This is Chapter 2 “About fault zones and block-in-matrix rocks” from my PhD thesis

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Best regards,
Alexander Kluckner

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Tunnelling at greater depths: Study on the ground and system behaviour when passing a stiff rock block in a weak zone

DOCTORAL THESIS

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Abstract

Title: **Tunnelling at greater depths: Study on the ground and system behaviour when passing a stiff rock block in a weak zone**

Keywords: deep tunnelling, conventional, brittle fault zone, block-in-matrix, stiff block, shear bands

A stiff block in brittle, weak fault zones can lead to unfavourable ground behaviour when being approached by a tunnel drive. It attracts stresses and may fail when it is close to the tunnel face endangering the tunnel stability. The thesis investigates the ground behaviour with a quasi-two-dimensional parametric study. The tunnel diameter is 10 m, the block height is 2 m, 5 m, or 10 m, and the distance between the block and the tunnel is 1 m, 5 m, or 10 m. One critical case is analysed in three dimensions. Another study simulates a real tunnel drive that crosses a block with a height of over 25 m. Strain data from a lining segment measured at the construction site with a distributed fibre optic sensing system is used to set up the Burgers-Mohr model simulating the shotcrete material behaviour. All simulations consider an interface between the block and the matrix material. From the block, shear bands form towards the tunnel. In the parametric study, even if the block-matrix stiffness contrast is high or the block is close to the tunnel, differences in the tunnel displacements between cases with block and related cases without block are little. Of the cases analysed, those with a hydrostatic primary stress state are least favourable. If the primary stresses are anisotropic, the effect of the block on the ground behaviour strongly depends on the block distance. The case study suggests that the block must be not too high to be hazardous if it fails. Otherwise, stresses redistributed because of the tunnel drive cannot concentrate at the block's top and bottom. In case the stresses are high enough at the moment of block failure, large-scale shear failure of the rock mass close to the tunnel may occur. If the location of blocks is unknown, state-of-the-art approaches to evaluate tunnel displacements must be applied to increase the probability of identifying blocks in time during tunnelling. Making the system stiffer of less stiff (e.g., by adapting the moment of ring closure) may not lead to a less hazardous situation. It is advised to minimise the unreinforced rock mass volume close to the tunnel face to prevent shear bands from reaching the tunnel.

Contents

Chapter 2

About fault zones and block-in-matrix rocks

A fault is a discontinuity in rock masses. According to [404, p. 92], the term *discontinuity* is "used for all structural breaks in geologic materials which usually have zero to low tensile strength. Discontinuities also may be healed. Discontinuities comprise fractures (including joints), planes of weakness, shears/faults, and shear/fault zones."

The term *fault*, however, does not imply any information on the discontinuity characteristics (e.g., deformability, geometric properties, strength). The difference between a fault and other types of discontinuities (including fractures[1]) is that along a fault significant movement occurred and a measurable ([406, p. 166]) offset of the branches of a marker layer on opposite sides of the fault exists ([241, p. 101ff], [405, term 'Fault']). Fig. 2.1 illustrates a case where the marker layer, which was continuous before the shearing, has been set off significantly because of a downward slip of the hanging wall. The shearing is a result of the deformation of the earth's crust during tectonic events (cf. [114, p. 182]).

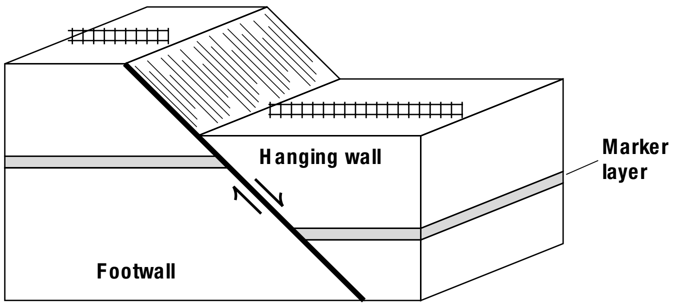

Figure 2.1: Sketch of a *normal fault* (from [406, Fig. 8.1a, p. 167]).

Along shears (or shear fractures) also shear displacement occurred, but the amount of movement is in a range of mm to dm ([125, p. 125, 178]) and the offset of marker features cannot be established ([131, p. 35]), at least at the macroscale.

In general, faults can be anywhere in the Earth ([406, p. 166]). However, the use of the term is usually restricted to discontinuities that have formed mostly because of brittle deformation mechanisms ([406, p. 166]). Such mechanisms dominate at crustal depths ([116, p. 1562]). [125, p. 178] relates faults and the brittle domain to the upper crust (cf. Fig. 2.2) which extends to

[1]Fracture (joint) ... Crack or break in rocks along which no movement has occurred. [405, term 'Fracture (joint)']

depths of 10 to 15 km (cf. also [406, p. 190, 200]). At such depths, the temperature is relatively low (cf. Fig. 2.3).

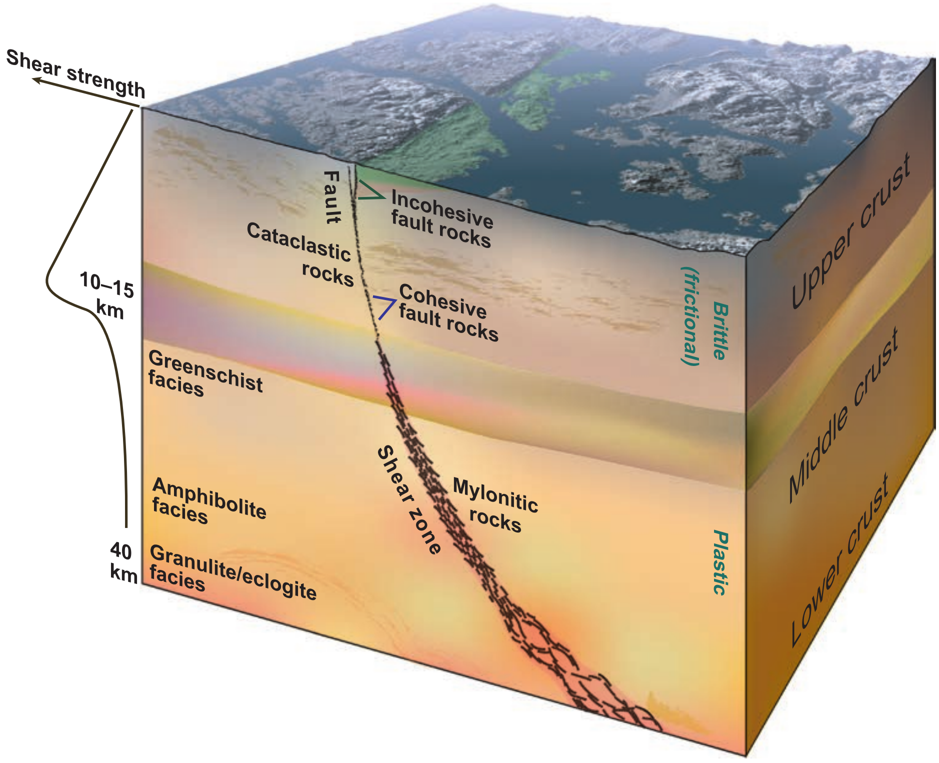

Figure 2.2: Simplified model of the connection between faults and classic ductile shear zones (from [125, Fig. 16.1, p. 330]).

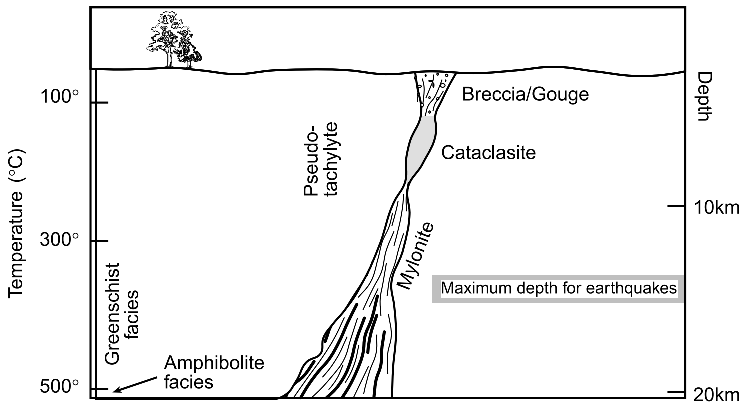

Figure 2.3: Change in fault character with depth for a steeply dipping fault (from [406, Fig. 8.26, p. 190]). Note the change in fault zone width and types of structures[2] with depth.

The temperature, pressure, and strain rate primarily determine the dominating deformation mechanisms. At low temperature conditions and high strain rates, the mechanisms are of the brittle or purely mechanical type ([299, 356, 372], [324, p. 13], [114, p. 182]): brittle fragmentation of grains by microcracking, frictional grain-boundary sliding, and dilatancy and rigid-body rotation of crystal and grain fragments.[3] The crushing of rocks to a finer-grained

[2]Structure . . . "The arrangement of the parts of a rock mass irrespective of scale, including spatial relationships between the parts, their relative size and shape and the internal features of the parts." [53, p. 4]

[3]Note that if on the microscale the dominant deformation mechanisms are of brittle character but on the macroscale the material shows strain hardening in the post-peak region, one may term the material ductile (phenomenologically). [241, p. 73]

material is termed *cataclasis* (cf. [125, p. 124, 475]). Usually, the cohesive strength decreases. Dissolution-precipitation processes may be involved. Low confining pressure and high fluid pressure, which results in an increase in the differential stress, promote brittle deformation. It's different at high temperature conditions and low strain rates. Here, ductile or plastic deformation is more prominent: intracrystalline deformation processes based on the movement of lattice defects ([137, 201]) accompanied by dynamic recovery and recrystallization ([299]). The cohesive strength is preserved or even increases (cf. also [114, p. 182], [324, p. 13]). The effective pressure is of less importance. At melting temperature of minerals, solid-state diffusion creep occurs. [60, p. 3ff]

Independent of whether the mechanisms involved are brittle, ductile, or a combination of both, with further displacement during tectonic events and the accommodation of strain (localisation), zones develop and increase in width and length: brittle fault zones, or ductile shear zones. In the former, strain concentrates more in the fault core. In the latter, the variation in accumulated strain across the zone is more gradual. [125, p. 216, 330]

Depending on the stress regime being active during faulting, masses displace relative to each other in a particular way. Fig. 2.4 shows four possible types. Additional types are oblique-slip faults and scissor faults (not shown), where the shearing direction is neither parallel to the dip direction nor to the strike. Both brittle fault zones and ductile shear zones can feature any of the fault types. [125, p. 331]

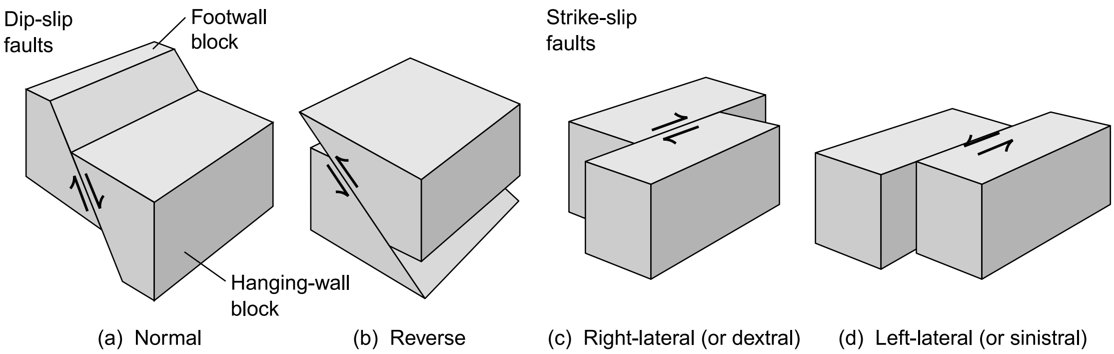

Figure 2.4: Block diagram sketches showing four types of faults in terms of the shearing direction (modified from [406, Fig. 8.4a–d, p. 170]).

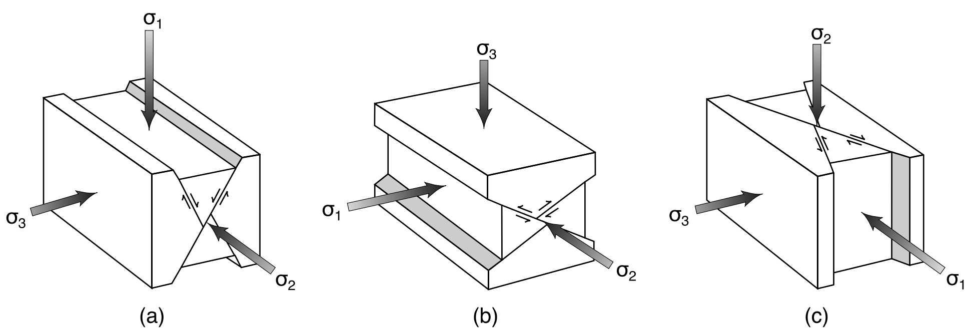

Figure 2.5: Anderson's theory of faulting predicts (a) (high-angle) normal faults, (b) low-angle reverse faults (or thrusts), and (c) vertical strike-slip faults; (from [406, Fig. 8.27, p. 191]).

A well-known theory relating the stress regime to the fault types is the Anderson's theory (cf. Fig. 2.5). It assumes that the fault planes are at an angle of about $45° - \varphi/2$ to the direction of the major principal stress, σ_1, ([406, p. 127ff, 191]). Differences between the theory and the reality must be attributed to several facts, e.g., (cf. [406, p. 191]): (1) the theory assumes homogeneous, isotropic rock mass conditions; (2) it also assumes that the faulting takes place in intact rock since pre-existing weakness planes alter the local stress field and, thus, the resulting structure of the fault system; and (3) it does not account for the effect the deformation of the rock mass has on the local stress field.

This thesis deals with brittle fault zones which are features of the upper crust (cf. [324, p. 13]). Thus, further information is limited to such. Section 2.1 briefly describes the genesis and some characteristics of brittle fault zones. And Section 2.2 outlines some relevant features of block-in-matrix rock. It's a rock mass type of which fault zones can be composed of and which can feature larger stiff blocks.[4]

2.1 Brittle fault zones

According to [62, p. 21, 30], the "development of fault zones and their associated fracture systems can be idealized as the coalescence and interaction of different fractures at the geologic macro scale" complying with strain and kinematics compatibilities. The resulting characteristics of a fault zone depend on, e.g., (cf. [114, p. 183], [116, p. 1559], [240] in [62, p. 39], [408, p. 3]):

- the stress regime during shearing; in particular the orientation of the principal stresses relative to the shear surfaces (cf. also text above);
- rock and rock mass properties; of the host rock (e.g., layering) but also of the developing fault rocks;
- magnitude and duration of movements;
- temperature and fluid phases.

If, for example, the environment around the developing faults shows variable stress states, the faults grow in a segmental manner. Individual segments propagate and—depending on the orientation and spacing—remain isolated or connect with others. [239] (cited in [62, p. 36])

Further, strain imposed on rock masses will be *absorbed* to a larger extent if the rocks feature an incompetent deformable fabric but will lead to more fractures in rocks with a stiffer fabric ([131, p. 358]). Also, the porosity of the host rock (or protolith) plays an important role. Both [116, p. 1559f] and [125, p. 193ff] cite the same different understanding of how fault zones develop depending on whether the rocks show a low or high porosity. If the porosity is low, the faulting is fracture-dominated. The fault grows as fractures of different type propagate and connect. Grinding and microfracturing weaken the walls of the slip surfaces forming a thin core of brecciated or crushed rocks. With ongoing movement, new fractures develop in the walls surrounding the core and, so, the fault zone steadily thickens. The fracture density and the level of cataclasis is highest in the core and lower in the zones next to the core. The latter are termed *damage zones*. At the transition from the core to the damage zone, usually the maximum fracture density can be observed. It decreases exponentially with increasing distance to the core. Note that in case of low-porosity rocks, during faulting the porosity in the process zone increases. In contrast, if the porosity of the protolith is higher, the formation of *deformation bands* dominates the faulting. In porous rocks there is space for grains and fragments to reorganise. Upon shearing strain localises in narrow zones (i.e., deformation bands). There, material crushes (cataclasis). The porosity decreases and leads to strain hardening. Thus, it is more likely that new deformation

[4] Also other rock mass types of fault zones may feature larger stiff blocks. However, it's a particularity of block-in-matrix rocks and related information (in this chapter, but also in the next) helps to comprehend to natural scatter of rock properties.

bands form next to existing ones. A zone of deformation bands forms. Now, if the deformation continues, slip surfaces develop within this deformation band zone. They propagate and connect (like fractures in low-porosity rocks; cf. text above). Here, too, a thin fine-grained core develops. Because of the different faulting mechanism, the fracture density does usually not decrease with increasing distance to the core but immediately drops to the initial level of the host rock. Anyway, the deformation band density may decrease exponentially. Note that in case of high-porosity rocks, during faulting the porosity in the process zone decreases.

Fig. 2.6 shows two typical structures of brittle fault zones. In both cases, the fault zones feature two main domains: the fault core and the damage zones. Note the different thicknesses of the two domains highlighted at the bottom of the graphs. The fault core is a high-strain zone comprising clastic fault rocks, slip surfaces, and shear lenses (i.e., preserved rock bodies) ([114, p. 184f], [125, p. 216]). The damage zone is a low-strain zone comprising a wide range of fractures and deformation bands varying in length and orientation ([116, p. 1558], [125, p. 178, 186, 216], [301, p. 179ff]). Important to note is that damages zone can be on both sides of the fault core, on one side only, or don't exist at all ([114, p. 185]).

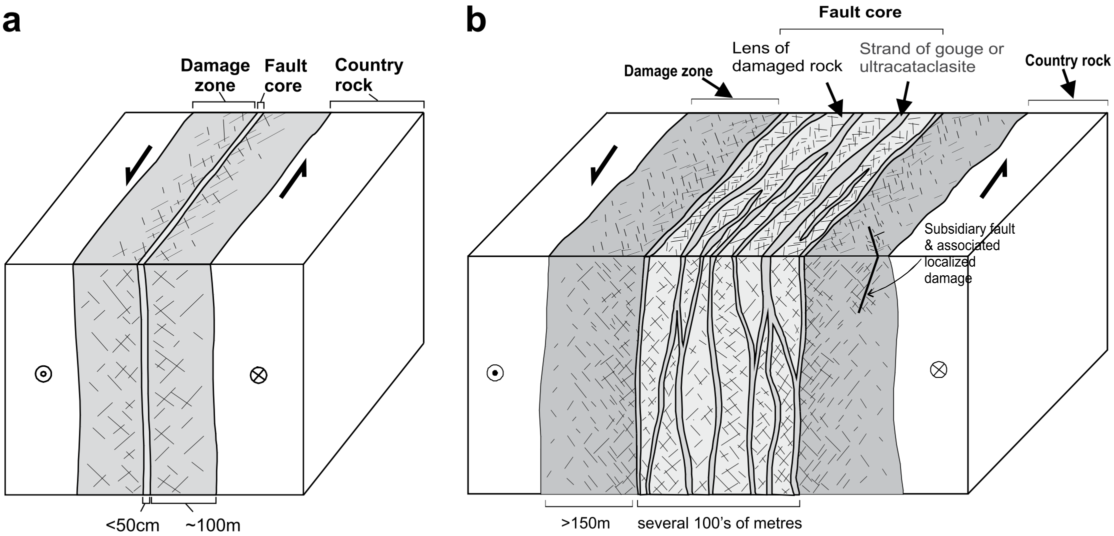

Figure 2.6: Typical strike-slip fault zone structures in a quartzofeldspathic host rock (from [264] after [115]), showing a (a) single fault core and a (b) multiple fault core, with associated damage zone.

The descriptions up to here, which provide just a small insight into the complex topic of fault zone formation, already give an idea of the manifold characteristics a fault zone can have. A fault zone is usually heterogeneous ([324, p. 14]), its thickness is rarely constant but increases with increasing fault displacement ([125, p. 183ff]), its continuous or discontinuous trace can be from dm to hundreds of km in length ([324, p. 13]), and boundaries between the domains are usually not sharp ([144, p. 1645]).

Now, larger fault zones may not only comprise (heavily) fractured, altered rocks but also re-cemented breccias or blocks of relatively undeformed wall rock randomly distributed within the fault gouge ([131, p. 354f], [324, p. 14]). The latter introduce high strength and stiffness contrasts into the rock masses of the fault zone ([62, p. 18]). Such rock masses may be termed tectonic block-in-matrix rock (bimrock) or tectonic mélanges: "a mixture of rocks, composed of geotechnically significant blocks within a bonded matrix of finer texture" ([255, p. 3]), or "a body of rock . . . characterized both by the lack of internal continuity of contacts or strata and by the inclusion of fragments and blocks of all sizes, both exotic and native, embedded in a fragmented matrix of finer-grained material" ([321] in [62, p. 41f]; cf. also Footnote 10 on p. 18). Because of the intense faulting during tectonic events, at some state, the matrix material may show soil-like behaviour (cf. [106, p. 67f], [324, p. 18]).

[78], for example, report about a diapiric mélange (cf. Fig. 2.7). It is a km-wide zone which can be divided into a core zone and a damage zone (in [78], the damage zone is termed *marginal zone*). The damage zone is 150 . . . 250 m wide, features a bimrock fabric and a pervasive cleavage. The size of the mainly lenticular shaped blocks (graywacke, mudstone, limestone, or chert) is between a few centimetres and a few decimetres. Within the mudstone matrix, they commonly align parallel to the cleavage and shear zones. In contrast, the 400 m wide (!) core zone comprises much larger blocks. They can be several metres wide and over 10 m long, and are mainly angular and irregularly shaped. The shaly matrix features a less pervasive cleavage. Therefore, probably, blocks are more randomly distributed within the matrix.

The following section gives some more general information on block-in-matrix rocks (bimrocks). Chapter 3 (p. 19) cites geometric and mechanical properties of bimrocks.

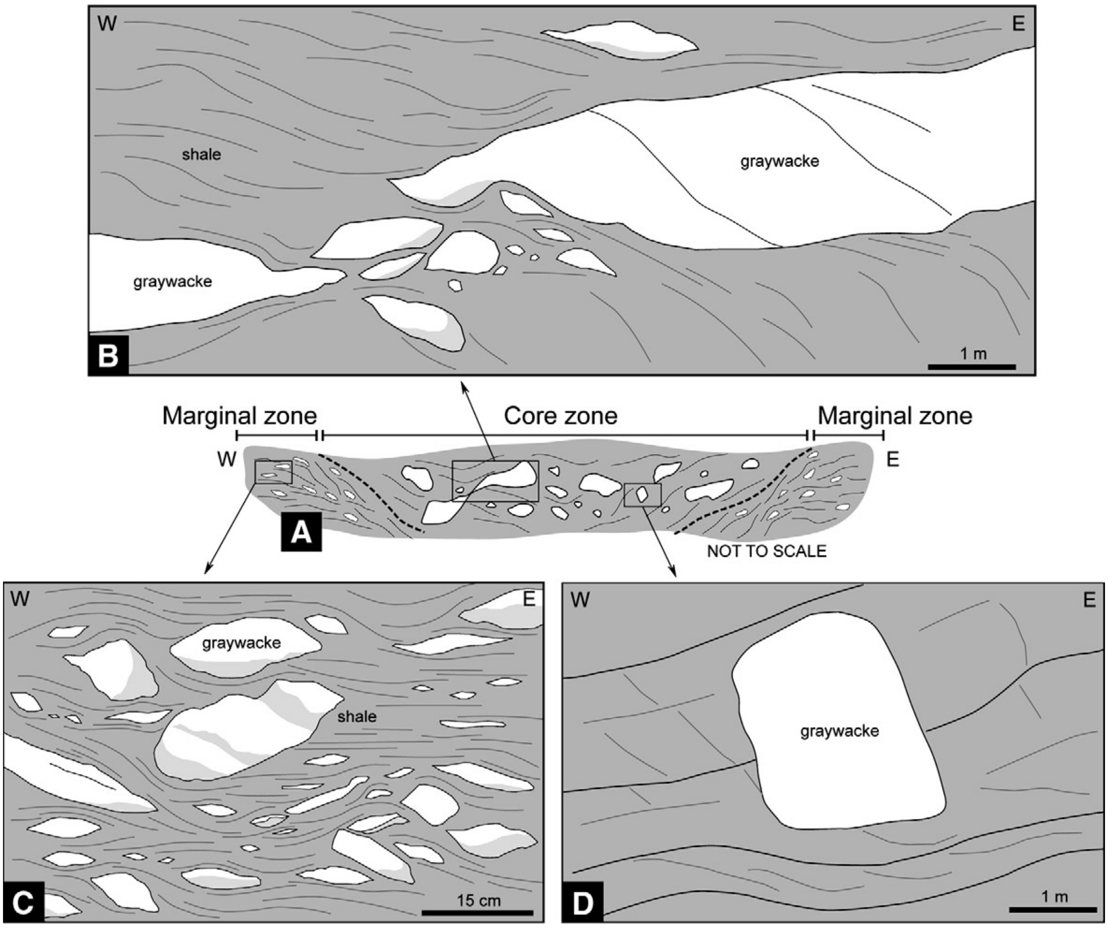

Figure 2.7: Bimrock in a fault zone: Outcrop sketches of a diapiric mélange in Pennsylvania, USA (from [78, Fig. 11, p. 224]). Both the marginal zone (= damage zone) and core zone feature a bimrock structure.

2.2 Block-in-matrix rocks

In the course of the faulting, zones detach from the host rock as fractures propagating through the host rock eventually link. Some of these zones may not get strained much ([114, p. 184]) and remain competent (compared to the surrounding material). These are the blocks within a brittle fault zone featuring a block-in-matrix (or bimrock) structure. Exemplarily, Fig. 2.8 illustrates the process of fracture initiation, propagation, and linkage for a pure strike-slip basement fault. Fig. 2.8D shows the moment blocks (here: lenses) are incorporated into the growing fault zone the first time. The types of fractures which link spatially determine the initial shape of the competent blocks ([114, p. 184]). With ongoing shearing (during the same or a subsequent event), further blocks are incorporated, some are preserved, while others fracture (compare Fig. 2.8D with Fig. 2.8E). During deformation, relative movement and kinematic or mechanical constraints (e.g., because of mobilisation of shear strength) cause blocks to rotate and to round off ([114, p. 184]; cf. also [62, p. 39]). Obviously, a wide range of block shapes seem possible within the same fault zone.

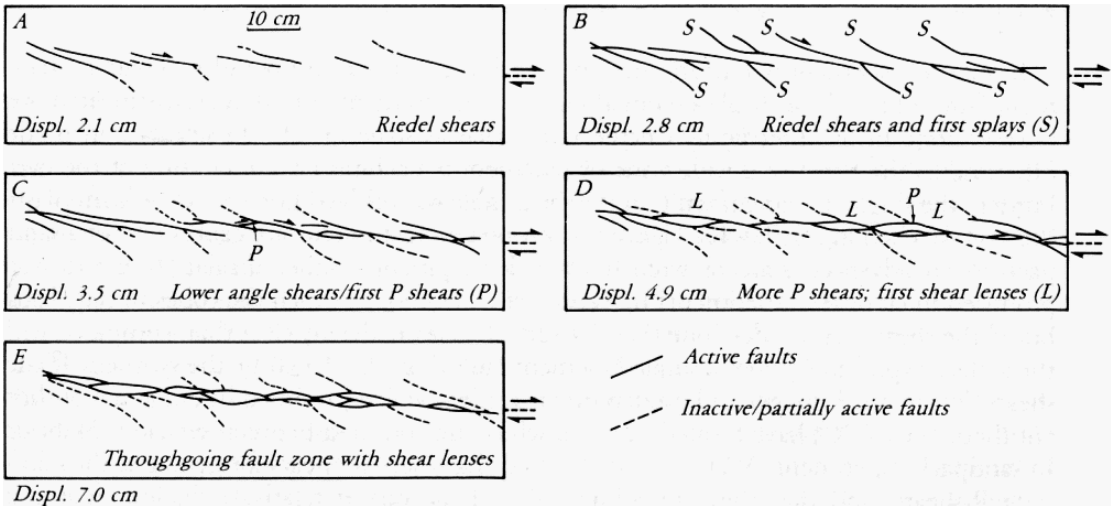

Figure 2.8: Evolution of an experimental shear zone above a single basement fault (after [273] in [240, Fig. 1.4-10, p. 143]). Plan views drawn from photographs of a sand pack surface at different stages of horizontal displacement along the basement fault. The sand pack is 10 cm thick; isotropic initial state of the horizontal stresses.

From the very beginning, fractures surround the blocks and constitute features of weakness. It is most likely that those weaknesses accommodate some subsequent deformation. Depending on the local conditions (e.g., stress field) and the evolutionary stage and present geometry of the fault zone (cf. Fig. 2.8), existing fractures either propagate independently, coalesce with other fractures (sometimes accompanied by secondary fracturing) or become inactive, new primary fractures form, or the through-going system of fractures (i.e., fault zone; cf. Fig. 2.8E) further develops or fails as a whole ([73, 322] in [62, p. 21f]).

These deformation processes are typical for brittle fault zones and do not depend on the scale ([114, p. 184]). Similar processes may take place at the sliding horizons of deep-seated landslides (cf., e.g., [106]). Fig. 2.9 graphs a few examples of the structure of linkage damage zones in strike-slip fault zones at different scales. They all show similarities independent of the scale (e.g., some larger zones enclosed by fractures remain undamaged; individual fractures accommodate most deformation). These similarities can be also found at tip and wall damage zones (cf. Fig. 3 and Fig. 7, respectively, in [196, p. 506, 510]), which are the two other characteristic types of damage zones around a strike-slip fault zone ([196, p. 504]). Irrespective of such a differentiation, according to [62, p. 38], damage characteristics are similar for all fault types (i.e., also for normal, reverse, or oblique-slip faults). At all scales, one can find competent rock blocks and a weak matrix which resulted from intensive shear and cataclasis (brittle fracturing and comminution of blocks and grains) ([324, p. 14, 17f], [114, p. 184]).

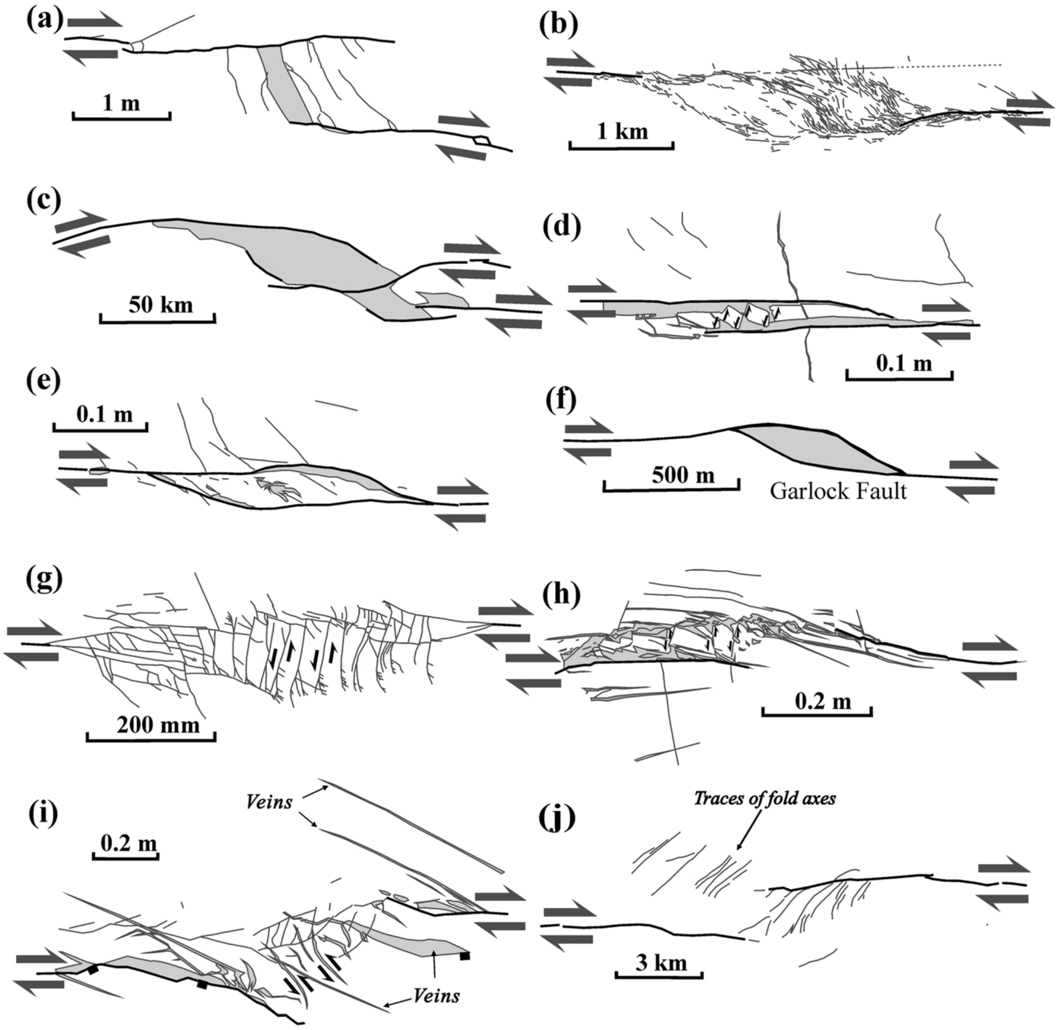

Figure 2.9: Examples of linkage damage zones in strike-slip fault zones at different scales (from [196, Fig. 5, p. 508]). Depending on the evolutionary stage and local conditions, the fault zones show different characteristics: (a) extension fractures and pull-aparts; (b) extension fractures and strike-slip duplexes; (c) pull-apart basin; (d) block rotation; (e) strike-slip duplexes or isolated lenses; (f) isolated lenses; (g) block rotation; (h) block rotation; (i) antithetic faults and connecting faults; (j) potential linkage in a fault zone. Thick line . . . major fault; thin line . . . minor fault; shading . . . vein in small scale examples and basin in large scale examples.

Blocks which feature a higher stiffness than the surrounding matrix material inevitably attract stresses because of unequal deformation ([227, p. 83]).[5] The contact surfaces between the blocks and the matrix material are already surfaces of weakness ([227, p. 113], [226, p. 847]) and must bear the additional load. [23, 24] simulated unconfined and confined compression tests on bimrocks numerically. Although they did not consider an interface between the competent and weak zones, they could show that stresses concentrate at the boundaries of the competent zones. In nature, stresses may accumulate as long as sufficient shear strength can be mobilised or kinematics prevent shear. Rather this state is simulated by [23, 24] (i.e., no slip along the interface). However, at any one time, such a contact surface may fail and weaken even more. In line with this, other researchers could observe that failure in bimrocks of brittle fault zones generally follows the block-matrix contacts ([227, p. 2, 71, 101f], [226, p. 847], [255, p. 154], [185, p. 1473]) and that these contacts may be the weakest components of the bimrocks ([251, p. 36], [254, p. 267]). Note that individual segments of block-matrix contacts may be part of distinct shears ([251, p. 36]).

In summary, the block-matrix contacts in brittle fault zones likely feature a lower strength and stiffness than the surrounding materials they separate. In contrast, the block-matrix contacts in bimrocks which formed by lithification[6] (sedimentary rock) or solidification[7] (igneous rock) may be stronger. Sedimentary rocks form by lithification when deposited loose clasts (i.e., fragments or grains) are cemented together ([246, p. 211]). Here, minerals precipitating from water solutions provide the cementing material ([246, p. 239]). The process may intensify when temperature and/or pressure increases (e.g., increasing overburden) ([246, p. 239]). Sedimentary bimrocks form when the deposit, which later lithifies, comprises smaller and (much) larger clasts (i.e., poorly sorted; e.g., debris flows, colluvium, or glacial till). If such a deposit, however, does not undergo the processes of lithification and remains more or less uncemented, one may refer to this mixture of large clasts (rock inclusions) and a fine matrix (soil) as a *bimsoil* ([193, p. 65], [248, p. 1031], [249, p. 153]). As for igneous bimrocks, molten rock[8] must enclose larger rock fragments and solidify thereafter. Metamorphic or weathering processes may further alter the bimrock. An example of a sedimentary bimrock is the Misis tectonic breccia (dolomitic limestone blocks embedded in fine-grained matrix of claystone) investigated by, e.g., [185, 186]. [9, 184] investigated the Ahauser tectonic breccia, another sedimentary bimrock comprising slate blocks and a carbonate matrix. It's a special bimrock since the matrix is stronger than the blocks (!). An example of an igneous bimrock is the Ankara agglomerate, a volcaniclastic mixture of Andesite blocks and a tuff matrix, investigated by, e.g., [376, 377, 378].

In literature one may read the term *welded* in the description of some igneous bimrocks (e.g., ignimbrite[9]). During the formation of such bimrocks, the molten rock is so hot that its constituents weld together ([246, p. 181]) by sintering ([11, *ignimbrite*, p. 296]). Some authors use the term *welded bimrock* also for non-igneous bimrocks, such as cemented conglomerates (e.g., [80, p. 3]), which might be wrong. Anyway, they probably use the term to highlight the strong bond between the constituents of sedimentary rocks which have formed under high temperature

[5]There would be no difference in deformation only if "the stresses within the block and the matrix material were different in exactly such a way that the materials [comment by author: different in stiffness] would undergo the same strains at their contact" ([227, p. 83]).

[6]Lithification is "the transformation of loose sediment into solid rock through compaction and cementation" ([246, p. G-14]). It is one aspect of diagenesis, i.e., of "all physical, chemical, and biological processes that transform sediment into sedimentary rock" ([246, p. 239]). According to [11, p. 344], lithification not necessarily involves burial alteration or compaction.

[7]Solidification is a synonym for freezing of a liquid (here: molten rock). [246, p. 128, 153]

[8]Molten rock is termed *magma* if it is beneath the Earth's surface, or *lava* if it is on top of the Earth's surface. [246, p. G-14]

[9]It's a synonym for welded tuff. [11, p. 630], [246, p. 469]

and/or pressure conditions. In welded bimrocks, the block-matrix contacts may be as strong as the lithified matrix material ([379, p. 1], [80, p. 3]). Some sort of bimrock may also form when physical and chemical weathering processes (e.g., dissolution of weaker minerals, or hydrolysis; [246, p. 195f]) alter an initially solid rock (e.g., decomposition of granite; [248, p. 1031]). [227, p. 113f] highlights that the results from his studies on artificial mélange[10] may not apply to, e.g., a core-stone bearing saprolite[11], as in such a special weathered bimrock the blocks grade into the matrix and, thus, the block-matrix contacts are not well-defined surfaces of weakness (in contrast to brittlely formed bimrocks). The same conclusion applies for cemented or welded yet unsheared bimrocks. For such bimrocks it would be valid to assume displacement compatibility between the blocks and the matrix material (i.e., no need for an interface in numerical models) ([396, p. 64]). Although the constituents of brittlely formed bimrocks in fault zones can also cement together, for the low permeability in even slightly cohesive fault rocks, pore-water circulation is limited and, thus, the cementation rate is normally very low ([339, p. 161]). As block-matrix contacts and shears surrounding the blocks are often the weakest elements, thus, being probably ground up most comprising very fine grains, they probably are also the elements within the matrix material with the lowest permeability. Hence, it seems more likely that pore-water circulation and related cementation processes will take place in less-strained matrix zones. Most block-matrix contacts may remain unaffected by cementation and, thus, weak.

[10] Mélange is a bimrock comprising competent blocks commonly embedded in sheared matrices of weaker rock. [254, p. 262], [11, p. 365]

[11] A saprolite is a rock chemically rotted in situ ([11, p. 512]). The decomposition of granite results to a bimrock which contains hard blocks (core-stones) surrounded by a matrix of dense sandy soil ([254, Fig. 1, p. 262]).

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