clay minerals.
- **Kakirite:** Unlithified incohesive cataclastic fault rock.

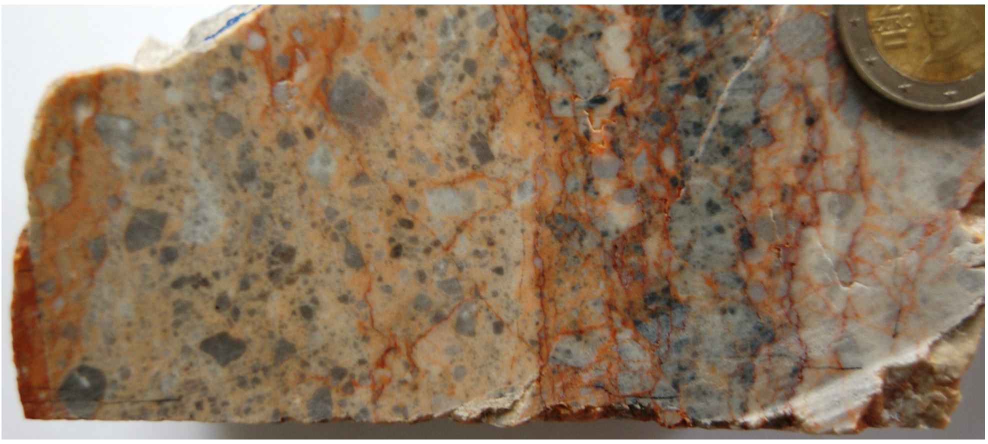


Fig. 5-2: Cataclasite

Layered cataclasite and ultracataclasite (red layer at left end of sample) formed from limestone protolith. SEMP Fault System, Wetterstein Fm., Eastern Alps.


Fig. 5-3: Cataclasite

Cataclasite formed from dolostone protolith. Hauptdolomit Fm., Eastern Alps.

Fig. 5-4: Dilation breccia

Breccia resulting from in-situ fracturing and formation of vein calcite in tension gashes. Note the fitted fabric in the upper right where the original position of grey limestone fragments is still preserved (Doldenhorn nappe, image width = 10 cm).

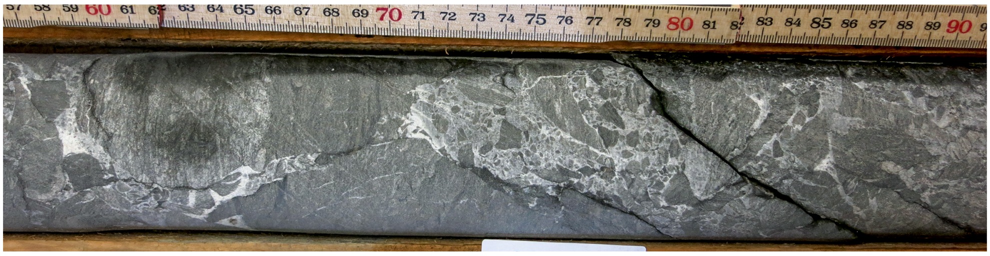


Fig. 5-5: Dilation breccia

Breccia resulting from in-situ fracturing and formation of vein calcite in tension gashes. Fitted fabric is mostly lost due to extensive volume gain. Host rock is Jurassic marly limestone.

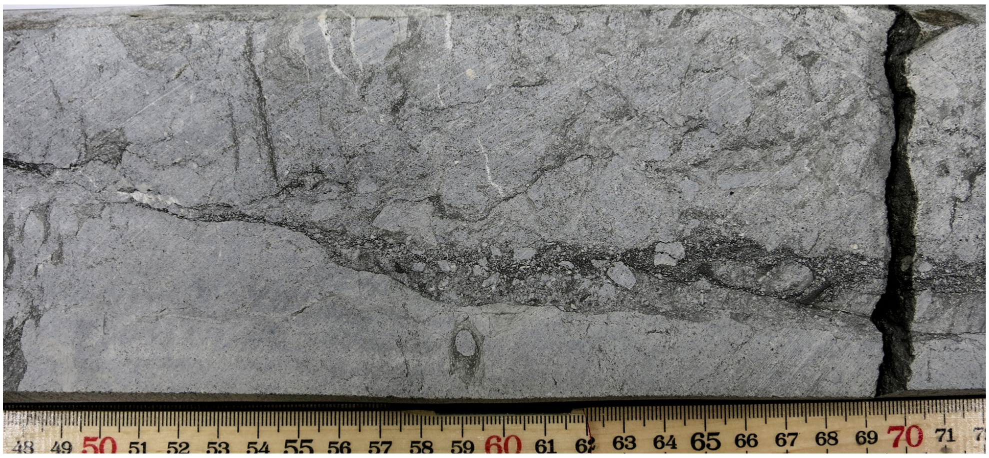


Fig. 5-6: Stylolitic breccia

Breccia resulting from carbonate dissolution along multiple anastomosing dissolution surfaces. Host rock is Jurassic marly limestone.

Fig. 5-7: Dissolution-precipitation (DP) fault rock

Network of reddish clay-decorated dissolution seams and limestone fragments with calcite-filled tension gashes. SEMP Fault system, Eastern Alps.

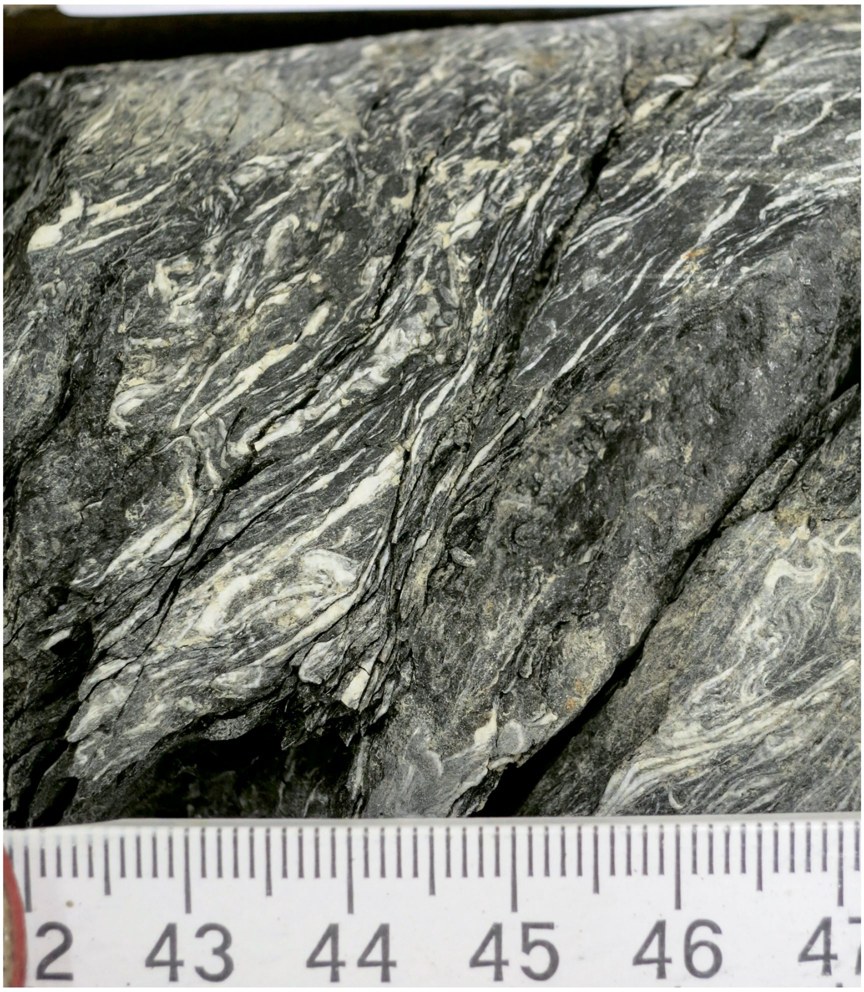



Fig. 5-8: Layered dissolution-precipitation (DP) fault rock

Marl with abundant shaly dissolution surfaces, calcite veins and fibrous slickensides. All types of layers derive from carbonate dissolution and re-precipitation in previously homogeneous marl.

# 6 Kinematic indicators

One of the goals of structural core analyses is the development of a predictive deformation model that explains the structures which characterise the hydrogeological and geotechnical properties of the rock mass. A reliable structural model needs to be based on a comprehensive structural dataset that is not limited to the orientation and classification of fractures and other structures. Additionally, required data include the orientations of fault slickenlines and the determination of shear sense and cross-cutting relations between structures of different age.

The development of a deformation model is clearly beyond the scope of the core description. However, analysis of Nagra's drill cores is expected to include the careful analysis and recording of all data required for the development of a predictive deformation model.

## 6.1 Definition of the sense of shear

The sense of shear between two adjacent blocks of rock is defined as follows (Fig. 6.1-1):

- The relative movement of the hanging wall with respect to the footwall (top down or top up). The hanging wall is the rock above a non-vertical fault or shear zone. The footwall refers to the rock below the fault. Faults with the hanging wall "top up" are denoted as reverse and thrust faults, also caused by compression. Faults with the hanging wall moving down are indicated as normal faults, which are caused by extension of tension. These denotations are used particularly for dip-slip faults and oblique faults with a high dip-slip component.
- In the case of strike-slip faulting along a near vertical fault plane with horizontal or sub-horizontal striation, the sense of shear is defined as "sinistral" ("left-lateral") or "dextral" ("right-lateral"). The denotation refers to the relative movement of the opposite rock mass to left or right, respectively.

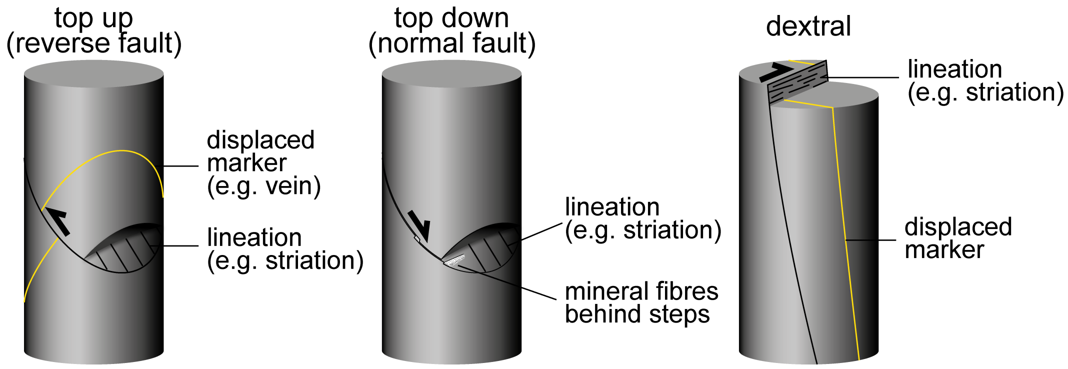



Fig. 6.1-1: Sense of shear

Sense of shear is defined by the movement of the hanging wall. Hanging wall can move upwards or downwards with respect to the footwall. For horizontal slip vectors, sense of shear is defined relative to opposite rock block; dextral if the opposite block moves to the right or sinistral if it moves to the left. Shear sense is determined from indicators such as displaced markers, steps on the fracture plane, mineral fibres grown in pressure shadows, and/or Riedel shears.

## 6.2 Shear sense indicators

Shear sense indicators are discrete features that reveal the direction of displacement along a fault, fault zone or shear zone. Shear sense indicators include (Fig. 6.2-1):

- Displaced markers or layers on opposite blocks of rock. Most useful are planar features that cross the fracture and show an offset along this plane (e.g. bedding, veins)
- Striation on the fracture surface due to abrasive scratching in the direction of displacement (Fig. 6.2-2)
- Steps on the fracture surface facing perpendicular to striation
- Mineral fibres (typically calcite) growing behind steps of the fault plane with directional fibrous growth of minerals in the direction of displacement into opening cracks (slickenfibres); steps on the fracture plane face perpendicular to the striation
- Riedel shears, which are fractures that are orientated oblique to the main fault plane (Fig. 6.2-1). Resulting fabrics on the fault plane are chatter marks, which are small asymmetric steps facing perpendicular to the striation
- The geometry of SC- and SCC'-type shear bands (see Section 3.2)

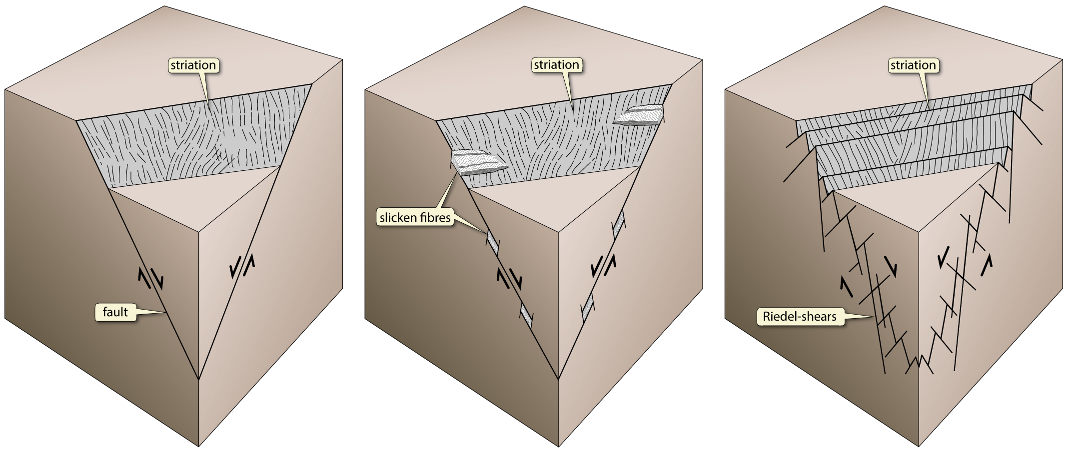



Fig. 6.2-1: Shear sense indicators
Striation, slickenfibres, syn- and antithetic Riedel shears.

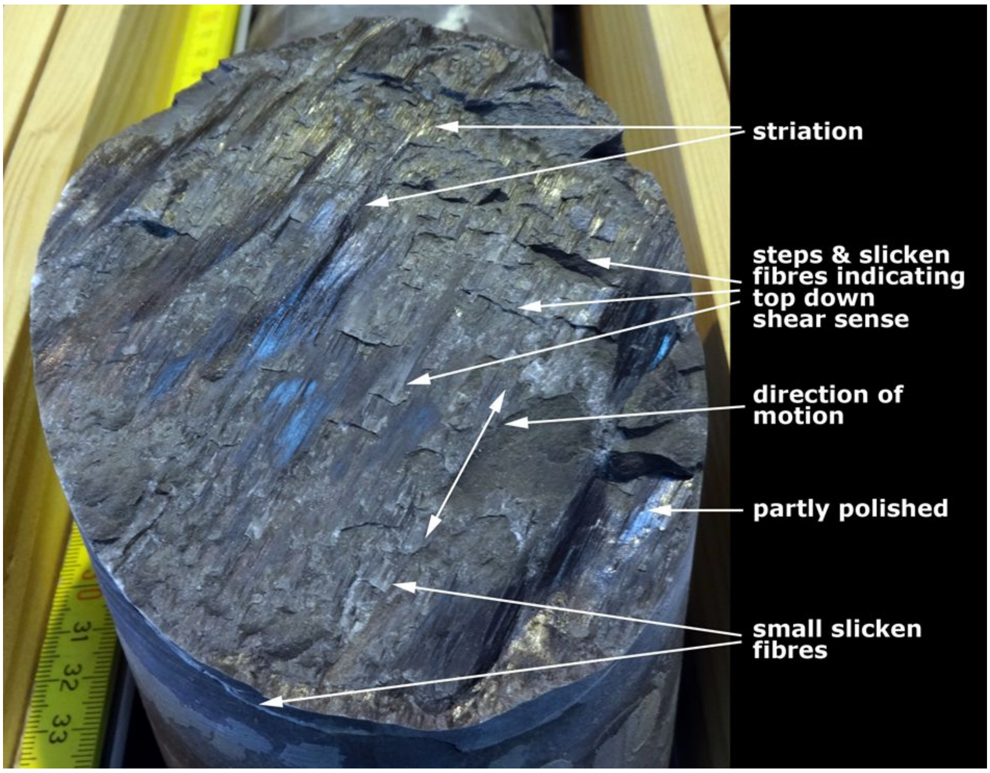



Fig. 6.2-2: Striation on a slickensided fault plane

Striation and partly polished slickensides with steps on the fault surface filled with synkinematic slickenfibres, indicating sense of shear top to lower-left corner of image, Oftringen borehole, 632.20 m.

## 6.3 Displacement

The displacement along a fault is measured from the offset of two originally adjacent points on each side of the slip surface. Fig. 6.3-1 and Fig. 6.3-2 present two such examples of displacement: displaced bedding and veins, respectively. Due to the small size of drill cores, measurements of displacements in cores are mostly limited to core diameter.

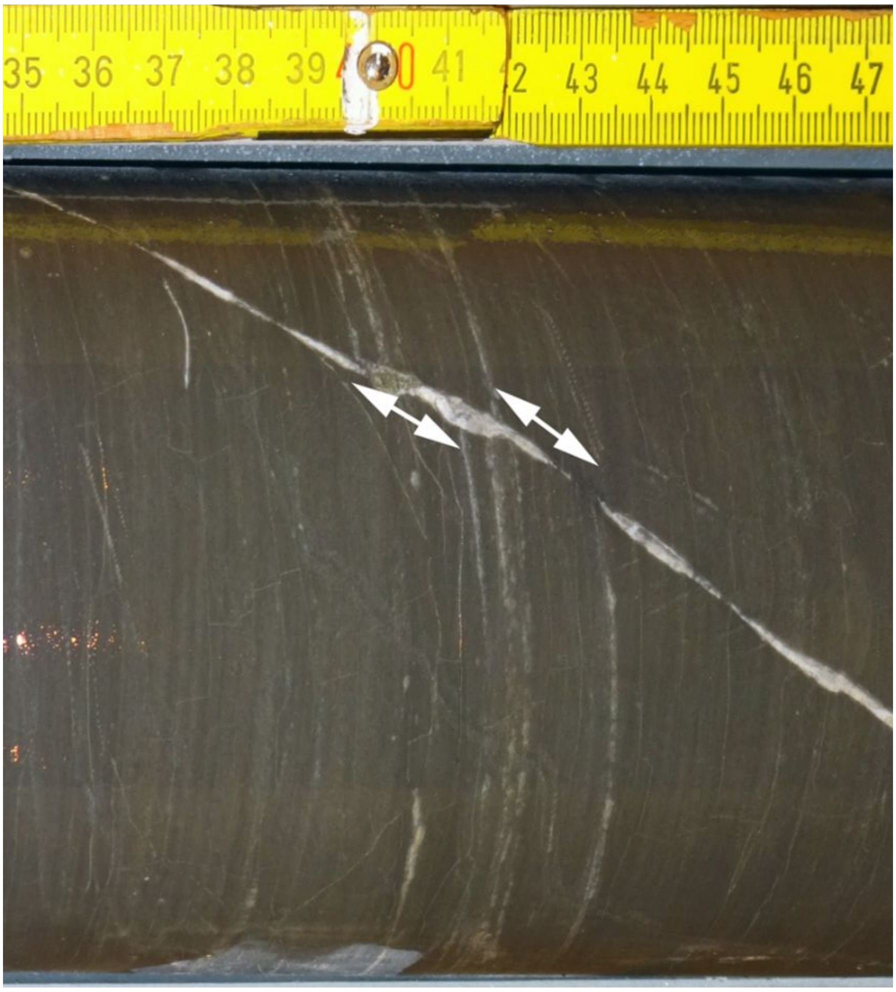



Fig. 6.3-1: Displacement of bedding at a mineralised fault

About 1.5 cm apparent offset of bedding planes with thin light grey layers indicating a normal fault (white arrows). The true offset may be larger depending on the slip vector of the fault, Oftringen borehole, 465.35 m.


Fig. 6.3-2: Displacement of vein

Along two fault planes, the vein is offset (red arrows). The orange arrows mark the displacement of the bright vein within the marl. Sense of shear is sinistral/top-down.

## 6.4 Cross-cutting relations and relative ages of structures

Usually structures form at different time periods and under varying physical conditions (e.g. temperature, stress) resulting in different generations of structures. Relative age relations of structural discontinuities can be determined based on intersections, truncations, and different types of mineralisation, e.g. a younger fault can cut an older vein or fault and displace the opposite vein/fault fragments (Fig. 6.4-1 and Fig. 6.4-2).

The relative ages of structures may also be constrained by observations that indicate the concurrent formation of two types of structures, which are kinematically compatible (e.g. stylolitic solution surfaces and tension gashes; Fig. 6.4-3). Experience shows that unequivocal observations of cross-section relations are rare in drill core analysis. Thus, correct observations of cross-cutting relations are, however, crucial for the development of a deformation model.

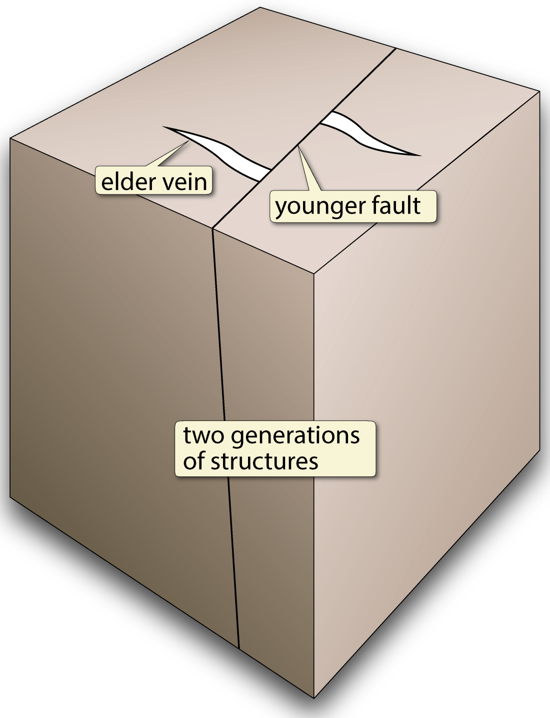



Fig. 6.4-1: Cross-cutting relations
Older vein cross-cutting and being displaced by younger fault.

Fig. 6.4-2: Cross-cutting faults
Fault plane with dip-slip striation (facing towards the observer) cutting older fault. Jurassic marly limestone.

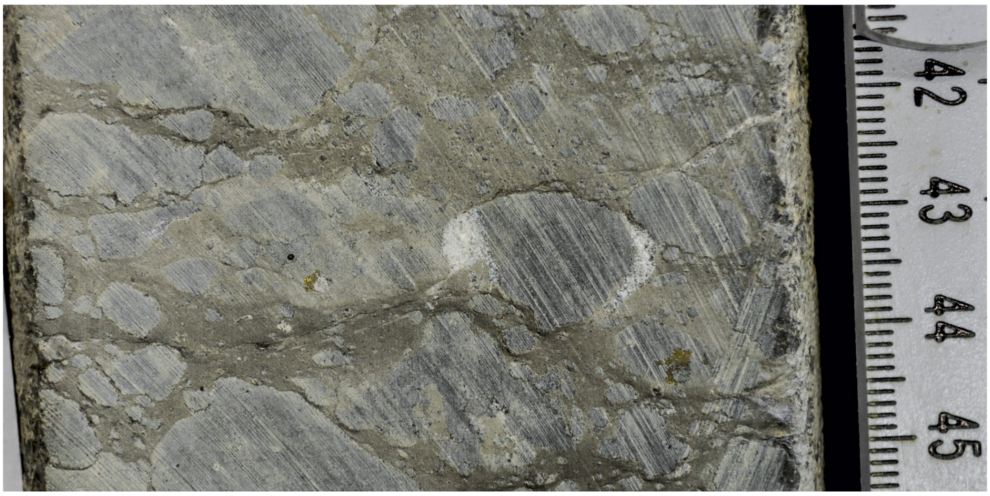



Fig. 6.4-3: Cogenetic structures formed during the same deformation event
Sub-horizontal dissolution seams and calcite-filled tension gashes indicative of vertical shortening and concurrent extension.

## 6.5 Fault geometry

Faults are classified according to the direction of the relative movement between fault blocks (hanging wall and footwall) and the dip of the slip vector (dip-slip versus strike-slip). Three main fault classes can be distinguished: normal, reverse (thrust), and strike-slip faults. The corresponding fault geometries are shown in Fig. 6.5-1. The fault geometry can be defined at all scales.

According to Anderson's law, the three types of faults are associated with different stress systems (Tab. 6.5-1):

In the case of a **normal fault,** the hanging wall has moved down relative to the footwall (extensional fault). Younger rocks are thrust over older ones. The associated stress field is characterised by vertical $S_1$.

In the case of a **reverse fault,** the hanging wall has moved up and over the footwall. Old rocks are thrust over younger ones. If the fault plane is a low-angle **reverse fault** and the hanging wall was thrust onto the footwall, this is termed a **thrust fault** (dip angle less than 30°). The associated stress field is characterised by vertical $S_3$.

If the movement is laterally on a nearly vertical fault plane, the fault is termed a **strike-slip fault**. The sense of the strike-slip displacement is described by the terms sinistral and dextral (Fig. 6.1-1). The associated stress field is characterised by vertical $S_2$.

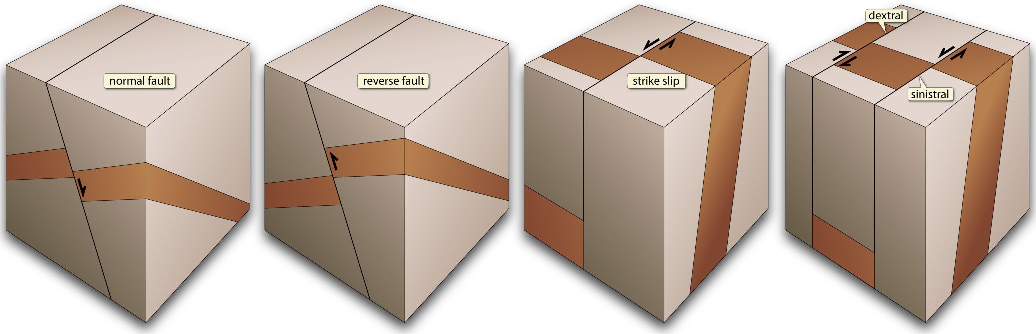



Fig. 6.5-1: Fault geometry

Tab. 6.5-1 Fault regimes and related stress

$S_v$=vertical stress, $S_{Hmax}$=maximum horizontal stress, $S_{hmin}$=minimum horizontal stress, applied to Earth's crust $S_1$ is the max. principal stress, $S_2$ the intermediate principal stress and $S_3$ the least principal stress.

| **Regime** | **Stress** | | |
|---|---|---|---|
| Principal stress in Earth's crust | $S_1$ (greatest) | $S_2$ (intermediate) | $S_3$ (least) |
| Normal fault | $S_v$ | $S_{Hmax}$ | $S_{hmin}$ |
| Strike-slip fault | $S_{Hmax}$ | $S_v$ | $S_{hmin}$ |
| Reverse and thrust faults | $S_{Hmax}$ | $S_{hmin}$ | $S_v$ |

# 7 Mineralisation and opening of structures

## 7.1 Distinguishing between open and closed structures

When structural discontinuities are observed and quantified, the state of structure opening when core is recovered as well as the in-situ structure opening is of interest. The state of opening is relevant for the interpretation of recent and former fluid flow potential. The criteria are given in Tab. 7.1-1, examples are given in Fig. 7.1-1 and Fig. 7.1-2. Tension gashes may be fully cemented (closed), partly cemented (partly open) or uncemented (open). Joints are closed by definition (no measurable offset/opening at the observation scale). An unambiguous determination whether the in-situ structure was closed or open prior to the core drilling may be difficult.

Tab. 7.1-1: Possible criteria for distinguishing open from closed structures

| State of opening in **recovered** rock | | Assumed state of **in-situ/natural** opening | |
|---|---|---|---|
| Open structure | Closed structure | Open structure | Closed structure |
| Core diverges along the structure (cohesion loss)<br>Core breaks into two pieces<br>Evidence for interstice volume (e.g. Opposing fracture surfaces do not fit together, mud filling) | Structural discontinuity is closed (no cohesion loss)<br>Rock kept its integrity across structure<br>No indication for interstice volume | Mud filling in the structure<br>Opposing fracture planes do not fit together<br>Mineral filling, walls coated by idiomorphic crystals (minerals growing into open volume)<br>(same structure can be identified on acoustic borehole image) | Structural discontinuity is closed (no cohesion loss)<br>Structure is sealed |

Based on Tab- 7.1-1, three general types of opening should be distinguished:

- **Closed structure:** is closed in recovered core, the structure is also naturally closed.
- **Artificially opened structure:** was closed prior to drilling but was artificially opened due to drilling and core recovery.
- **Naturally/in-situ open structure:** based on the criteria listed in Tab. 7.1-1, the in-situ state of opening can be assessed. Evidence of idiomorphic mineral growth on fracture planes is regarded as the most reliable criterion.
- **Naturally/in-situ partly open structure:** both fully cemented and open streaks occur along the fracture trace. As such, the aperture and length of the open interval and its connectivity to other open "patches" along the fracture (if observable) need to be described.

Note: Artificial drilling-induced fractures that are always open can be distinguished from natural fractures by careful observation of shape, relative position and orientation of the structure relative to the core.

Fig. 7.1-1: Open and closed structure

Black marked joint is closed (no cohesion loss). White marked joint must be identified as open after core removal. However, the white marked joint was perhaps also closed in-situ.

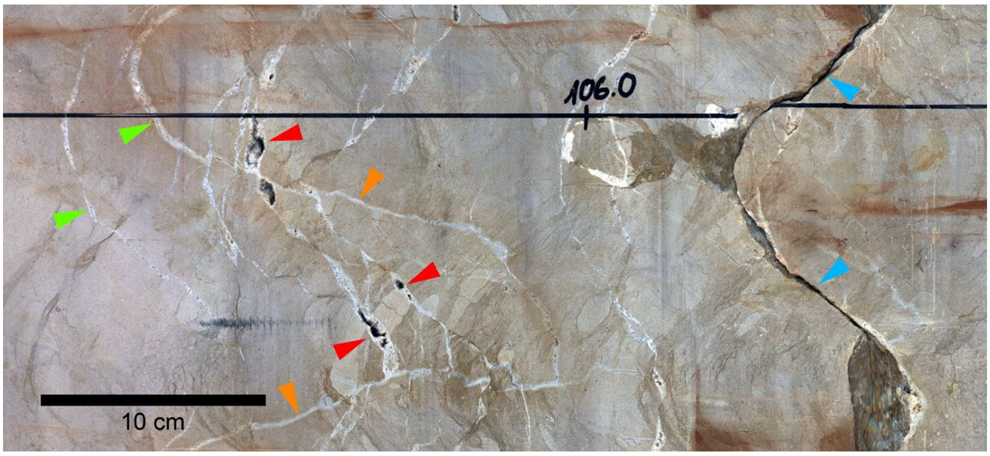



Fig. 7.1-2: Opening and mineralisation status

Different mineralisation types and opening geometries. Red arrows: Partly in-situ opened mineralisation (druse-like cavities). Orange: No mineralisation but bleaching due to fluid flow along fracture planes. Green: Closed mineralised discontinuities. Blue: Open and mineralised structure (most likely not opened in-situ), Malm, Bözberg B2/13 borehole.

## 7.2 Mineralisation/filling of structures

In this manual, mineralisation is a distinct polycrystalline mineral volume that precipitated from an aqueous fluid within a rock (Fig. 7.2-1). The mineral filling can be of one or more minerals. Typical examples are: veins, recrystallised fossils, mineral coating on fracture surfaces, and mineralised faults. Mineralisation is an important indicator for former fluid flow. It reveals that discontinuities have been at least temporarily opened. Mineralisation is an important key for interpreting the history of deformation as well as of fluid flow and geochemical processes. Therefore, observation and quantification of mineralisation is crucial during the structural analysis of cores (Tab. 7.2-1).

Mineralisation and resulting features are a very complex and it is not within the scope of this manual to define and describe all terminologies, geometries, mineral fabrics, and growth processes (e.g. antitaxial or syntaxial). For more details, see Ramsay & Huber (1983) and Passchier & Trouw (1996).

Mineralisation is closely linked with the opening status of a structure (see also Section 7.1). Mineralisation can be predominant in a fault due to the existence of many generations of slickenfibres, veins, and precipitation during faulting or cataclasis.

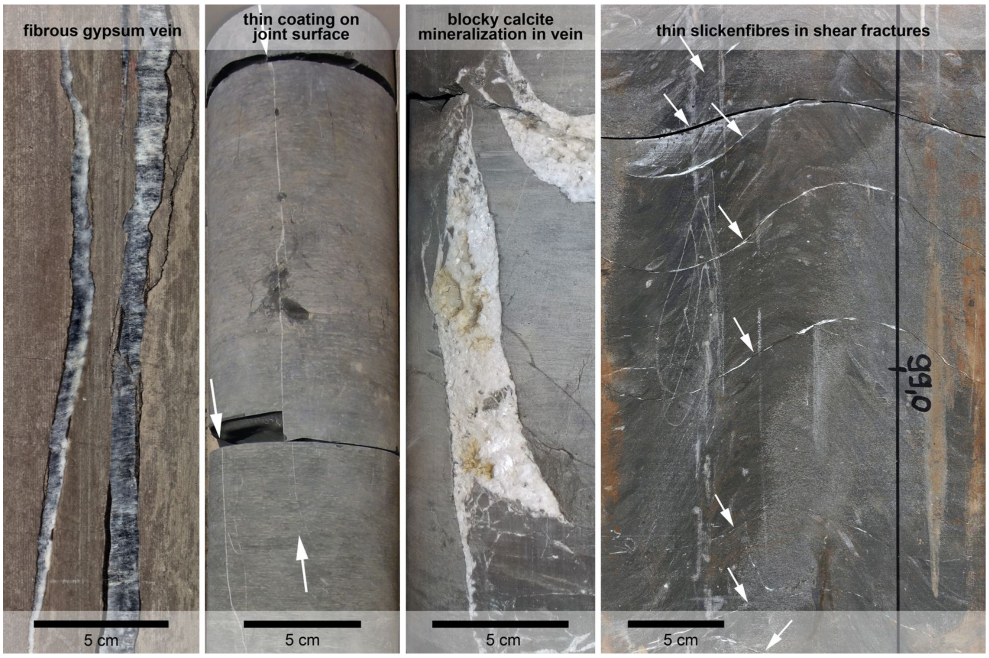



Fig. 7.2-1: Types of mineralisation

Tab. 7.2-1: Mineralisation parameters

The following mineralisation parameters should be described and quantified in the case of a general core analysis:

| **Parameter:** | **To define:** | **Additional comments:** |
|---|---|---|
| Mineralisation | Visible yes/no | Is there any mineral filling within the discontinuity (e.g. Fault, tension gash/vein)? |
| Completness of mineralisation | Completly filled; partly open; druse-like cavities | |
| Mineralisation width, aperture | Measured in mm | Mean and max. Mineralisation width perpendicular to fracture plane and width of open or partly open vein cavities |
| Mineralogy | Define minerals | Most common minerals are: calcite, quartz, clay minerals, pyrite |
| Geometry (macroscopic), coincidence with other observations of discontinuities | E.g. Planar, lenticular, sigmoidal, or irregular shaped;<br>Sharp, rough, or smooth boundaries;<br>Pressure fringes; recrystallised fossil | The 3d shape of the complete discontinuity as well as the shape of the interface to the host rock is of interest |
| Geometry of mineral grains (µm to mm scale) | **Blocky** (= equidimensional & randomly orientated crystals)<br>**Elongated crystals** (= aligned and moderately elongated crystals, length/width ratio up to 10)<br>**Fibrous** (= much higher length-width ratio than for elongated crystals, aligned crystals, approximately with same shape) | The microscopic morphology relates to the texture and shape of crystals inside the mineralised structure. It is a result of abrupt or periodic/continuous opening, the fluid pressure, changing kinematics of deformation, changing orientation of stress field, and/or the geochemical composition of fluid, etc. |
| Growth morphology | (changing) **direction** of long axis of crystals<br>**Syntaxial** (= latest precipitated crystals are located at the median plane, while oldest/first precipitated crystals are located at mineral – wallrock contact → only one growth plane)<br>**Antitaxial** (= usually mineralogy of vein material differs from host rock; usually fibrous; two growth surfaces at outer margins of vein, youngest crystals are located outside and oldest in the middle of the vein → median plane marked by line of wallrock inclusions)<br>**Symmetric** or **asymmetric** crystal fabric | Elongated or fibrous crystals represent direction of growth. Changes in direction of crystals' long axis reveal changes in growth direction (stress field, opening). Relicts/inclusions of host rock in the mineralisation can indicate the opening surface |

## 7.3 Thickness/aperture of discontinuity

The thickness of a planar structural discontinuity is defined by the offset of two opposite surfaces of the host rock (Fig. 7.3-1), while the aperture describes the width of the open structure (Fig. 7.3-2). The thickness/aperture is measured perpendicular to the opposing fracture surfaces. The thickness of a vein is defined by the averaged maximum width of vein mineralisation, likewise measured perpendicular to the two opposing surfaces of the host rock.

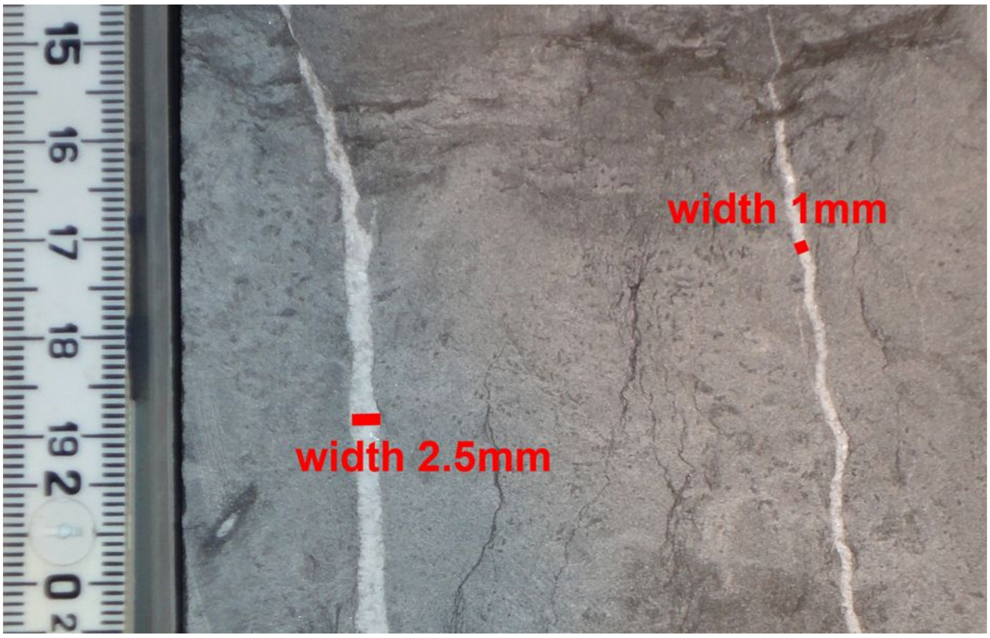



Fig. 7.3-1: Thickness of calcite-filled tension gashes
Two veins with 2.5 and 1 mm thickness.

Fig. 7.3-2: Opening of partly cemented tension gash
Open gash with about 4 mm aperture, Hauptdolomit Fm., Eastern Alps.

# 8 Spatial and geometric aspects of structural description

## 8.1 Depth of structure

All types of structures are recorded quantitatively along a scanline coincident with the core axis. The depth of a single planar structure (e.g. a fracture plane) is defined by the depth of the point where the discontinuity intersects the core longitudinal centreline Fig. 8.1-1). For steeply dipping planes, depth should be determined halfway between the top and the base of the intersection ellipse of the structure. If the structure or a structure zone extends several centimetres to metres in width, the structure top and base which cross-cut the core centreline are defined.

The depth of the structure is defined as labelled on the core, starting with 0 metres at ground level. Measured core depth is usually not equal to logging depth. Experience has shown that misfits of depths may reach up to several metres in deep boreholes. It is therefore necessary to correlate cores with geophysical logs, correlating structures which are observed in both core and image log and establishing a correlation between core and (image) log depths.

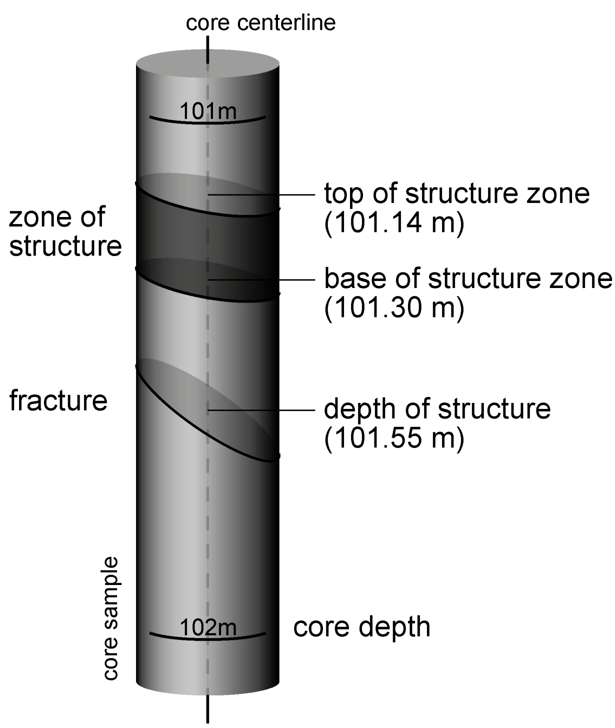



Fig. 8.1-1: Determination of structure depth

Depth of a single planar discontinuity is measured at the intersection of the core centreline and the planar discontinuity. Likewise, the depth of a structure zone is defined by the top and base of the zone.

## 8.2 Orientation of planar structures

Structural core analysis is performed on re-oriented cores to develop a comprehensive database of discontinuities in the rock mass. Aims are to:

- define the true orientation of structures for kinematic analyses using brittle structural geology techniques
- complement structures not imaged by logs for a comprehensive analysis of fracture density
- remove fake fractures, which are interpreted from logs that do not appear in cores

For the analysis, cores are re-oriented to their true orientation using dip data from image logs. The procedure requires an unequivocal correlation of at least one structure which is observed in both core and image, and the establishment of a correlation between core and image log depths (Fig. 8.2-1). If the observed fracture is not shown by the image log (or not interpreted), any available structure with known orientation should be used to re-orient the core and measure the true orientation of the structure under consideration.

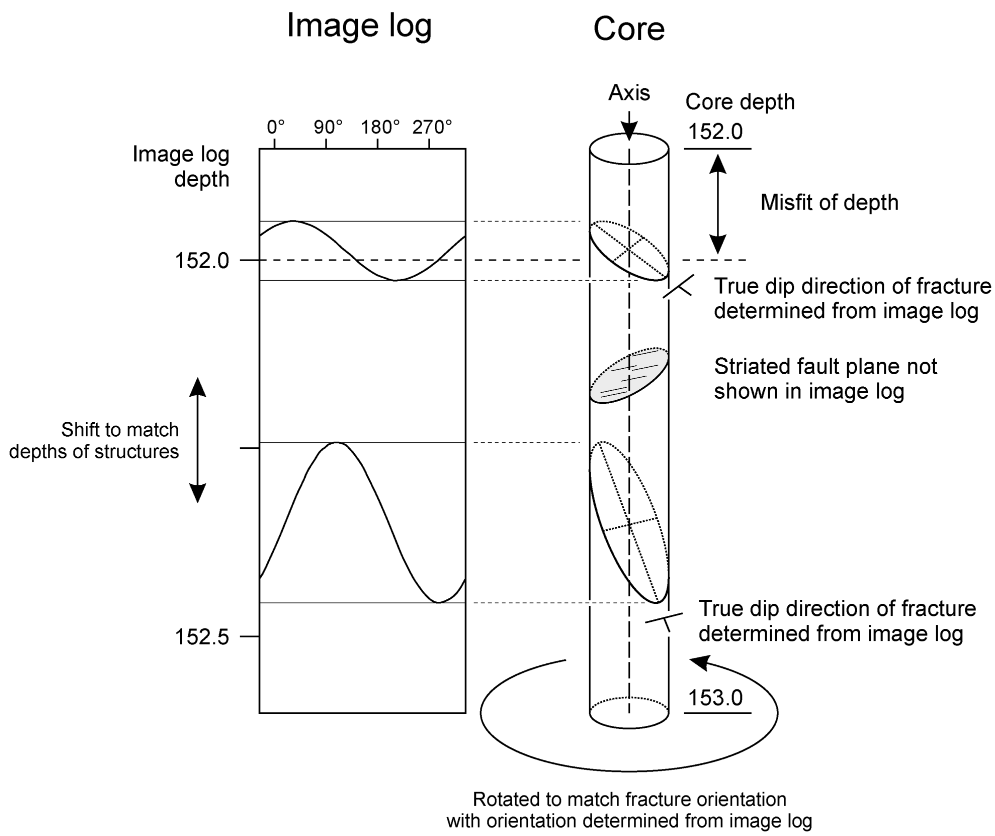



Fig. 8.2-1: Correlation of logging depth and core depth

Sketch illustrates the procedure for correlating the drill core with image log and orienting core to true north using unambiguously correlated structures.

The true orientations of structures cannot be determined in cases where no geophysical borehole logs are available or where an unequivocal correlation between core and image log is not possible. In such cases, only the dip of the structure in relation to the core axis or the orientation relative to bedding can be measured.

## 8.3 Orientation of fault striation

For describing the orientation and shear sense of striations on fault planes, which cannot be properly re-oriented to their true orientation, a classification discriminating between strike-slip, oblique slip and dip-slip should be used (Fig. 8.3-1). The limits between strike-slip and oblique slip are set at pitch angles of ± 15°, the conventional limits between oblique slip and dip-slip are set at pitch angles of ± 75°. The pitch angle of a lineation is defined as the angle between the strike line of the fault plane and the lineation.

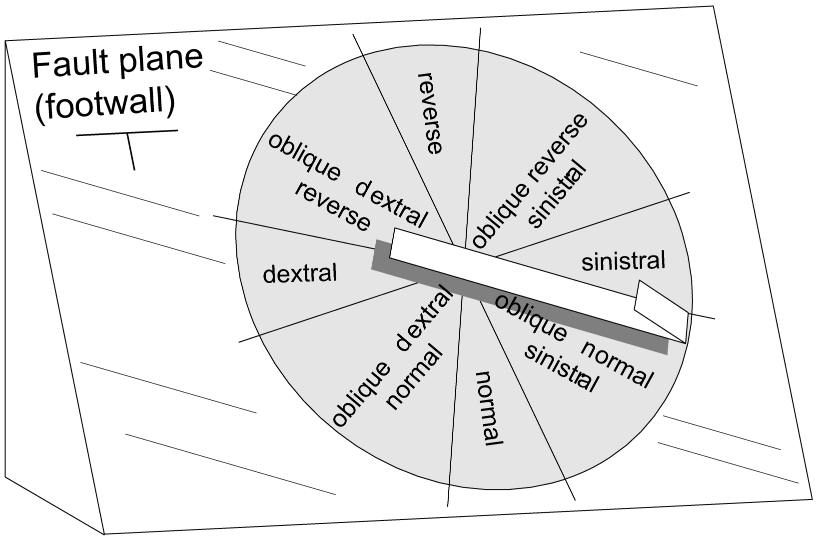



Fig. 8.3-1: Relative orientation of fault striation

# 9 Natural vs. artificial fractures

Depending on the load on the drill bit, mud weight and rock properties, drilling-induced fractures develop during or shortly after drilling. Three main types can be distinguished: Core discing, centreline fractures and petal fractures (Fig. 9-1). All types resemble each other in several aspects: they are always open, usually not mineralised, show no shear indications and show strict geometric relations with respect to the orientation of the core axis.

In contrast, natural structures originating prior to drilling often show typical features such as mineralisation, shear indications, or offsets of displaced markers. They are not restricted to the core space and extend widely in the bedrock. Natural structures can be naturally open or closed. Additionally, natural structures can be artificially opened due to drilling or core recovery. Criteria are given in Section 7.1.

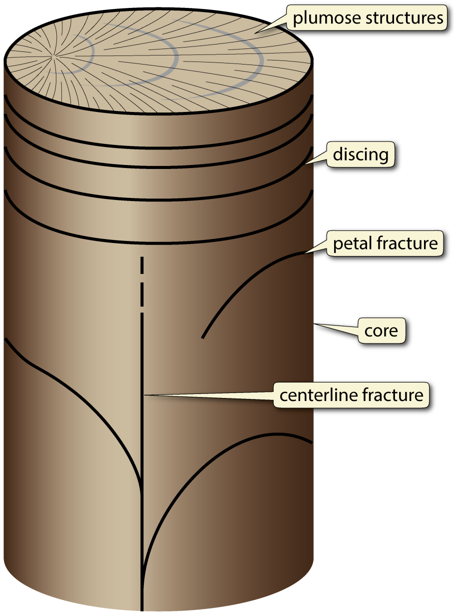



Fig. 9-1: Artificial drilling-induced fractures

Three main drilling-induced fractures can be distinguished: Discing with fracture planes orientated almost perpendicular to the core long axis, petal fractures that bend from the core rim into the core centre, and centreline fractures that split the core in half along the core centreline.

# 10 Glossary and definition of terms

| English | German | Definition |
|---|---|---|
| Alteration | Alterationen | Rims (mm to cm wide) of different coloured rock mass along discontinuities. Alteration is a chemical reaction between the host rock and circulating fluid in the discontinuity. |
| Aperture | Öffnungsweite | The width of an open structural discontinuity measured in the direction perpendicular to the two opposite surfaces. |
| Bedding | Schichtung | Separates two beds of sediments or sedimentary rocks, and its existence is determined during the deposition of the beds. |
| Brittle deformation | Spröde Verformung | The failure of rock by fracturing and loss of cohesion. Mohr-Coulomb type brittle deformation processes are independent of strain rate and temperature. The resulting features are faults, fault zones, joints or veins. |
| Cataclasite | Kataklasit | Fault rock resulting from brittle fragmentation of minerals or grains, with rotation of grain fragments, grain boundary sliding, grain flaking and fracturing, grain size reduction, and commonly volume change (Sibson 1977; Peacock et al. 2017). |
| Centreline fracture | Zentralaxiale Risse | Drilling-induced fracture that typically splits a core approximately in half. |
| Clay gouge | Störungston | Fine-grained fault rock mostly consisting of clay minerals |
| Closed structure | Geschlossene Struktur | A structural discontinuity that has kept its cohesion and shows no opening at the observation scale. |
| Concordant | Konkordant | The discontinuity is orientated subparallel to the bedding. |
| Core discing/saddle structure | Kern-Disking/Sattel Struktur | The formation of discs of relatively uniform thickness which fracture on surfaces approximately normal to the axis of the core. |
| Core sample | Bohrkern | Cylindrical rock sample derived from core drilling. |
| Core scanner | Kernscanner | 360° unwind of the core mantle for data archiving and data analysis. |

| English | German | Definition |
|---|---|---|
| Damage zone | Zerrüttungszone | The initiation, propagation, interaction and build-up of slip along faults, creating a volume of deformed wallrock around a fault. Damage zones are frequently characterised by a gradual decrease in deformation with distance from the master fault/fault core (Peacock et al. 2017). |
| Deformation | Verformung | Change in shape and orientation of objects or volumes of rock from an initial to a final state (Paschier & Trouw 1996). |
| Depth of structure | Strukturteufe | The intersection point of the structure and the core axis. |
| Dextral | Dextral | Notation of shear sense referring to a dextral fault. |
| Dilation breccia | Dehnungsbreccie | Fragmented rock in which there has been a net volume increase during formation; e.g., fault rock with angular wallrock fragments surrounded by calcite-filled tension gashes of various orientation and fine-grained matrix consisting of wallrock fragments and calcite cement, frequently showing jigsaw puzzle texture (fitted fabric) (Tarasewicz et al. 2005). |
| Dip/azimuth of structure | Strukturorientierung | The orientation of a discontinuity in a core is defined by dip and dip direction. |
| Dip of structure | Einfallen der Struktur | A discontinuity is measured in relation to the core axis (apparent) or in accordance with a Cartesian coordinate system (true). |
| Dip-slip fault | Transpressive oder Transtensive Störungen | The displacement vector subparallel to the dip line of the fault (normal or reverse). |
| Discing | Disc | See "core discing" |
| Discontinuity | Diskontinuität | Mechanical defect, flaw, or plane of weakness in the rock mass without regard to its origin or kinematics. |
| Discordant | Discordant | The discontinuity is orientated unconformable to the bedding. |
| Displacement | Verschiebung | The offset of two originally adjacent points on each side of a fault. |
| Dissolution cavity | Lösungshohlraum | Formed by dissolution of rock (e.g. in evaporite-rich carbonates). |

| English | German | Definition |
|---|---|---|
| Dissolution-precipitation fault rock | N/A | Fault rock resulting from the combination of carbonate dissolution by pressure solution at stylolitic surfaces and nearby re-precipitation of the dissolved carbonate in tension gashes and fibrous calcite. |
| Drilling-induced fractures | Künstliche Risse | Collective term for fractures created by forces associated with drilling and coring procedures Depending on load on drill bit, mud weight and rock properties, drilling-induced fractures develop during drilling, or shortly thereafter. Based on the aperture, fracture surface, and geometric relationships, drilling-induced fractures can be distinguished from natural fractures. Drilling-induced fractures are always open and never mineralised. |
| Druse/geode | Druse/Geode | Rock cavity that is partially mineralised with walls coated by idiomorphic minerals, usually within open fractures or other voids (e.g. fossil shells). |
| Ductile deformation | Duktile Verformung | Deformation leading to permanent changes in the shape of rocks without loss of cohesion. In viscous deformation, rock strength depends on both temperature and strain rate. |
| Fault | Verwerfung | See fault plane or fault zone. |
| Fault breccia | Störungsbreccie | Fault rock composed of fragments of the host rock and 0-10 % matrix composed of fine-grained rock fragments and/or cement (Sibson 1977). |
| Fault core | Störungskern | Fault cores that are part of a fault zone characterised by volumes of newly formed fault rocks typically bounded by sub-parallel margins or fault planes and/or extremely dense networks of kinematically compatible faults (e.g. sub-parallel faults with similar slip direction and identical shear sense). |
| Fault gouge | Gesteinsmehl | Fault rock which is incohesive at present-day outcrop, composed of < 30 % large clasts (> 2 mm in size); fault gouge may be non-foliated (random fabric orientation) or foliated (Woodcock & Mort 2008). |
| Fault plane | Störungsfläche | Planes of shear failure, i.e. planes along which there has been movement parallel to the plane (Peacock et al. 2017). |

| English | German | Definition |
|---|---|---|
| Fault zone | Störungszone | Zone having a volume that includes interacting and linked fault segments, densly fractured rock and/or fault rocks; zones are typically bounded by sub-parallel margins or fault planes (modified from Peacock et al. 2017). |
| Fold | Falte | One or a stack of originally flat and planar surfaces, such as sedimentary rocks, that are bent or curved due to applied external stress. Folds appear at various scales and shapes. |
| Foliation | Foliation | Planar fabric element that occurs penetratively on a mesoscopic scale in rock. Primary foliation includes bedding (Paschier & Trouw 1996). |
| Fracture | Bruch | General term for structure without preserved evidence for the mode of fracturing, i.e. it is applicable to structures formed by extension or shear; fractures can include approximately planar discontinuities such as dykes, faults, joints and veins (Peacock et al. 2017). |
| Fracture density | Strukturdichte | Numerical value that reflects a quantitative measure of the abundance of fractures in rock mass (e.g. fractures per metre, fracture area per rock volume). |
| Generations of structural discontinuities | Strukturgenerationen | Chronology age of structural discontinuities determined based on intersections, truncations and type of mineralisation. |
| Geode | Geode | See "druse" |
| Geophysical borehole logs | Geophysikalische Bohrlochlogs | Recording of physical rock properties in the borehole. |
| Gouge | Gesteinsmehl | See "clay gouge" |
| Induced fracture | Induzierter Bruch | Collective term for fractures created by forces associated with the drilling, coring, handling and processing. |
| Joint | Kluft | A barren, closed fracture on which there is no measurable slip or dilation at the scale of observation. If any mineral fill, including crystal growth fibres, is visible, the structure is better called a vein (Hancock 1985). |
| Kakirite | Kakirit | Unlithified cataclastic fault rock. |
| Layered DP fault rock | N/A | Fault rock with closely spaced calcite-filled gashes and fibrous slickensides occurring together with stylolitic slip surfaces and clay seams resulting from pressure solution. |

| English | German | Definition |
|---|---|---|
| Lineation | Lineation | Linear fabric element that occurs penetratively on the mesoscopic scale in a rock. Striation and fibres are not normally considered to be lineations since they do not occur penetratively on the mesoscopic scale (Paschier & Trouw 1996). |
| Mineralisation | Mineralisation | The precipitation of minerals in a discontinuity (e.g. cavity, vein, slickenside). |
| Mirror-like fault plane | Spiegelharnisch | Smoothed, polished or shiny fault plane. |
| Mylonite | Mylonit | Strongly deformed rock from a ductile shear zone with a planar foliation and usually with a stretching lineation (Paschier & Trouw 1996). |
| Normal fault | Abschiebung | Fault that moved the hanging wall down relative to the footwall ($\sigma_V > \sigma_H > \sigma_h$). |
| Open pore | Offene Pore | Isolated open volume, e.g. within a fossil shell or at a releasing fault bend. |
| Open structure | Offene Struktur | Structural discontinuity containing open pore volume. |
| Petal fracture | Randliche Blattbrüche | Drilling-induced fracture with convex-up geometry cutting a core downwards starting from its perimeter. Petal fractures form immediately ahead of the drill bit as a result of excessive bit weight during coring. They propagate downhole. |
| Plumose structure | Plumose Struktur | Relief pattern on fracture surface similar to a feather, indicating the growth of cracks in fine-grained rocks. |
| Recrystallisation | Rekristallisation | Rearrangement of crystalline matter to a modified set of crystals by migration and modification of grain boundaries (Paschier & Trouw 1996). |
| Reverse fault | Aufschiebung | Fault moving the hanging wall up relative to the footwall ($\sigma_H > \sigma_h > \sigma_V$). |
| Rock Quality Designation | RQD | Provides a quantitative estimate of rock mass quality from drill core logs. It is defined as the percentage of intact core pieces longer than 100 mm in the total length of core (Deere 1966). Drilling-induced fractures are also considered in the calculation of the RQD. |

| English | German | Definition |
|---|---|---|
| Schistosity | Schieferung | Secondary foliation defined by preferred orientation of equant fabric elements in a medium to coarse-grained rock . Individual foliation-defining elements (e.g. micas) are visible with the naked eye (Paschier & Trouw 1996). |
| Sense of shear | Schersinn | Direction of movement of volumes of rock adjacent to a fault or shear zone. |
| Set | Schar (von Strukturen) | Group of fractures of the same type and similar orientation in a volume of rock. |
| Shear band | Scherband | Minor shear zone; planar zone of relatively intense deformation in which progressive deformation is non-coaxial (Paschier & Trouw 1996). |
| Shear band, SCC'-type | SCC'-Scherband | Minor shear zone containing two planar fabrics that can be divided into a sigmoidal penetrative foliation (S-planes) and discrete planar shears that displace the foliation (C and C' surfaces) (Blenkinsop & Treloar 1995). |
| Shear band, SC-type | SC-Scherband | Minor shear zone with fabric consisting of C-type shear band cleavage and S-planes. S-planes define a foliation that is cut by C-type shear band cleavage or C-planes (Paschier & Trouw 1996). |
| Shear indicator | Scherindikatoren | Structure with a monoclinic symmetry that can be used to find the sense of shear in a rock (Paschier & Trouw 1996). |
| Shear zone | Scherzone | Planar zone of relatively intense deformation in which progressive deformation is non-coaxial (Paschier & Trouw 1996). |
| Sinistral | Sinistral | Notation of shear sense referring to a sinistral fault. |
| Slickenside | Rutschharnisch | Striated fault surface. |
| Strain | Verformung | Tensorial quantity describing change in shape; a strain situation is commonly represented as an ellipsoid, compared with an unstrained situation represented by a sphere (Paschier & Trouw 1996). |
| Stress | Spannung | Tensorial quantity with six independent variables describing the orientation and magnitude of force vectors acting on planes of any orientation at a specific point in a volume of rock (Paschier & Trouw 1996). |

| English | German | Definition |
|---|---|---|
| Striation | Striemung | Linear stripes or scratches on a fault plane, formed by the movement on the fault (Paschier & Trouw 1996). |
| Strike-slip fault | Seitenverschiebung | Subvertical fault with subhorizontal slip vector (sinistral or dextral). |
| Stylolite | Stylolith | Irregular, commonly jagged surface in a rock formed by local removal of material by pressure solution (Paschier & Trouw 1996). |
| Stylolitic breccia | Stylolithische Breccie | Fault rock characterised by abundant pressure solution surfaces (stylolites) leading to a net volume decrease during formation. |
| Stylolitic fault plane | Stylolithische Störungsfläche | Fault plane with dissolution seams and stylolites that bear columns that are oblique or parallel to the plane (modified from Hancock 1985). |
| Synkinematic calcite fibres | Synkinematische Kalzitfaser | Fibrous calcite along a fault surface, subparallel to the fault and parallel to the direction of movement (Paschier & Trouw 1996). |
| Vein | Ader | Extensional fracture filled by secondary mineral crystallisation. |
| Tension gash | Zerrspalte | Vein formed by dilatation; tension gashes may be fully cemented (vein), partly cemented (partly open) or open (Paschier & Trouw 1996). |

# 11 References

Barton, N. (1976): The shear strength of rock and rock joints. Int J Rock Mech Min Sci & Geomech Abstr 13/9: 255-279.

Barton, N. & Choubey, V. (1977): The shear strength of rock joints in theory and practice. Rock mechanics 10/1–2: 1–54.

Bauer, H., Rogowitz, A., Grasemann, B. & Decker K. (2018): Intracrystalline deformation of calcite in the upper brittle crust. Geology, 46: 375-378.

Bauer, H., Schröckenfuchs, T. & Decker K. (2016): Hydrogeological properties of fault zones in a karstified carbonate aquifer (Northern Calcareous Alps, Austria). Hydrogeology Journal, 24: 1147-1170.

Blenkinsop T.G. & Treloar P.J. (1995): Geometry, classification and kinematics of S-C and S-C' fabrics in the Mushandike area, Zimbabwe. J Structural Geology 17/3: n397-408.

Deere D. & Miller R.D. (1966): Engineering classification and index properties for intact rock. University of Illinois, Technical Report No. AFWL-TR-65-116.

Deere, D. (1989): Rock quality designation (RQD) after 20 years. U.S. Army Corps Engrs Contract Report GL-89-1. Vicksburg, MS: Waterways Experimental Station.

Hancock, P.L. (1985): Brittle microtectonics: principles and practice. J Structural Geology 7/3-4: 437-457.

Passchier, C.W. & Trouw R.A.J. (1996): Microtectonics. Springer, 289 pp.

Peacock, D.C.P. et al. (2017): Glossary of fault and other fracture networks. J Structural Geology 92: 12-29.

Ramsay, J.G. & Huber, M. I. (1983): The Techniques of Modern Structural Geology. Volume 1: Strain Analysis. London, Orlando: Academic Press.

Schröckenfuchs, T., Bauer, H., Grasemann, B. & Decker K. (2015): Microstructural investigations of rock pulverization and localization of a strike-slip fault zone in dolomite rocks (Salzach-Ennstal-Mariazell-Puchberg fault, Austria). Journal of Structural Geology, 78: 67-85.

Sibson, R.H. (1977): Fault rocks and fault mechanisms. J Geol Soc London 133: 191-213.

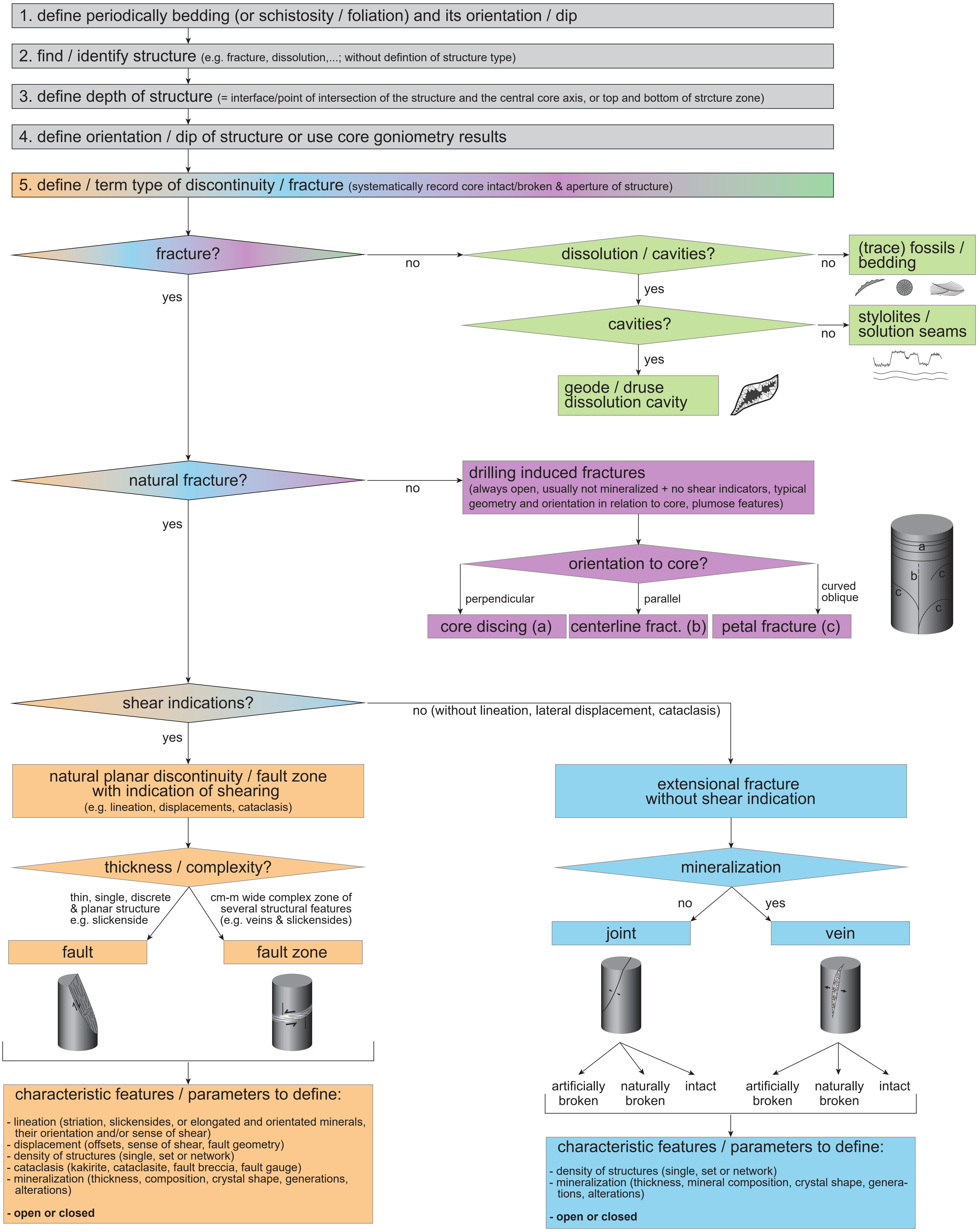
Tarasewicz, J.P.T., Woodcock, N.H. & Dickson, J.A.D. (2005): Carboate dilation breccias: Examples from the damage zone to the Dent Fault, northwest England. Geological Society of America Bulletin, 117, 736-745.

Woodcock, N.H. & Mort K. (2008): Classification of fault breccias and related fault rocks. Geological Magazine 145.

# Appendix A

## Flow-chart for the structural geological analysis

# Flow-chart for the structural geological analysis




| | | |
|---|---|---|
| **nagra** | | **NAB 19-12** |
| Flow-chart for the structural geological description of rocks in Northern Switzerland | | |
| | February 2019 | **APPENDIX A** |

# Appendix B

## Wellsite structural core analysis: Template and explanatory notes

# Wellsite Structural Core Analysis

Scale 1:15

| Borehole: | Depth: | From | To | Analyst / Company: | Date: | Sheet: | RQD: |
|---|---|---|---|---|---|---|---|

| No. | Depth | | | Bed. | Structure | | | | | *Properties* | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Consecutive no. of structure | Depth MD / Top MD [m.cm] | Bottom MD [m.cm] | **Lithology** | Angle with core axis [°] | Type (1) | Angle with core axis [°] | Angle with bedding [°] | Parallel to structure no. [°] | Offset observed | Mineralization / Fault Rock (2) | Thickness [mm] | Open / Closed (3) | Width [mm] | Length [mm] | Fracture cond. (4) | (5) |
| | | | | | | | | | | | | | | | | |
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**Legend and abbreviations**

**(1)**

| | |
|---|---|
| J | Joint |
| TG | Vein / tension gash |
| Styl | Stylolite |
| FP | Fault plane |
| MirFP | Mirror-like fault plane |
| StylFP | Stylolithic fault plane |
| FZ | Fault zone |
| SB | Shear band, type undefined |
| SC | Shear band, SC-type |
| SCC' | Shear band, SCC'-type |
| S | Schistosity |
| OP | Open pore |
| FdA | Fold axis |
| FdP | Fold plane |
| DIF | Drilling-induced fracture |
| C-DIF | Centerline fracture |
| P-DIF | Petal fracture |
| Disc | Core discing |
| F | Fracture (undifferentiated) |

**(2)**

| | |
|---|---|
| Anhd | Anhydrite |
| CC | Calcite |
| synCC | Synkinematic calcite fibers |
| CL | Clay |
| Dol | Dolomite |
| Gyp | Gypsum |
| StylBrec | Stylolitic breccia |
| Gouge | Clay gouge |
| DP | Dissolution-precipitation fault rock |
| LDP | Layered DP fault rock |
| DB | Dilation breccia |
| FB | Fault breccia |
| Cata | Cataclasite |
| Kak | Kakirite |

**(3)**

| | |
|---|---|
| O [mm] | Open (opening width) |
| P [mm/mm] | Partly open (width/length) |
| C | Closed |

**(4)**

| | |
|---|---|
| B | Broken |
| NB | Naturally broken |
| AB | Artificially broken |
| I | Intact |

**(5)**

| | |
|---|---|
| (no.)O/(no.)Y | Cross-cutting (old/young) |
| dis [cm] | Displacement |
| KA | Karstified |
| JPG | Photo |
| DRW | Drawing |

| cm | Structures | No. | Sample | No. of fracture sets |
|---|---|---|---|---|
| 0 | | | | |
| 20 | | | | |
| 40 | | | | |
| 60 | | | | |
| 80 | | | | |
| 100 | | | | |
| 120 | | | | |
| 140 | | | | |
| 160 | | | | |
| 180 | | | | |
| 200 | | | | |
| 220 | | | | |
| 240 | | | | |
| 260 | | | | |
| 280 | | | | |
| 300 | | | | |
| 320 | | | | |

# Explanatory notes for the template “Wellsite Structural Core Analysis”

February 2019

Dr. Kurt Decker

# Table of Contents



# List of Figures

# 1 Introduction and purpose

NAGRA requires a structural core description at the drill site prior to the removal of samples from the core material and prior to a dedicated and detailed structural assessment of the cores in the storage facility.

Structural descriptions at the drill site should, as far as possible, be based on structural geology techniques to record deformation structures which are relevant for the geotechnical and hydrogeological properties of the rock mass. Records should include bedding planes, folds, fault planes, fault zones, shear zones, mineralised tension gashes, open gashes, stylolitic pressure solution surfaces and joints. Besides the occurrence of a certain type of structure, information on fault rock type, fault rock thickness, mineralisation and opening should be recorded.

NAGRA is aware that the core description at the drill site is usually done under operational pressure. Nevertheless, the records are of the utmost importance for providing a comprehensive structural log without any gaps as core intervals sampled for lab analyses will not be available for the dedicated structural analysis.

**Analyses and descriptions on-site should be given the highest priority for description of cored intervals that are sampled for lab analyses and thus not available for further structural investigation.**

Having detailed records on these intervals and less comprehensive data from the remaining core is strongly preferred over high-quality assessments of those core intervals which remain available for subsequent investigations.

# 2 Files and templates

The following files and templates should be used for core analyses on-site and the subsequent electronic documentation of the data:

### Wellsite_Structural_Core_Analysis_TEMPLATE.PDF

Form for obligatory use at the drill site (DIN A3 format). The use of the template is explained in the current document. The form is designed to be completed in writing using one sheet per core interval (usually 3 m).

### Wellsite_Structural_Core_Analysis_TEMPLATE.XLS

Form for obligatory use for electronic data documentation (DIN A4 format). All data for a single borehole should be listed in one file. Contents and format are consistent with the template used in the core storage facility.

The spreadsheet includes the following ***data sheets***:

***Data_to_print:*** Form to be completed for electronic data documentation.

***Abbreviations:*** Annotations and abbreviations used in the document.

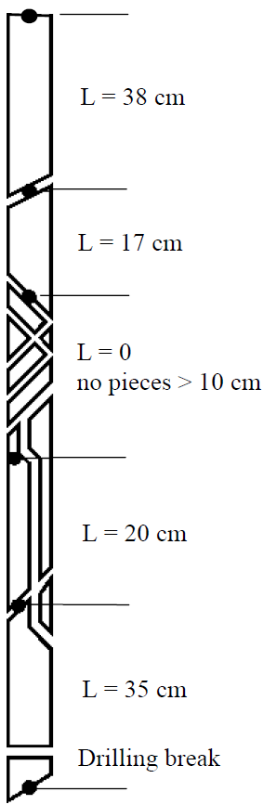
# 3 Explanations to the columns of the template

## 3.1 row [Borehole, etc.]

Insert borehole name, depth interval described in the sheet, identify analyst and date; sheets should be numbered consecutively for each borehole.

## 3.2 row [Borehole, …, RQD]

Estimate the Rock Quality Designation index (RQD; Deer & Miller 1966). The RQD index provides a quantitative estimate of rock mass quality from drill core logs. It is defined as the percentage of intact core pieces longer than 100 mm in the total length of one core section (fragmentation of the cores by fractures). Drilling-induced fractures are also considered in the calculation of the RQD. The procedures for measurement of the length of core pieces and the calculation of RQD are summarised in Fig. 1.




Total length of core run = 200 cms

$$RQD = \frac{\Sigma \text{ Length of core pieces} > 10 \text{ cm length}}{\text{Total length of core run}} \times 100$$

$$RQD = \frac{38 + 17 + 20 + 35}{200} \times 100 = 55\ \%$$

Fig. 1: Definition of Rock Quality Designation (RQD) after Deere (1989)

## 3.3 column [No. – Consecutive no. of structure]

Consecutive number of the recorded structure consisting of a prefix corresponding to the number of the cored interval and a consecutive number. ***Example:*** 78-4 denotes the 4th recorded structure (counted from the topmost of the cored interval) in the cored interval 78. The number is a unique identifier of the structure.

### 3.4 column [Depth – Depth MD / Top MD, Bottom MD]

All types of structures are recorded quantitatively along the scanline of the core axis. The depth of the structure is measured at the point where it cuts the core axis (Fig. 2). For steeply dipping planes, depth should be determined half-way between the top and the base of the intersection ellipse of the structure.

If a zone is recorded (e.g. fault zone, shear band, fracture density class), specify the top (Top MD) and the base (Bottom MD) of the zone in the corresponding columns.

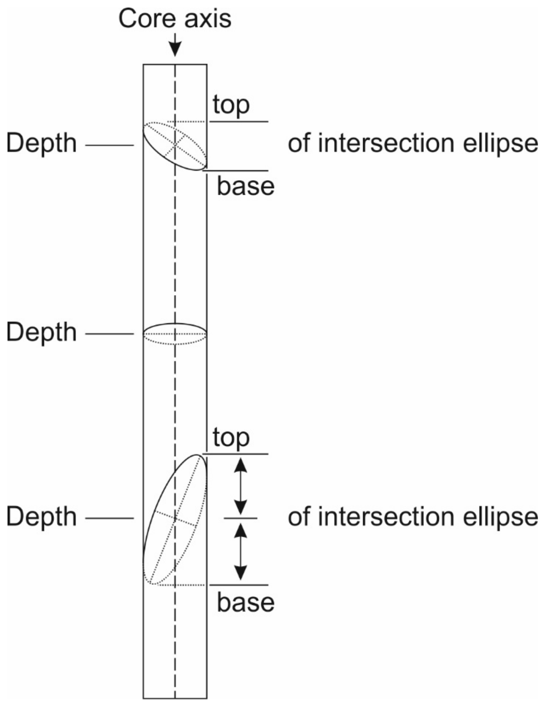



Fig. 2: Depth reference

The depth of a structure is measured from the bisection of the interval between the highest and lowest point of the intersection ellipse.

### 3.5 column [Lithology]

Fill in rock type according to common geological standards.

### 3.6 column [Bed. – Angle with core axis]

Fill in dip of bedding planes. One reading per core metre is sufficient in cases where bedding is constant throughout the core interval.

### 3.7 column [Structure – Type] (1)

Fill in the type of structure using the abbreviations listed in footnote (1) of the template.

### 3.8 column [Structure – Angle with core axis]

Record the angle between the core axis and the structure under consideration.

### 3.9 column [Structure – Angle with bedding]

Fill in the angle between the structure and the bedding planes (only if bedding is not sub-horizontal).

### 3.10 column [Structure – Parallel to structure no.]

List the number (or numbers) of structures which are parallel to the structure under consideration. The data are important for identifying sets of sub-parallel fractures.

### 3.11 column [Structure – Offset observed]

Note with "yes" (Y) or "no" (N) whether offset across the structure is observed or not.

### 3.12 column [Properties – Mineralisation / Fault rock] (2)

List any type of filling, mineralisation or fault rock associated with the structure using the abbreviations listed in footnote (2).

### 3.13 column [Properties – Thickness]

Note thickness of filling, mineralisation or fault rock (if present). Thickness is measured in the direction perpendicular to the plane.

### 3.14 column [Properties – Open / Closed] (3)

Provide information on whether the vein/tension gash is open (displaying a continuous aperture), partly open (displaying discontinuous aperture) or closed at the observation scale (i.e. the naked eye). Also note the width of the aperture and the observed lengths of open streaks for partly open structures.

### 3.15 column [Properties – Core cond.] (4)

Note whether the core is broken naturally or artificially at the structure under consideration or intact. If you cannot specify, if the break occurred naturally or artificially, use broken.

### 3.16 column [Remarks] (5)

List any relevant additional observations such as cross-cutting relationships between two structures, displacement, alteration (e.g. karstification) of fractures, etc.

Structures which are regarded as important in terms of their hydrogeological, rock mechanical or structural implications should additionally be documented in photos and/or sketches (preferably both – photo plus sketch with explanations). Pictures and sketches should be numbered using a unique identifier (to be listed in the template).

Pictures and sketches should preferably be made for structures in core intervals that are sampled for lab analyses and therefore not available for further investigations.

## 3.17 sketch [Structures]

Sketch all observed structures starting from the top of the core interval. The scale of the sketch is 1:15, with the smallest depth interval representing 5 cm and the width of the sketch being equal to 10 cm. The odd scale was selected to plot the standard core interval of 3 m on a single page.

## 3.18 sketch [No.]

Identify each structure by its consecutive number (consisting of a prefix corresponding to the number of the cored interval and a consecutive number) written in the space between the column "Structures" and "Samples".

## 3.19 sketch [Samples]

Sketch the location of core samples removed for lab analyses, including the sample number. The scale of the sketch is 1:15, with the smallest depth interval representing 5 cm and the width of the sketch being equal to 10 cm. The odd scale was selected to plot the standard core interval of 3 m on a single page.

## 3.20 sketch [No. of fracture sets]

The number of fracture sets should be denoted by an integer representing the number of fracture sets, or "R" to denote random (or apparently random) orientation (Fig. 3).

A fracture set is defined as a group of sub-parallel fractures.

The assessment of the number of fracture sets is based exclusively on fracture orientation without considering different classifications of fractures, meaning that:

- sub-parallel joints and fault planes are counted as one set of fractures
- conjugate fault planes or joints are counted as two sets
- fracture networks which lack parallelism are described as "random".

The number of fracture sets can be used to determine the joint set number ($J_n$) and parameters for rock mass classification are based on this number.

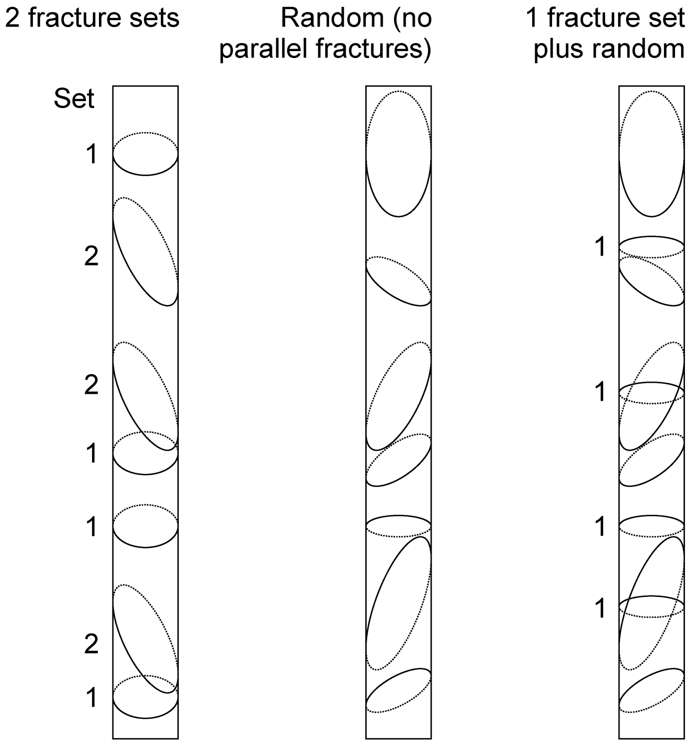



Fig. 3: Definition of the number of fracture sets.

1 and 2 denote different sets of sub-parallel fractures.

# 4 References

Deere D., Miller R.D. (1966): Engineering classification and index properties for intact rock. University of Illinois, Technical Report No. AFWL-TR-65-116

Deere, D. (1989): Rock quality designation (RQD) after 20 years. U.S. Army Corps Engrs Contract Report GL-89-1. Vicksburg, MS: Waterways Experimental Station.

# Appendix C

## Detailed structural core analysis: Template and explanatory notes

# Detailed Structural Core Analysis

| Borehole: | Depth: | From | To | Analyst / Company: | Date: | Sheet: |
|---|---|---|---|---|---|---|

| No. | | Depth | | | | Bed. | | Struc. | | Plane | | Lineation | | | | Properties | | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Consecutive no. of structure | Core orientation line no. | Depth MD / Top MD [m.cm] | Bottom MD [m.cm] | **Correl. with log** | **Lithology** | Dip direction [°] | Dip [°] | Type (1) | Length [cm] (2) | Dip direction [°] | Dip [°] | Azimuth [°] | Plunge [°] | Shear Sense (3) | Shear Sense Q (3a) | Mineralization / Fault Rock (4) | Thickness [mm] | Open / Closed (5) | Width [mm] | Length [mm] | JRC Roughness | Fracture cond. (6) | (7) |
| Core oriented by correlating structure no. | | | | | | to image log depth | | | | | | | | | | | | Depth shift: core depth = image depth | | | | [+/- m.cm] | |
| | | | | | | | | | | | | | | | | | | | | | | | |
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**Legend and abbreviations**

**(1)**
- J — Joint
- TG — Vein / tension gash
- Styl — Stylolite
- FP — Fault plane
- MirFP — Mirror-like fault plane
- StylFP — Stylolithic fault plane
- FZ — Fault zone
- SB — Shear band, type undefined
- SC — Shear band, SC-type
- SCC' — Shear band, SCC'-type
- S — Schistosity
- OP — Open pore
- FdA — Fold axis
- FdP — Fold plane
- DIF — Drilling-induced fracture
- C-DIF — Centerline fracture
- P-DIF — Petal fracture
- Disc — Core discing
- F — Fracture (undifferentiated)

**(2)** To be measured if structure does not cut whole core diameter, or cuts core axis at <20° (long axis of the intersection ellipse)

**(3)**
- Up — Reverse
- Down — Normal
- Dex — Dextral
- Sin — Sinistral

**(3a)**
- 1 — Good
- 2 — Fair
- 3 — Poor

**(4)**
- Anhd — Anhydrite
- CC — Calcite
- synCC — Synkinematic calcite fibers
- CL — Clay
- Dol — Dolomite
- Gyp — Gypsum
- StylBrec — Stylolitic breccia
- Gouge — Clay gouge
- DP — Dissolution-precipitation fault rock
- LDP — Layered DP fault rock
- DB — Dilation breccia
- FB — Fault breccia
- Cata — Cataclasite
- Kak — Kakirite

**(5)**
- O [mm] — Open (opening width)
- P [mm/mm] — Partly open (width/length)
- C — Closed

**(6)**
- B — Broken
- NB — Naturally broken
- AB — Artificially broken
- I — Intact

**(7)**
- (no.)O/(no.)Y — Cross-cutting (old/young)
- dis [cm] — Displacement
- dis>C — Displacement > core diameter
- KA — Karstified
- JPG — Photo
- DRW — Drawing

**(8)** Fracture density classification for or unrestorable disintegrated cores:
- FDC2 — Closely fractured
- FDC3 — Very closely fractured
- FDC4 — Extremely fractured

**Scale 1:10**

| cm | Structures | Lithology | No. | FDC (8) |
|---|---|---|---|---|
| 0 | | | | |
| 20 | | | | |
| 40 | | | | |
| 60 | | | | |
| 80 | | | | |
| 100 | | | | |
| 120 | | | | |
| 140 | | | | |
| 160 | | | | |
| 180 | | | | |
| 200 | | | | |

# Explanatory notes for the template “Detailed Structural Core Analysis”

February 2019

Dr. Kurt Decker

# Table of Contents

## List of Figures

# 1 Introduction and purpose

Structural core analysis uses structural geology techniques to record deformation structures which are relevant for the geotechnical and hydrogeological properties of the rock mass. Data are recorded from bedding planes, folds, fault planes, fault zones, shear zones, mineralised tension gashes, open gashes, stylolitic pressure solution surfaces, and joints. Besides fault orientation and fault kinematics, data on fault rock type, fault rock thickness, mineralisation and fracture roughness are systematically recorded. Core analyses include both qualitative (mineralisation, opening, surface morphology, surface roughness) and quantitative analyses of discontinuities.

In the ideal case, the listed structures are recorded together with their true orientation. This is achieved by core goniometry using image log data and 360° core photographs from the same interval of the borehole (see below).

**To achieve the goals listed below, as many cores as possible should be re-oriented.**

The overall goals of the analysis are summarised as follows:

1. Describe in as much detail as possible the multiphase deformation and stress history of the investigated area starting from Triassic times onwards up to the present-day. The resulting core-derived structural model can be validated by independently derived existing analyses based on surface data. The validated structural model will then serve as a predictive basis for the assessment of the structural conditions in the exploration target, which is not drilled.
2. Describe in as much detail as possible the relationships of lithology / lithofacies to different types of structures and their abundance. Deformation mechanisms strongly depend on rock type, and hydrogeological and geotechnical properties of structures depend on deformation mechanisms. Differences in deformation mechanisms may further lead to strain partitioning between, e.g., limestone and shale.
3. Provide a comprehensive and complete database of all structures with sizes exceeding the core diameter along with a complete set of descriptive parameters defining their geotechnical and hydrogeological properties.
4. Deliver a complete dataset for the determination of the fracture density (P32, measured in $m^2$ per $m^3$ rock) and fracture density classes (in core intervals which are heavily disintegrated and not restorable) for geotechnical and hydrogeological analyses.

# 2 Files and templates

The following files and templates are available for structural core analyses in NAGRA's core storage facility and the subsequent electronic documentation of the data:

### Detailed_Structural_Core_Analysis_TEMPLATE.PDF

Form for necessary use in the core storage facility (DIN A3 format). The use of the template is explained in the current document. The form is designed to be completed in writing using two sheets per core interval (usually 3 m).

### Detailed_Structural_Core_Analysis_TEMPLATE.XLS

Form for necessary use for electronic data documentation (DIN A4 format). All data for a single borehole should be listed in one file. Contents and format are consistent with the template used to note data in the core storage facility.

The spreadsheet includes the following ***data sheets***:

***Data_to_print:*** Form to be completed for electronic data documentation.

***Core_re-orientation:*** Form to document the process of core re-orientation using image log data. For each re-oriented core interval, the number of the structure(s) and the depth(s) of the correlated sinusoids of the image logs should be listed together with the core interval which has been re-oriented by this correlation.

***Abbreviations:*** Annotations and abbreviations used in the document.

# 3 Explanations to the columns of the template

## 3.1 row [Borehole, etc.]

Insert borehole name, depth interval described in the sheet, identify analyst and date; sheets should be numbered consecutively for each borehole.

## 3.2 row [Core oriented Yes / No, etc.]

Structural core analysis should be performed on re-oriented cores to develop a comprehensive database of discontinuities in the rock mass. The aims are to:

- define the true orientation of structures for kinematic analyses using brittle structural geology techniques
- complement structures not imaged by logs for a comprehensive analysis of fracture density
- remove fake fractures, which are interpreted from logs but do not appear in cores.

For the analysis, cores are re-oriented to their true orientation using dip data from image logs. The procedure requires an unequivocal correlation of at least one structure which is observed in both core and image, and the establishment of a correlation between core and image log depths (Fig. 1).

The number of the correlated structure [column No.] and the depth of the correlated sinusoid in the image log (depth of the bisection of the interval between the highest and lowest point of the sinusoid) should be quoted in the template together with the applied depth shift.

Experience has shown that discrepancies of depths may reach up to several metres in deep boreholes.

## 3.3 column [No. – Consecutive no. of structure]

Consecutive number of the recorded structure consisting of a prefix corresponding to the number of the cored interval and a consecutive number. ***Example:*** 78-4 denotes the 4$^{th}$ recorded structure (counted from the topmost of the cored interval) in core interval 78. The number is a unique identifier of the structure.

The number must be identical with the number given by the wellsite geologist. In cases where the drill site record is incomplete, newly described structures should be denoted with the ending a, b, c, etc. ***Example:*** Detailed analysis requires three structures to be inserted between the structures 78-4 and 78-5, which were recorded by the wellsite geologist. These structures should be numbered 78-4a, 78-4b and 78-4c.

Erroneous records from the drill site should be kept in the list and annotated as errors. ***Example:*** Close inspection of structure 78-6 identifies the structure as a fracture resulting from core handling rather than a tectonic fracture. The number should remain in the list and annotated accordingly, e.g. by the remark “non-natural fracture due to core handling”.

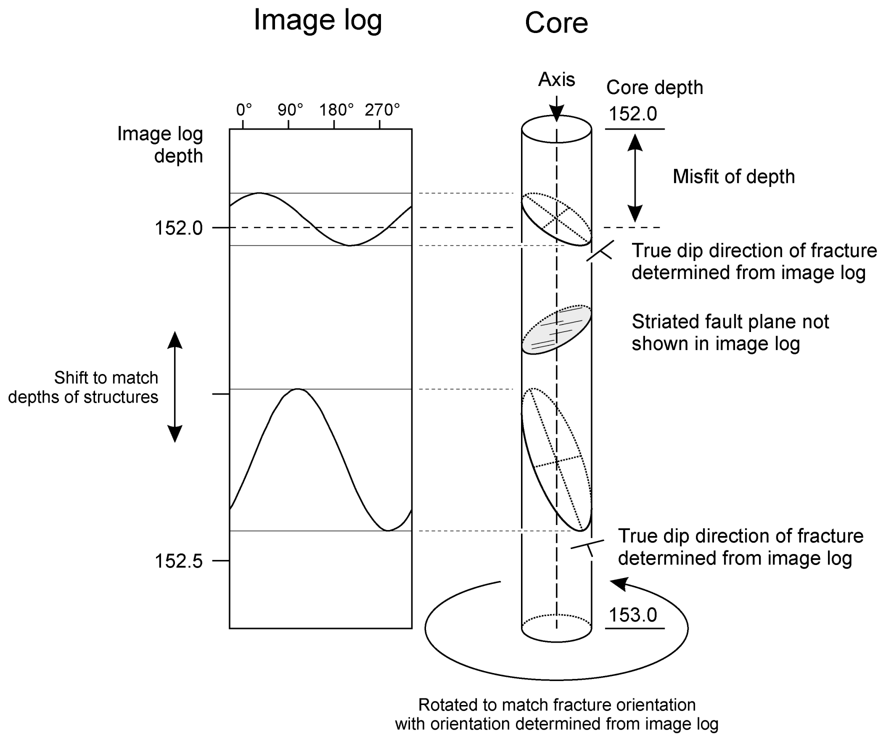



Fig. 1: Core to image log correlation

Sketch illustrating the procedure used to correlate core with image log and orient core to true north using unambiguously correlated structures.

## 3.4 column [No. – Core orientation line no.]

After the extraction of the core from the inner tube, the core pieces are juxtaposed together whenever possible. Continuous sections without drilling breaks, demarcated by grinding, crushed or core loss zones, are marked with a core orientation line and denoted with a consecutive number. This number enable to link the recorded structure with the key structure of this orientation line section that was identified on the borehole image.

## 3.5 column [Depth – Depth MD / Top MD, Bottom MD]

All types of structures are recorded quantitatively along the scanline of the core axis. The depth of the structure is measured at the point where it cuts the core axis (Fig. 2). For steeply dipping planes, depth should be determined half-way between the top and the base of the intersection ellipse of the structure.

If a zone is recorded (e.g. fault zone, shear band, fracture density class), specify the top (Top MD) and the base (Bottom MD) of the zone in the corresponding columns.

## 3.6 column [Correlation with log]

Mark "yes" (Y) for structures which can be correlated with the image log, and "no" (N) for structures which cannot be correlated, or which are not shown by the image log.

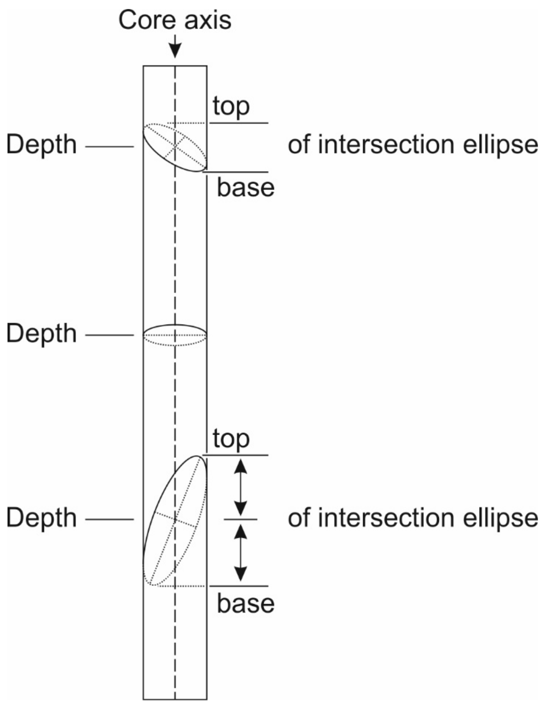



Fig. 2: Depth reference

The depth of a structure is measured from the bisection of the interval between the highest and lowest point of the intersection ellipse.

## 3.7 column [Lithology]

Fill in rock type according to common geological standards.

## 3.8 columns [Bed. – Dip direction, dip]

Fill in dip direction and dip of bedding planes. Leave [Dip direction] blank for cores which cannot be re-oriented using the image log. One reading per core metre is sufficient in cases where bedding is constant throughout the core interval.

## 3.9 column [Struc. – Type] (1)

Fill in the type of structure using the abbreviations listed in footnote (1) of the template.

## 3.10 column [Struc – Length] (2)

The length of the long axis of the intersection ellipse should be measured for structures which cut the core axis at acute angles (dipping with more than about 70°) and structures which do not cut through the entire core diameter (footnote 2 of the template). The measured length will be used for the calculation of fracture density P32 (see Chapter 5). Measurements are required to reduce the inaccuracy resulting from calculating fracture areas solely from the angle between the structure and the core axis (Chapter 4).

### 3.11 columns [Plane – Dip direction, dip]

Fill in dip direction and dip of the structure. Leave [Dip direction] blank for cores which cannot be re-oriented using the image log.

### 3.12 columns [Lineation – Azimuth, plunge]

For fault planes and shear bands, fill in dip azimuth and plunge of the lineation observed on the measured plane. Leave [Azimuth] blank for cores which cannot be re-oriented by the image log.

### 3.13 columns [Struc. – Shear Sense, Shear Sense Q] (3) (3a)

Note shear sense of fault planes and shear bands according to the abbreviations listed in footnote (3) of the template and provide information on the reliability of the shear sense observation using quality indices of footnote (3a).

### 3.14 column [Properties – Mineralisation / Fault rock] (4)

List any type of filling, mineralisation or fault rock associated with the structure using the abbreviations listed in footnote (4).

### 3.15 column [Properties – Thickness]

Quote thickness of filling, mineralisation or fault rock (if present). Thickness is measured in the direction perpendicular to the plane.

### 3.16 column [Properties – Open / Closed] (5)

Provide information on whether the vein/tension gash is open (displaying a continuous aperture), partly open (displaying a discontinuous aperture) or closed at the observation scale (i.e. the naked eye). Also note the width of the aperture and the observed lengths of open streaks for partly open structures.

### 3.17 column [Properties – JRC Roughness]

Classify the roughness of the structure using the Joint Roughness Coefficient (JRC) chart (Fig. 3). The JRC gives a picture of the classification of fracture smoothness and waviness (planarity) along 10 cm length of the fracture (Fig. 3; Barton 1976; Barton & Choubey 1977). The value is determined by visual comparison of the fracture surface with the diagram. The parameter can be used for assessment of the shear strength of fractures. JRC roughness is preferred over other roughness scales due to its scale, which fits the requirements of core description.

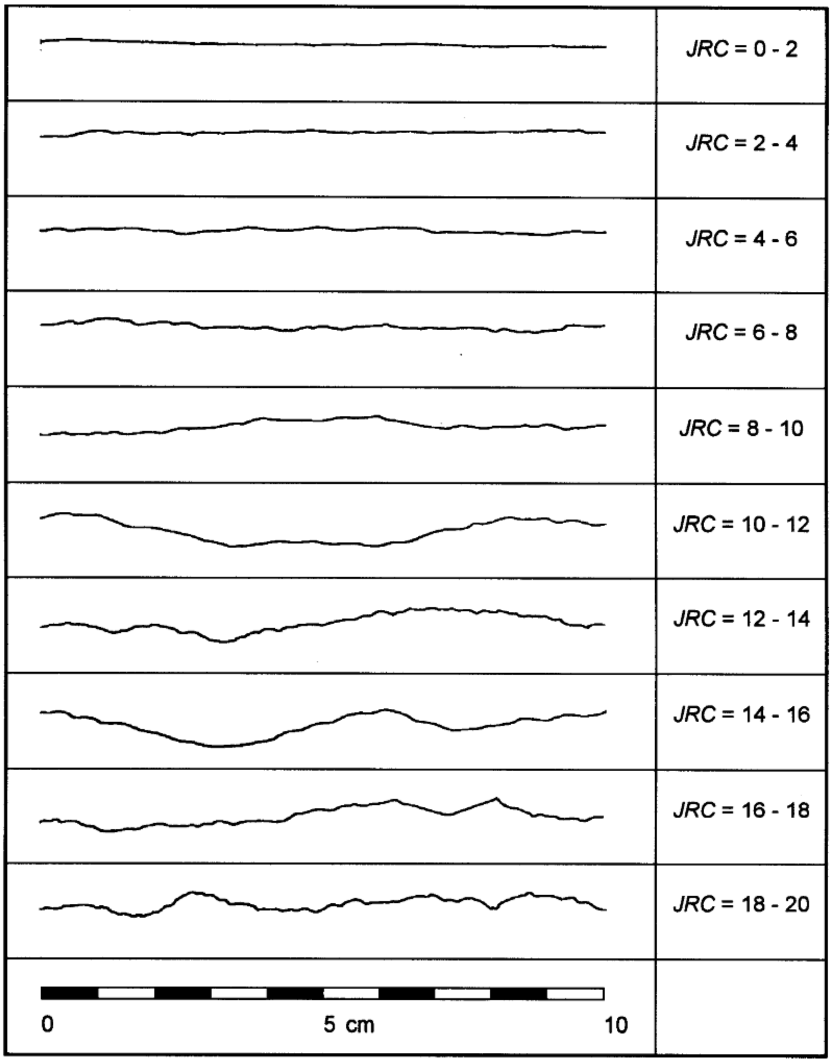



Fig. 3: JRC roughness chart

(Barton & Choubey 1977) used for the classification of fracture roughness.

## 3.18 column [Properties – Core cond.] (6)

Note whether the core is broken naturally or artificially at the structure under consideration or intact. If you cannot specify, if the break occurred naturally or artificially, use broken.

## 3.19 column [Remarks] (7)

List any relevant additional observations such as cross-cutting relationships between two structures, displacement, alteration (e.g. karstification) of fractures, etc.

Structures which are regarded as important in terms of their hydrogeological, rock mechanical or structural implications should additionally be documented in photos and/or sketches (preferably both – photo plus sketch with explanations). Pictures and sketches should be numbered using a unique identifier (to be listed in the template).

## 3.20 sketch [Structures]

Sketch all observed structures starting from the topmost of the core interval. The scale of the sketch is 1:10 with the smallest grid cells representing 2 cm.

## 3.21 sketch [Litholog]

Sketch, if necessary, lithological alterations, thick fault rocks and core intervals with abundant structures that are too small or too frequent to be analysed on a structure-by-structure basis. Such core intervals may be: rocks with abundant stylolites, which may be non-planar and too short to cut the entire core diameter; rocks with abundant small-scale tension gashes or joints; etc. The scale of the sketch is 1:10 with the smallest grid cells representing 2 cm.

## 3.22 sketch [No.]

Identify each structure by its consecutive number (consisting of a prefix corresponding to the number of the cored interval and a consecutive number) written in the space between the column "Lithology" and "FDC".

## 3.23 sketch [Fracture Density Class FDC] (8)

The column should be completed in cases where cores or parts of a core are heavily disintegrated and not able to restore order. For such core intervals, the density of natural fractures cannot be calculated accurately. Fracture density should be estimated using the following classification (Bauer et al. 2016):

***Fracture Density Class 2:*** Closely fractured rock refers to closely fractured rock characterised by three or more fracture sets with average spacing of sub-parallel fractures of about 5 to 10 centimetres. The sizes of multifaceted core fragments vary between about 5 to 10 cm. Estimated fracture densities (P32) for FDC 2 range from about 20 to 60 $m^2/m^3$.

***Fracture Density Class 3:*** Very closely fractured rock are difficult to recognise or appear at random orientation. Close spacing of intersecting fractures at distances of about 1 to 5 centimetres results in multifaceted rock fragments with maximum diameters of a few centimetres (Fig. 4). Estimated fracture densities (P32) for FDC 3 are about 60 – 200 $m^2/m^3$.

***Fracture Density Class 4:*** Extremely fractured rock (FDC 4) is assigned to extremely closely fractured rock with randomly oriented fractures. Joints and microfractures spaced at distances of 1 centimetre or less resulting in multifaceted rock fragments with diameters of 1 centimetre or less (Fig. 5). Sedimentary features are not recognised due to the heavy fracturing. Such heavily fractured rocks typically appear in damage zones of faults. Estimated fracture densities (P32) for FDC 4 are higher than about 200 $m^2/m^3$.

When assessing FDCs it should be ensured that core disintegration results from natural fractures and not from drilling action or core handling. Arguments for tectonic origin of fracturing may derive from the observation of striations, fillings or stylolites on many or most of the fractures delimiting multifaceted core fragments. Arguments for drilling-induced core destruction may be found in drilling reports.

The scale of the sketch is 1:10 with the smallest grid cells representing 10 cm.


Fig. 4: FDC 3 Disintegrated core assigned to Fracture Density Class 3 (FDC 3).

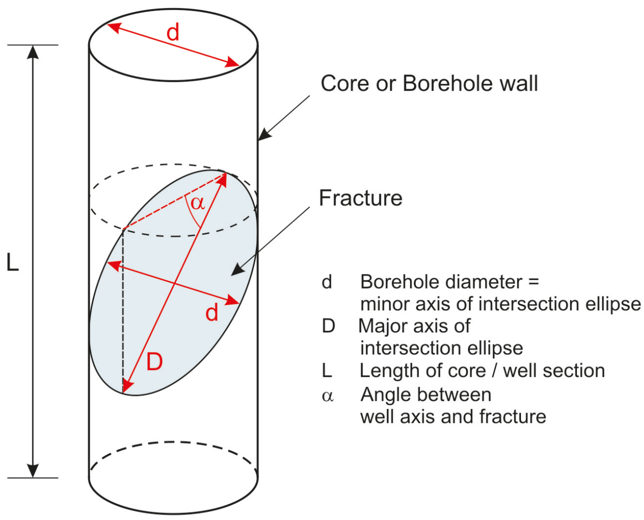
Note that virtually all rock fragments are delimited by polished slickensides confirming the tectonic origin of fractures (Bözberg B2/13 borehole, 181.90 m).


Fig. 5: FDC 4 Disintegrated core assigned to Fracture Density Class 4.

Note that virtually all rock fragments are delimited by slickensides confirming the tectonic origin of fractures (Bözberg B2/13 borehole, 199.80 m).

# 4 Quantitative analysis of fracture density P32

Three-dimensional fracture density (P32) can be calculated for all cores irrespective of knowing their true orientation. The value is measured as the total fracture area per unit rock volume ($m^2/m^3$) given by the total area of fractures (A) within the core interval divided by the volume of the rock mass (V) of that interval:

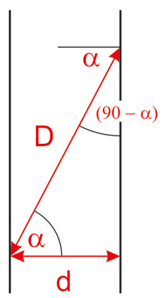



$$A_{frac} = \frac{d}{2}\,\frac{d}{2\cos\alpha}\,\pi$$

$$A_{frac} = \frac{d^2}{4\cos\alpha}\,\pi$$

$$V_{core/well} = \frac{d^2 \pi L}{4}$$

$$D = \frac{d}{\cos\alpha}$$




Fracture Density ($m^2/m^3$) =

$$A_{frac} / V_{core/well} = \frac{d^2 \pi}{4\cos\alpha}\,\frac{4}{d^2 \pi L}$$

$$\text{Fracture Density } P_{32}\ (m^2/m^3) = \sum_{n=1}^{n} \frac{1}{L\cos\alpha_n}$$

Fig. 6: Three-dimensional fracture density (P32) calculation.

The calculation is based solely on the intersection angle between the individual fractures and the borehole axis as shown below:

The procedure described provides sufficiently accurate values for fractures with dips up to about 70°, i.e. fractures that include angles of less than 20° with the core axis in vertical boreholes. The areas of steeply dipping fractures with inclinations of less than 20° with respect to the core axis should be calculated from the borehole diameter (d) and the measured length of the major axis (D) of the intersection ellipse. The same procedure should be applied to fractures which do not cut the entire core diameter.

# 5 References

Barton N. (1976): The shear strength of rock and rock joints. Int J Rock Mech Min Sci & Geomech Abstr 13/9: 255-279

Barton N., Choubey V. (1977): The shear strength of rock joints in theory and practice. Rock mechanics 10/1–2: 1–54

Bauer H., Schröckenfuchs T., Decker K. (2016): Hydrogeological properties of fault zones in a karstified carbonate aquifer (Northern Calcareous Alps, Austria). Hydrogeology Journal, 24: 1147-1170

# Appendix D

## Factsheet joint

# Factsheet joint

## Definition:

A joint is defined as a *"barren, closed fracture on which there is no measurable slip or dilatation at the scale of observation* (Hancock 1985)". Accordingly, planar fractures that are closed and display no measurable slip parallel to the fracture plane or dilatation perpendicular to plane are referred to as joints. The *"scale of observation"* is the naked eye.

A joint set is defined as a group of sub-parallel joints. Two cogenetic joint sets may combine to form a system of conjugate joints.

| Typical characteristics | Shear indications | Lineation on fracture surface | Mineralisation | Difficult distinctions to similar structures | Minimum characteristics to be defined |
|---|---|---|---|---|---|
| • sharp and straight planar structural discontinuity / fracture<br>• no displacement parallel to fracture plane<br>• in cores sometimes with small extensional opening due to core relaxation / depressurisation<br>• usually steeply dipping | • no shear indications such as striations or slickenfibres | • no striation formed by shearing<br><br>occasionally observed:<br>• radial plume (plumose) structures showing direction of rapid fracture propagation<br>• ribs / arrest lines showing cyclic fracture propagation<br>• hackle marks at the fringes of fractures | • no mineralisation<br>• mineralised fractures are defined as tension gashes (including mineralisations << 1mm in width) | • drilling-induced fractures are always open and specifically orientated with respect to core axis | • depth and dip & azimuth<br>• existence of joint sets<br>• open (due to core relaxation) – closed<br>• roughness in accordance with JRC standard<br><br>additional characteristics:<br>• joint architecture (X, Y, I, T styles)<br>• joint termination (abut against each other, abut on bedding planes, etc.)<br>• connectivity (abundance of I, X and T joint-joint intersections) |

Fig. 1: Joints (white arrows) in Lias (Riniken borehole 445 m)

Fig. 2: Joint in Opalinus Clay (indicated by white arrows, uncoiled core scan, Lausen borehole 21.50 m)

Fig. 3: Two parallel joints in Opalinus Clay (Schlattingen borehole 896.70 m)

## Development:

Joints may form as extensional or shear fractures. Rock is separated by a sharp and straight planar discontinuity. The resulting opposite fracture planes remain in tight contact because no shear or dilatational displacement has taken place. Joint surfaces are smooth, planar and with low relief. Some fracture planes are decorated with plumose structures, rib marks and/or hackle marks. Joints do not show mineralisation (otherwise the structures are termed tension gashes or veins).

The spacing and architecture of joints may vary between beds with different rheological properties. Joint spacing is further a function of bed thickness. In stiff and / or thin layers, the spacing of joints is closer. The joints often form in sub-parallel sets (group of joints with similar orientation) or result in complex fracture networks.

A genetic interpretation of whether joints formed as extensional or shear fractures is mostly difficult. Such assessment may be based on the geometric relation of a joint set to other structures (e.g. joints oriented parallel to a set of tension gashes may reasonably be interpreted as tensional fractures; two joint sets which intersect each other at about 60° and which are parallel conjugate planes may reasonably be interpreted as a system of conjugate shear fractures).

# Appendix E

## Factsheet vein/tension gash

# Factsheet vein / tension gash

## Definition:

Vein formed by dilatation (Passchier & Trouw 1996). A 'vein' is an extensional fracture filled with crystallised minerals that precipitated from an aqueous solution.

| Typical characteristics | Shear indications | Lineation on fracture surface | Mineralisation | Difficult distinctions to similar structures | Minimum characteristics to be defined |
|---|---|---|---|---|---|
| • sharp structural discontinuity<br>• planar or irregular fracture plane<br>• often lenticular shaped<br>• obvious mineral filling<br>• parallel fracture plane displacement approximately perpendicular to fracture plane<br>• extensional opening / mineralisation | • no shear indications on fracture plane<br>• special case: en-echelon arranged tension gashes with a sigmoidal vein shape indicate growth in a shear zone marking the direction of instantaneous stretching; en-echelon tension gashes allow determination of the orientation, shear sense and slip vector of the shear zone | • no striation on fracture surface parallel to the fracture<br>• the orientation of fibrous or elongated minerals indicates the direction of vein opening | • mineral filling can exist of orientated crystal fibres or non-orientated blocky crystals<br>• one or several different mineral phases<br>• mineralisation can be symmetrical, asymmetrical, syntaxial or antitaxial depending on the active wall(s) and the direction of mineral growth within the vein<br>• mineralisation may not fill the entire volume of the tension gash (open or partly open tension gashes) | • joints do not show opening at the scale of observation | • depth<br>• dip & azimuth<br>• width of mineralised body<br>• mineral composition<br>• crystal shapes<br>• open – closed – partly open<br>• if partly open: aperture width & length |

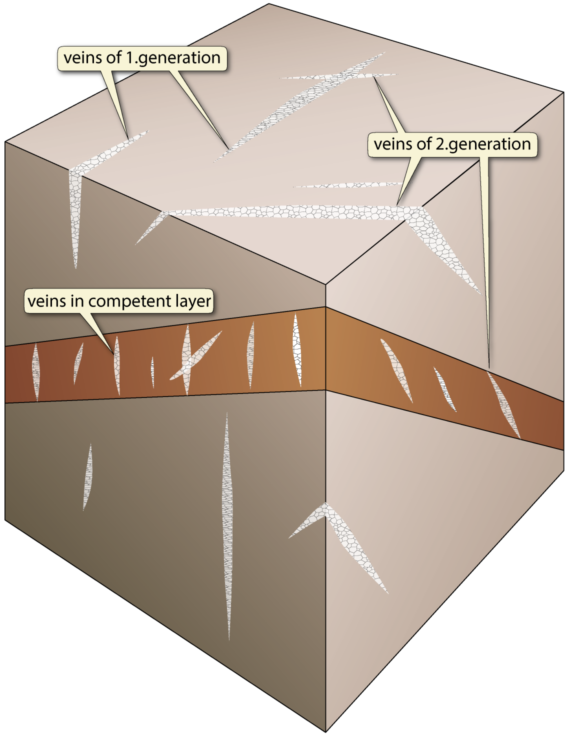



Fig. 1: Sketch of veins of two generations in weak and stiff layers

Fig. 2: Two sets of veins in Valanginian marls, Morcles nappe, width of vein = 1-2 cm


Fig. 3: Veins in "Brauner Dogger", Schafisheim borehole 969 m


Fig. 4: En-echelon array of sigmoidal veins in a shear band, sinistral shear sense, Öhrlimergel of Doldenhorn nappe

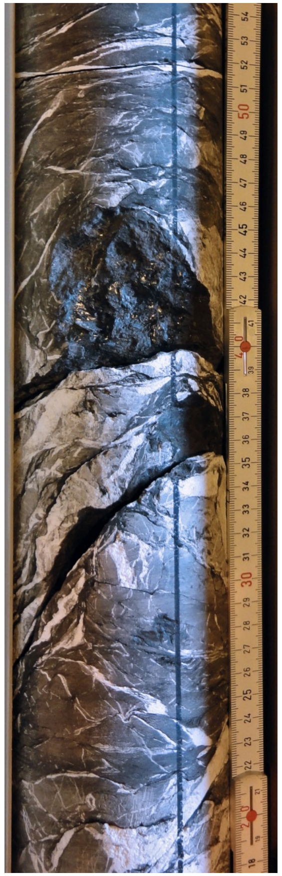


Fig. 5: Fault zone with many, partly deformed calcite veins of different generations, Oftringen borehole 638 m

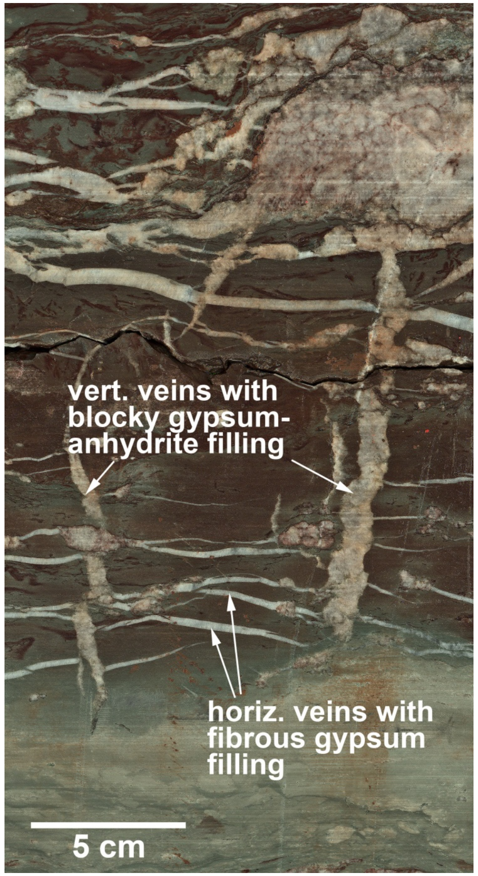



Fig. 6: Veins in dolomitic marls of Klettgau Fm., Lausen borehole 133 m

**Development:**

In anisotropic stressed rock, extensional fractures ideally develop perpendicular to the minimum principal stress direction and open in the direction of the minimum principal stress. Extensional fractures are typical for deformation under high fluid pressure which exceeds the minimum principal stress. When fractures open in the presence of an aqueous solution, mineral precipitation occurs, simultaneously forming mineral-filled tension gashes. Depending on the rate of opening, the possibility of fluid flow / transport of vein-forming material to the fissure and fluid (super-)saturation, crystals grow blocky or in a fibrous habit. In the case of continuous reopening of the tension gash, a crack-seal filling with elongated crystals (textures) occurs. In this case, the orientation of fibrous mineralisation indicates the direction of vein opening (i.e. the direction of the minimum principal stress during vein formation). Other veins can include metalliferous vein deposits generated when hydrothermal fluids rise towards the surface and deposition occurs in open fissures.

Pressure fringes are special types of veins with fibrous mineralisation that form on the low-pressure sides of a rigid object similar to pressure shadows with diffuse boundaries and non-fibrous mineralisation.

In contrast to synkinematic mineralisation, minerals can be deposited in pre-existing open fissures. Minerals may precipitate from water flowing through the gash due to precipitation of dissolved substances at relatively low confining pressures. Veins are always an important source of information for fluid flow and deformation history.

# Appendix F

## Factsheet fault plane

# Factsheet fault plane

## Definition:

Faults are planes of shear failure, i.e. planes along which there has been movement parallel to the plane (Peacock et al. 2017). A fault is a single, thin, planar and sharp structural discontinuity with negligible volume. Fault planes show shear indications such as different types of striation. Faults with significant volumes of, e.g., fault rock are termed fault zones.

| Typical characteristics | Shear indications | Lineation on fracture surface | Mineralisation | Difficult distinctions to similar structures | Minimum characteristics to be defined |
|---|---|---|---|---|---|
| • single, sharp and straight planar structural discontinuity<br>• indications of displacement parallel to fracture plane<br>• shear indications on fault surface<br>• up to several mm wide (thicker displacement zones are better termed fault zones) | • slickensides with polishing in clay-rich rocks and / or striation (= abrasion scratches) on fault surface indicating the displacement direction<br>• offsets of markers<br>• steps facing perpendicular to striation<br>• synkinematic slickenfibres behind steps with fibres orientated in direction of displacement<br>• all shear indicators can occur simultaneously | • striation<br>• slickenfibres | • synkinematic slickenfibres formed during fault movement<br>• cements at releasing fault bends | • distinction between fault and fault zone may be ambiguous; deformation at faults is compensated by a single structural discontinuity; fault zones consist of several structures and / or a variety of different types of structural discontinuities<br>• transition from single fault to fault zone is smooth: a fault zone is more complex, expanded<br>• veins: can be similar in width and mineralisation but show no indication of shearing | • depth<br>• dip & azimuth<br>• shear indications (orientation of striation, shear sense)<br>• type (polished mirror-like fault plane, stylolitic fault plane)<br>• mineralisation<br>• open – closed<br>• roughness according to JRC standard |

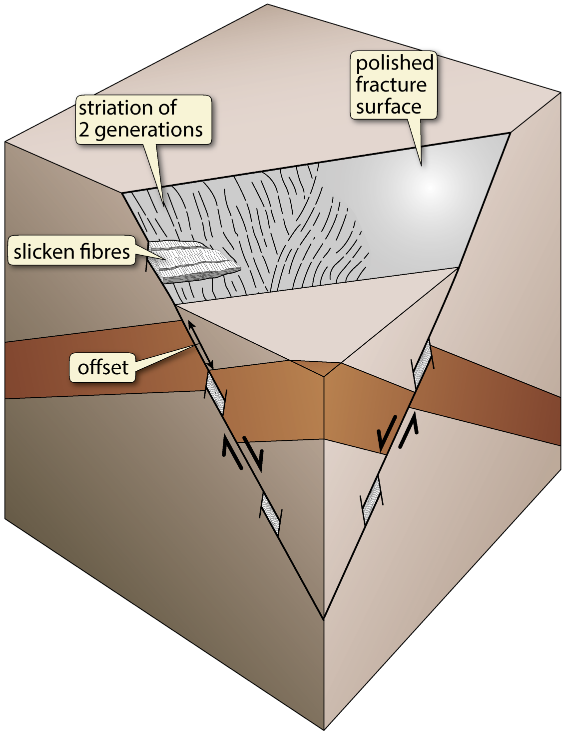



Fig. 1: Sketch of a fault

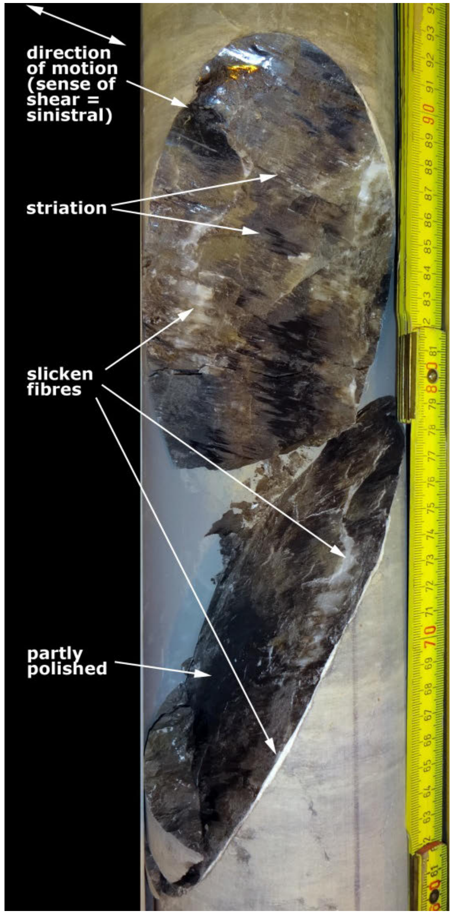



Fig. 2: Fault with slickenside in Effingen Mb. (Oftringen borehole 430.40 m)

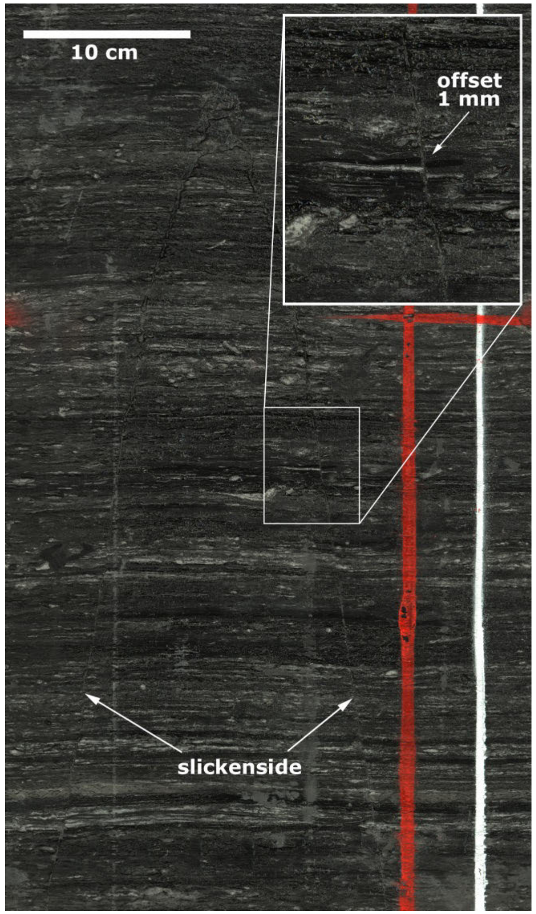



Fig. 3: Thin fault identified from the displacement of bedding (Opalinus Clay, uncoiled core scan, Lausen borehole 54 m)

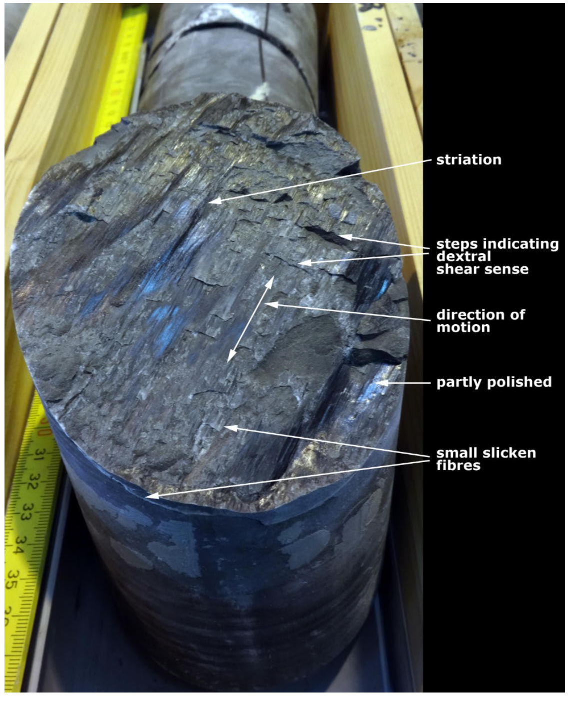



Fig.4: Slickensided fault with striation, partly polished surface and small synkinematic slickenfibres (shear sense is top towards the observer) (Effingen Mb., Oftringen borehole 632 m)

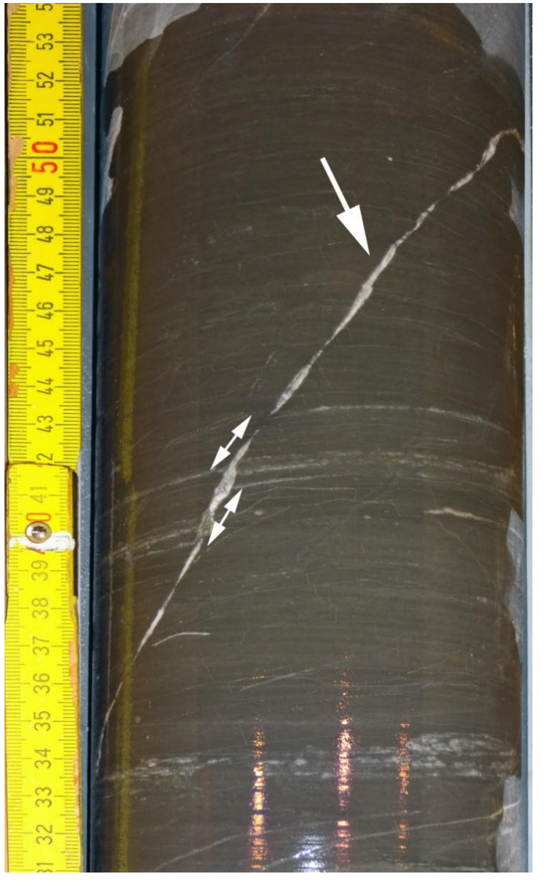


Fig. 5: Fault with displacement and thicker mineralisation at releasing fault bend (Effingen Mb., Oftringen borehole 465.35 m)

Fig. 6: Set of similar orientated faults with shear indications and slickenfibres (uncoiled core scan, Bözberg B2/13 borehole, 99 m)

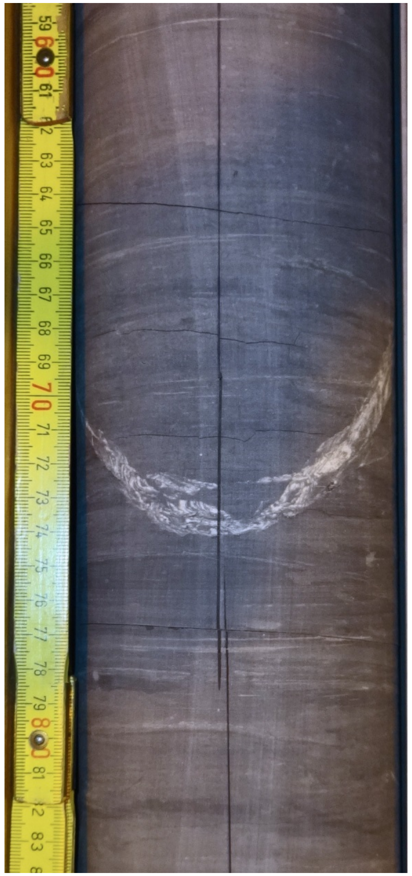


Fig.7: Mineralised fault with wallrock fragments in cement (Effingen Mb., Oftringen borehole 473.30 m)

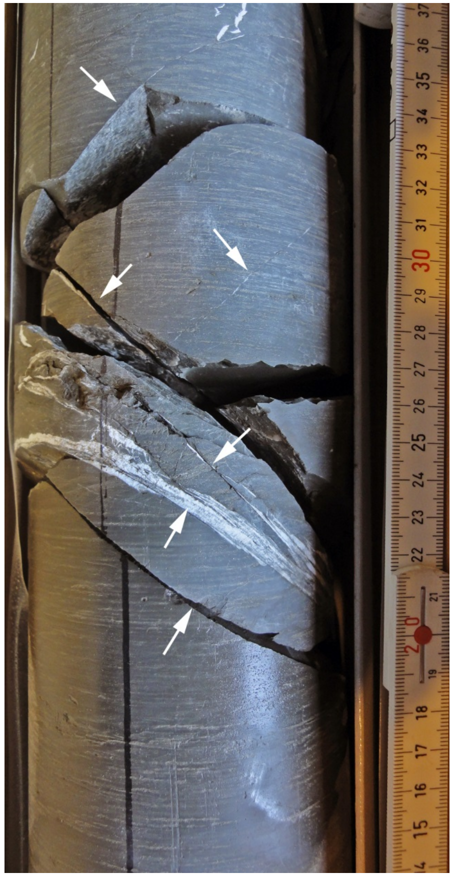


Fig. 8: Fault vs. fault zone: left-dipping fractures (upper arrows) are termed faults; right-dipping fault planes (lower arrows) constitute a fault zone (Effingen Mb., Oftringen borehole 622.70 m)

Fig. 9: Mineralised fault with wallrock fragments in cement (large arrow) and thin faults displacing bedding (small arrows) (Effingen Mb., Oftringen borehole 633.40 m)

## Development:

At a fault, opposite blocks of rock move with respect to each other, producing striation on the fracture plane (slickenside). The striation may be visible in polishing or scratching of the fracture surface, pressure solution forming slickolites, or the formation of synkinematic mineral fibres. Polishing is typical for clay- or coal-rich rocks, resulting in polished and reflective fracture surfaces, here termed mirror-like fault planes. The striation is caused by scratching / abrasion of outsticking irregularities along the fracture surface.

If the fracture surface is non-planar, typical step-like slickenfibres are generated. The mineral fibres (mostly calcite) grow during fault movement in small extensional (pull-apart) segments along the fracture surface in the direction of motion. These fibres are extremely reliable shear sense indicators. Displacement directions often change over time, resulting in differently orientated generations of slickenfibres and / or striations. Additionally, displacement along the fault plane can be determined by offsets of markers on opposite rock blocks.

# Appendix G

## Factsheet fault zone

# Factsheet fault zone

## Definition:

A fault zone is defined as a zone having a volume that includes interacting and linked fault segments, densely fractured rock and / or fault rocks; zones are typically bounded by sub-parallel margins or fault planes (modified from Peacock et al. 2017). A fault zone is a complex planar structural discontinuity with a significant thickness that is characterised by displacement and shear indications. Deformation is not compensated by a single structural discontinuity. A fault zone is further characterised by the occurrence of multiple structures, different structure types like slickensides, faults or veins and / or the formation of fault rock (clay gouge, cataclasite, DP fault rock, stylolitic breccia, dilation breccia, etc.). Fault zones may contain a fault core and damage zones adjacent to one or both sides of the fault core.

| Typical characteristics | Shear indications | Lineation on fracture surface | Mineralisation | Difficult distinctions to similar structures | Minimum characteristics to be defined |
|---|---|---|---|---|---|
| • complex planar structural discontinuity with significant thickness / volume<br>• obvious displacement parallel to fault plane<br>• shear indications on fault surface<br>• usually cm to m wide<br>• characterised by multiple structures like faults, veins and formation of fault rock: clay gouge, cataclasite, etc. in fault core<br>• structures can be overprinted by younger fault reactivation | • slickensides with polishing in clay-rich rocks and / or striation on fault surface<br>• offset and drag of bedding or other discontinuities<br>• mineralised slickenfibres behind steps with fibres orientated in direction of displacement<br>• cataclastic and / or ductile rock fabric<br>• all shear indicators can occur simultaneously and / or as multiple generations and hence overprint each other | • striation in direction of displacement<br>• slickenfibres with crystal growth in direction of displacement<br>• intersections with joints or shear fractures (Riedel shears) perpendicular to slip direction | • frequent, e.g. in the form of slickenfibres or veins<br>• often network of different generations of veins | • distinction between fault and fault zone may be ambiguous; deformation at faults is compensated by a single structural discontinuity; fault zones consist of several structures and / or a variety of different types of structural discontinuities | • depth, width (top & bottom depth)<br>• dip & azimuth if possible<br>• shear indications (type, direction, shear sense) and displacement (offset)<br>• fault rock<br><br>additional characteristics:<br>• characteristics of individual structures within the fault zone should be defined as far as reasonable |

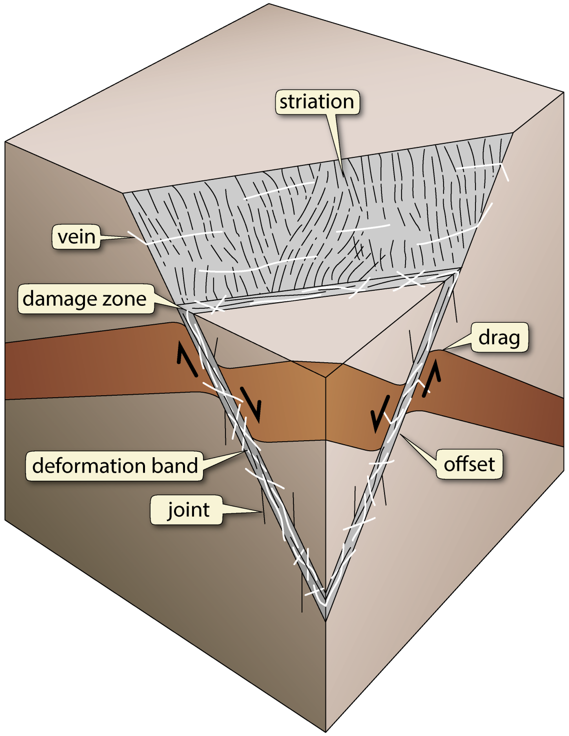



Fig. 1: Sketch of a fault zone with normal displacement

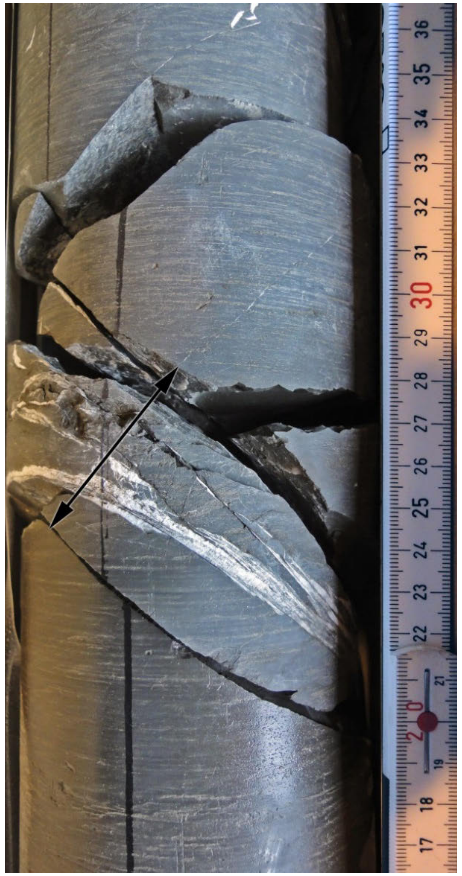


Fig. 2: Fault zone consisting of five individual faults with identical kinematics (Effingen Mb., Oftringen borehole 622.70 m)

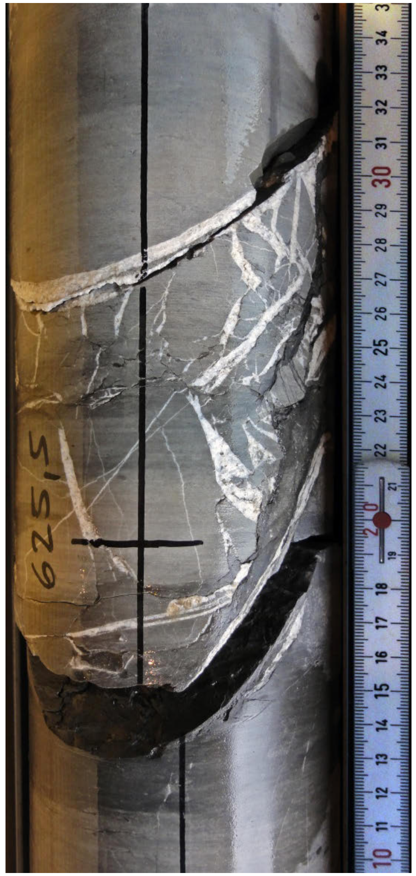



Fig. 3: Fault zone sandwiched between two sub-parallel fault planes; the fault zone contains multiple generations of tension gashes and faults (Effingen Mb., Oftringen borehole 625.50 m)

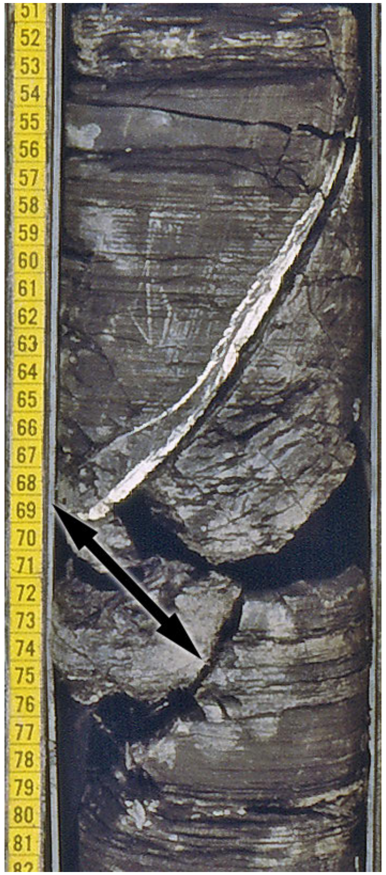


Fig.4: Fault zone in Opalinus Clay consisting of multiple faults which are partly mineralised (Schafisheim borehole 1,056.70 m)

Fig. 5: Complex fault zone in Effingen Mb. (Oftringen borehole 638.20 m)

Fig. 6: Fault zone with hundreds of slickensides and slickenfibres at intervals of mm in Opalinus Clay (Bözberg B2/13 borehole, 95.85 m

## Development:

In contrast to a fault, a fault zone does not consist only of a single sharp structural discontinuity. Fault zones rather contain multiple structures that compensate displacement and / or fault rock formed by various processes during fault activity. Displacement at fault zones is significantly larger than the displacement at single faults.

Fault zones may contain a fault core and damage zones adjacent to one or both sides of the fault core. Outcrop studies show that the delimitation of fault cores and damage zones is not straightforward and open to some subjectivity. The following characterisation may be helpful for the purpose of structural drill core analysis: Fault cores are characterised by volumes of newly formed fault rocks typically bounded by sub-parallel margins or fault planes, and / or extremely dense networks of kinematically compatible faults (e.g. sub-parallel faults with similar slip direction and identical shear sense). Damage zones form by the initiation, propagation, interaction and build-up of slip along faults, creating a volume of deformed wallrocks around a fault (Peacock et al. 2017). Damage zones are frequently characterised by a gradual decrease in deformation with distance from the master fault / fault core. In drill cores, damage zones may contain faults which are kinematically compatible with the structures in the fault core (e.g. faults sub-parallel to the master fault; syn- and antithetic Riedel shears and / or en-echelon tension gashes) or fractured rock with fracture intensity decreasing with distance from the master fault / fault core.

# Appendix H

## Factsheet stylolite

# Factsheet stylolites

## Definition:

Irregular, commonly jagged surfaces in a rock formed by local removal of material by pressure solution (Passchier & Trouw 1996). Stylolites are seams of insoluble residues like clay and iron oxides that form grey to black, sawtooth-like exposure lines of insoluble residual material. The stylolitic surfaces show a dark and *"mountainous"* rough surface. If developed, columns (or teeth) are oriented at high angles with respect to the stylolitic surface.

| **Typical characteristics** | **Shear indications** | **Lineation on fracture surface** | **Mineralization** | **Difficult distinctions to similar structures** | **Minimum characteristics to be defined** |
|---|---|---|---|---|---|
| • dark sawtooth exposure line of insoluble residues<br>• residual seam (teeth) usually < 1 mm wide, mm to cm long<br>• surface is rough and / or polished | • no shear indications | • stylolitic teeth may be oriented at oblique angles to the dissolution surface<br>• dissolution surfaces with stylolitic teeth oriented sub-parallel to the surface are indicative of shearing; such structures should be described as stylolitic fault planes | • insoluble minerals such as clay and Fe oxides accumulate passively at the dissolution surface | • stylolitic slickensides: exposure line of slickolites is straighter and depicts small angles between stylolitic teeth and exposure line | • depth<br>• dip & azimuth<br>• thickness of residual seam<br>• roughness according to JRC standard<br>• open – closed<br><br>additional characteristics:<br>• roughness of structure (e.g. width and shape of stylolitic teeth: cone-like, columnar-like, less or varying sutured) |

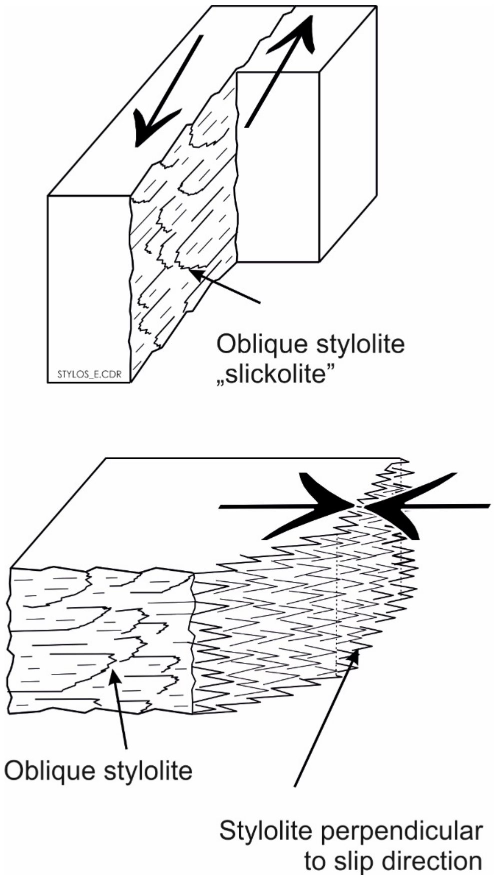



Fig. 1: Sketch of parallel, oblique and highly oblique stylolites. The latter are referred to as slickolites and should be noted as stylolitic fault plane

Fig. 2: Stylolite indicative of horizontal shortening in Geissberg Mb. (Gösgen borehole 66 m)

Fig. 3: Stylolitic surface in Effingen Mb. (Weiach borehole 396 m)

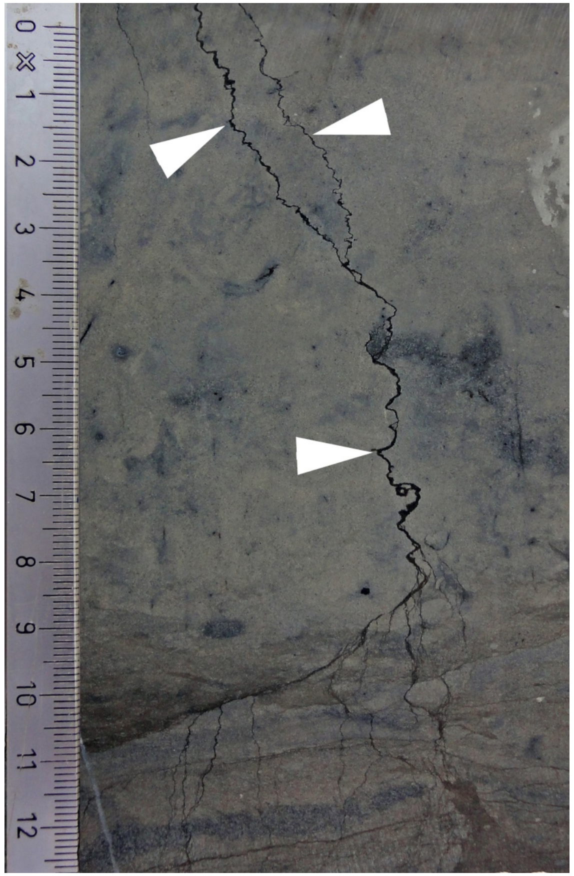


Fig. 4: Sawtooth-shaped exposure line of stylolite in Malm limestone (Weiach borehole, 391 m)

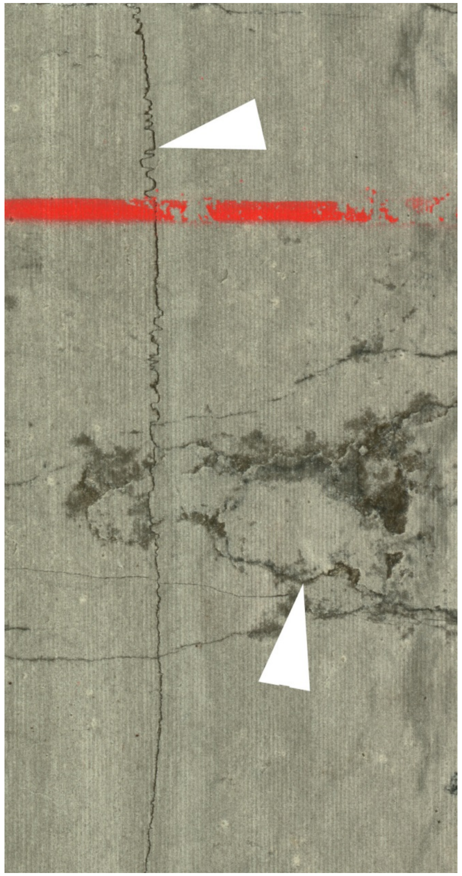


Fig. 5: Horizontal and vertical stylolite in Bänkerjoch Fm. (Lausen borehole, 142.80 m, image rotated by 90°CCW, image width = 8 cm)

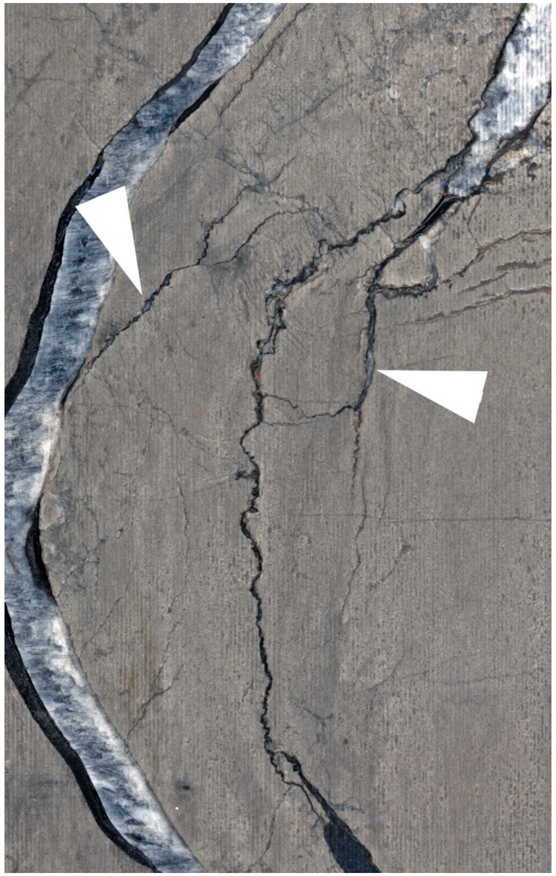


Fig. 6: Stylolites partially mineralised with gypsum in Bänkerjoch Fm. (Lausen borehole, 142.40 m, image rotated by 90°CCW, image width = 10 cm)

**Development:**

Stylolites resulting from pressure solution are common in marly limestone and marl. Stress concentrates at the contact between mineral grains cause chemical dissolution. Soluble calcareous minerals are removed, and insoluble residuals are accumulated along an irregularly shaped seam. The shortening direction and the direction of the main principal stress $S_1$ is sub-parallel to the orientation of the teeth of the stylolite and mostly perpendicular to the dissolution surface. The length of the interlocking teeth of a stylolite indicates the minimum amount of shortening compensated by the structure. The thickness of insoluble material is proportional to the amount of dissolved material. In clay-rich rocks, pressure solution results in less serrated but wavy seams of insoluble material. These structures are often called solution seams. Depending on their shape, stylolites may form weak discontinuities, whereby dislocations would accumulate that allow separation. Resulting features can be mineralised fractures or slickensides along the stylolitic surfaces.

# Appendix I

## Factsheet open voids

# Factsheet open voids

## Definition:

Voids are open volumes in the rock mass. Voids may result from a variety of processes such as incomplete cementation of veins or tension gashes, dissolution of soluble material including fossil shells, preserved cavities in fossils (druses, geodes), etc. Hydrologically, the most important voids are planar voids along incompletely or non-cemented fractures that provide streaks of high permeability within the rock mass. Isolated voids such as hollow shells are less important as they are not connected to other open porosity.

| Typical characteristics | Shear indications | Lineation on fracture surface | Mineralisation | Difficult distinctions to similar structures | Minimum characteristics to be defined |
|---|---|---|---|---|---|
| • open cavity<br>• walls usually coated by idiomorphic mineral crystals that indicate growth into open volume<br>• related to open fractures or fossils | • fossils: no shear indications<br>• planar voids can be associated with both fault planes and tension gashes; faults may contain open voids at releasing fault bends | • voids associated with fossils and tension gashes: no striation<br>• voids associated with faults typically show striation overgrown by idiomorphic crystals | • usually surrounded by mineralisation<br>• dissolution cavities, e.g. in evaporate-rich carbonates, usually do not indicate mineralisation | • none | • depth<br>• opening width and length of the opening<br>• mineralisation degree<br>• related to fossil, fracture or dissolution<br><br>additional characteristics:<br>• connectivity (isolated vs. connected along fracture plane) |

Fig. 1: Partly open mineralised shear fracture with druse / geode (Lias, Schafisheim borehole, 1,080 m)

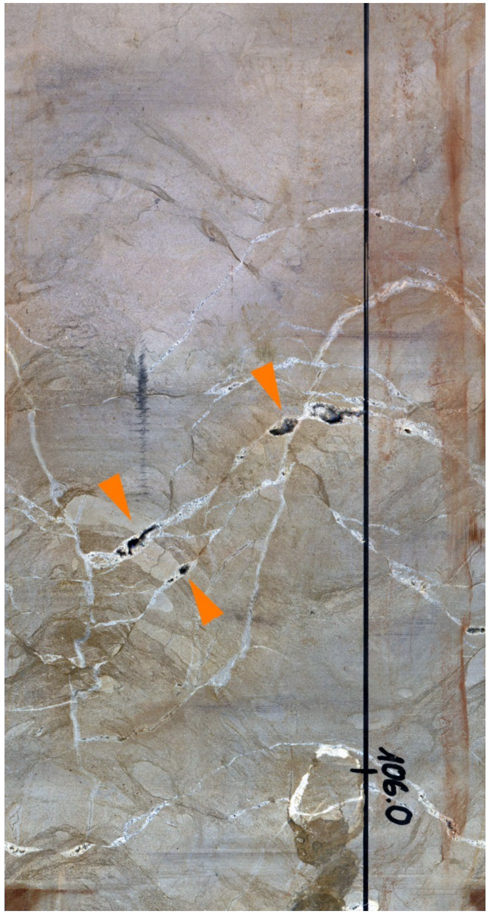



Fig. 2: Partly open mineralised fractures with druses / geodes (Villigen Fm., Bözberg B2/13 borehole, 105.85 m, uncoiled core scan, image width 20 cm)

Fig. 3: Druse / geode in fossil (Lias, Lausen borehole, 76.50 m, uncoiled core scan, image width 16 cm)

## Development:

Voids relate to openings of fractures, originally unfilled or dissolved fossils or dissolution of rock material (e.g. in evaporate-rich carbonates, where evaporites are dissolved). Consequently, the shape of the voids may differ widely from continuous planar voids along fractures and disconnected patches of planar voids along fractures to irregularly shaped pockets and spherically shaped openings. The minerals contained within the cavities were deposited from saturated fluid flow through the opening cavities / fractures.

# Appendix J

## Factsheet drilling-induced fractures

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## Definition:

Drilling-induced fractures can be distinguished from natural fractures based on the aperture, fracture surface and geometry in relation to the core. Drilling-induced fractures are always open, never mineralised and show no shear indications. Core discing or saddle fractures split the core into parallel discs. The corresponding fracture surfaces are generally perpendicular to the core centre axis. Centreline fractures are (sub-) vertical with respect to the core centre axis and split the core in half. Petal fractures bend from the core rim into the core centreline and are arranged step-like.

| Typical characteristics | Shear indications | Lineation on fracture surface | Mineralization | Difficult distinctions to similar structures | minimum character-istics to define |
|---|---|---|---|---|---|
| • sharp and straight planar structural discontinuity / fracture<br>• always open<br>• never mineralised<br>• no shear indications<br>• typical geometry in relation to core | • no shear indications (no striations or slickenfibres) | • plumose structures possible | • only relicts of raised natural structures | • Joints: cross-cut the entire core, can continue on subsequent core run. Usually orientated differently with respect to core. Often mineralised and / or closed | • depth<br>• structure density per metre core |

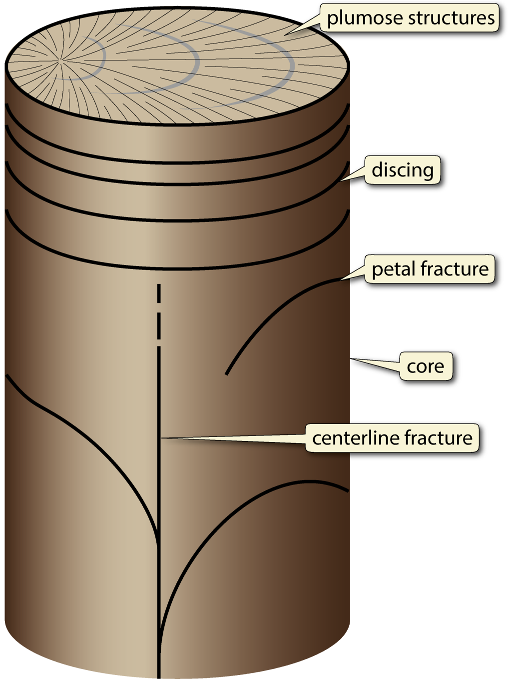


Fig. 1: Sketch of drilling-induced fractures

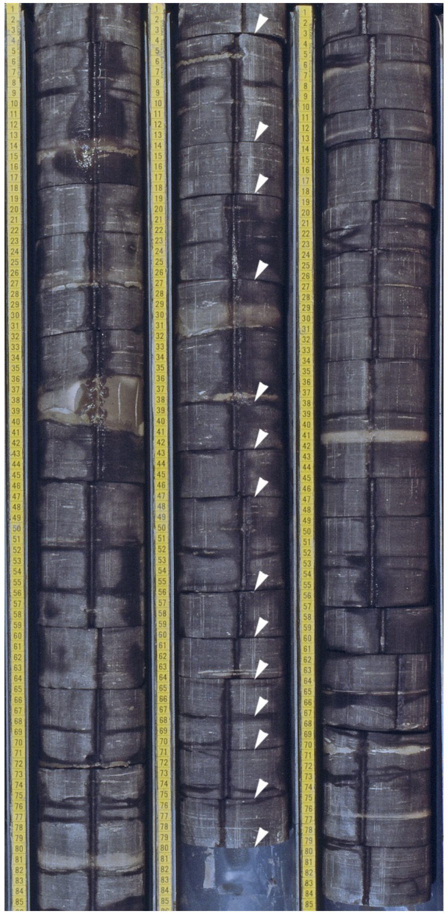

Fig. 2: Core discing in Opalinus Clay (Weiach borehole, 565.63 - 568.18 m)

Fig. 3: Core centreline fracture in Hauptrogenstein Fm. (Oftringen borehole, 689 m)

Fig.4: Petal fractures (right side) & horizontal saddle fracture (discing) in Hauptrogenstein Fm. (Oftringen borehole 484.5 m)

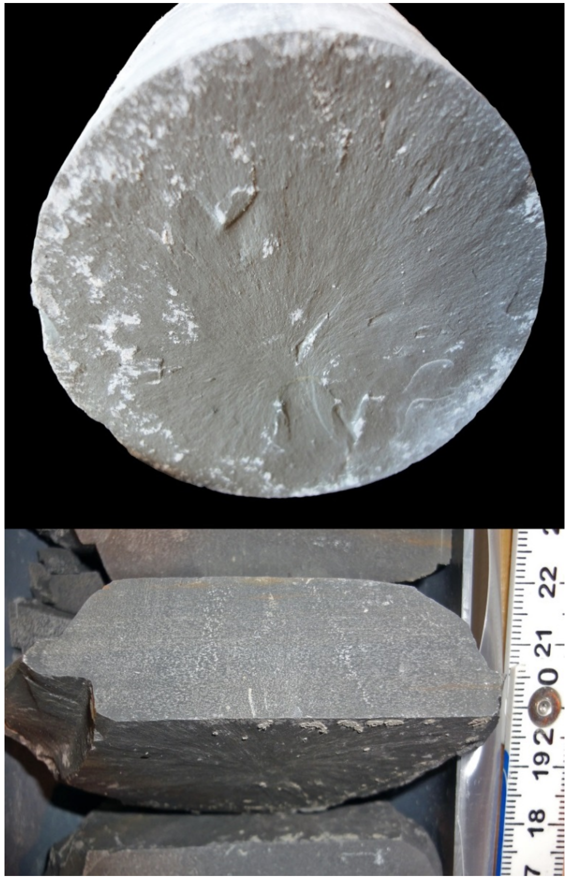

Fig. 5: Plumose structures on discing fracture surfaces in Effingen Mb. & Opalinus Clay (Gösgen & Weiach boreholes)


Fig. 6: Petal & centreline fractures (image from Patlan, 2008)

**Development:**

Depending on the load on the drill bit, mud weight and rock properties, drilling-induced fractures develop during or shortly after drilling. Core discing is induced as a result of unloading / stress relief under high in-situ stresses. In-situ stress magnitude, mechanical rock properties and drilling / core retrieval speed define the style and degree of discs. When initial stress is high, cores of intact hard rocks tend to split into parallel discs / slices with varying thickness. Fracture surfaces are generally perpendicular to the core centre axis. The discs are concave on the top and convex at the bottom. Consequently, the discing is also termed a saddle structure. Discs in homogeneous claystones develop not only due to stress relief but also due to drying-up and breaking along weak discontinuities (e.g. bedding). Centreline fractures are drilling-induced fractures in the core. They propagate ahead of the bit prior to coring as a result of high bit weight. Commonly, they are subvertical structures and split the core approximately in half. They tend to form perpendicular to the least principal stress, which is aligned perpendicular to the borehole. Petal fractures form immediately ahead of the drill bit as a result of excessive bit weight during coring. They propagate downhole. The fracture bends from the core rim into the core centreline. They are arranged step-like and are orientated similarly to the centreline fractures with respect to principal stress.