Fault zone characteristics, fracture systems and permeability implications of Middle Triassic Muschelkalk in Southwest Germany

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Abstract

Fault zone structure and lithology affect permeability of Triassic Muschelkalk limestone-marl-alternations in Southwest Germany, a region characterized by a complex tectonic history. Field studies of eight fault zones provide insights into fracture system parameters (orientation, density, aperture, connectivity, vertical extension) within fault zone units (fault core, damage zone). Results show decreasing fracture lengths with distances to the fault cores in well-developed damage zones. Fracture connectivity at fracture tips is enhanced in proximity to the slip surfaces, particularly caused by shorter fractures. Different mechanical properties of limestone and marl layers obviously affect fracture propagation and thus fracture system connectivity and permeability. Fracture apertures are largest parallel and subparallel to fault zones and prominent regional structures (e.g., Upper Rhine Graben) leading to enhanced fracture-induced permeabilities. Mineralized fractures and mineralizations in fault cores indicate past fluid flow. Permeability is increased by the development of hydraulically active pathways across several beds (non-stratabound fractures) to a higher degree than by the

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formation of fractures interconnected at fracture tips. We conclude that there is an increase of interconnected fractures and fracture densities in proximity to the fault cores. This is particularly clear in more homogenous rocks. The results help to better understand permeability in Muschelkalk rocks.

1. Introduction

Since fault zones show a different permeability structure compared with their host rocks, they may control crustal fluid flow (Chester and Logan, 1986; Caine et al., 1996; Sibson, 1996; Caine and Forster, 1999; Sibson, 2000; Agosta and Kirschner, 2003; Micarelli et al., 2006a; Caine et al., 2010; Faulkner et al., 2010; Gudmundsson et al., 2010; Agosta et al., 2012; Philipp, 2012; Reyer et al., 2012). They can either act as conduits or barriers, depending on their infrastructure and the local stress field (e.g., Caine et al., 1996; Agosta et al., 2010; Gudmundsson et al., 2010). In general, fault zones consist of distinct units with different properties. Namely, the fault core in the fault zone center, comprising fault gouge, brecciated material and mineral precipitations, and the surrounding damage zone, characterized by an increased fracture density and minor faults (Chester and Logan, 1986; Caine et al., 1996; Berg and Skar, 2005), where preexisting structures such as bedding are commonly preserved (e.g., Billi et al., 2003). The increased fracture densities in the damage zones may lead to an enhanced permeability (Caine et al., 1996; Faulkner et al., 2010; Gudmundsson et al., 2010). In contrast, fault gouge with reduced grain sizes as well as mineral precipitation within the fault core decrease permeability in many cases. During slip in active fault zones, however, fractures or pores may get interconnected and provide an enhanced permeability within this unit (e.g., Sibson, 1994; Caine et al. 1996).

The damage-zone/fault-core model based on of fault zones in brittle rock, however, is not applicable to all fault zones due to their formation in different rock types with various mechanical properties (e.g., porous sedimentary rocks). Some authors therefore describe

additional units in high porosity or unconsolidated sediments, such as mixed zones embedded between fault core and damage zone (Heynekamp et al., 1999), or a distal fault core at the margins of the fault core (Clausen et al., 2003). Furthermore, additional structures in porous rocks may form which show contrary effects on permeability compared to fractures: deformation bands (sandstones, carbonates) or stylolites (carbonate rocks), with enhanced sealing capacities (Aydin, 1978; Antonellini and Aydin, 1994; Tondi et al., 2006). These structures are the result of either grain movement, grain rotation or grain fracturing in narrow bands of localized strain (deformation bands), and pressure solution (stylolites) (Aydin, 1978; Antonellini and Aydin, 1994; Tondi et al., 2006), and may lead to a decreased permeability (Antonellini and Aydin, 1994; Fossen et al., 2007).

In fractured reservoirs fractures may have great effects on fluid flow, since they can either increase reservoir permeability or increase permeability anisotropy (Nelson, 1985; Gudmundsson, 2011; Philipp et al., 2013). Because matrix permeability in geothermal reservoir rocks is negligible in most cases and high flow rates are needed for successful geothermal projects, the characterization of fault zones and associated fracture systems is of particular importance (Paschen et al., 2003; Philipp et al., 2010; Stober et al., 2011; Reyer et al., 2012). In the present study we use outcrop analogues to analyze the effect of fault zones on fracture system parameters and permeability in fault-related and fractured geothermal reservoirs.

Outcrop analogues expose rocks similar to those found at geothermally relevant depths (in terms of stratigraphy, lithology, facies) and therefore provide an opportunity to study fracture-induced permeability of potential geothermal reservoir rocks (Philipp et al., 2010). We focus on the Middle Triassic Muschelkalk which forms one potential geothermal reservoir in a region with comparatively high geothermal gradient in Germany: the Upper Rhine Graben (URG; Paschen et al., 2003; Stober and Jodocy, 2009; Stober et al., 2011). We investigate whether the simplified fault core-/damage zone model is applicable to define the permeability

structure of fault zones crosscutting more or less brittle carbonates. In particular we focus on the fracture systems associated with the fault zones. Deformation bands or stylolites were not visible macroscopically in the field and therefore are not taken into account. We present results of eight fault zones crosscutting Muschelkalk rocks of the Kraichgau-Syncline located on the eastern graben shoulder of the URG (Fig. 1) aiming at characterizing fault zones and associated fracture systems. First, we show preferred orientations of fault zones and associated main fracture sets in the Kraichgau-Syncline. Here we aim at integrating fault zone developments in the context of the regional stress field evolution. Second, we characterize three selected fault zones in detail. We examine selected fracture system parameters (orientation, density, aperture, connectivity, vertical extension) within defined fault zone units and their distributions across the fault zones. Special attention is given to record mineral precipitations within the fault zone units and in particular within fractures to highlight preferred orientations of past fluid flow. With the studies we gain insights into the development of fracture-associated permeability of Muschelkalk rocks.

2. Geological setting

The URG forms the central part of the Cenozoic European Rift System, which extends from the North Sea to the Mediterranean Sea (Illies, 1972; Ziegler, 1992; Schumacher, 2002; Ziegler and Dèzes, 2005). This extensional structure, margined by master normal faults, was formed since Eocene in a weakened region, due to a thinned crust and a thermal anomaly, and exhibits a displacement of approximately 4 km (Illies, 1972; Illies and Greiner, 1978, Ziegler and Dèzes, 2005). The graben interior is filled with Tertiary and Quaternary sediments. The Variscan basement as well as Permian and Mesozoic formations crop out at the eastern and western graben shoulders (Illies, 1972; Walter, 2007), which were uplifted during subsidence within the graben (Schweitzer and Kraatz, 1982; Trunkó, 1984; Ziegler, 1992).

The URG shows an asymmetric setting with larger displacement at the eastern graben margin (Illies, 1972; Eisbacher and Fielitz, 2010). Due to a complex fault block structure within the graben and variations in displacement, lithological changes are common and an irregular graben floor is developed (Illies, 1972; Trunkó, 1984).

The URG evolution is marked by repeated stress field changes, for example in Oligocene and Miocene (Illies, 1972; Trunkó, 1984; Schuhmacher, 2002). In the Pliocene, the URG was reactivated again, resulting in strike-slip movements from changes in the regional stress field (Illies and Greiner, 1978; Schumacher, 2002). The shear components led to reactivations of primary normal faults as oblique-reverse faults in particular at the eastern graben margin (Illies, 1972; Ziegler, 1992). The recent stress field provides a strike-slip stress regime parallel to the graben axis as well (e.g., Ziegler, 1992, and references therein; Schumacher, 2002; Heidbach et al., 2008).

Our study area, the Kraichgau-Syncline (Fig. 1), is located on the eastern graben shoulder of the URG and part of the Franconian-Syncline (Walter, 2007). This syncline belongs to a system of ENE-WSW trending intramontane basins, which developed during the Stephanium and Early Permian due to reactivations of Variscan structures (Schuhmacher, 2002; Ziegler and Dèzes, 2005). In context of the URG tectonics the Kraichgau-Syncline was mildly uplifted compared with the adjacent highs of Odenwald and Black Forest on the eastern graben shoulder (Schweizer and Kraatz, 1982; Engesser and Leiber, 1991). Various fault zones crosscut the Kraichgau-Syncline with preferred orientations of SSW-NNE, SW-NE and NW-SE (Trunkó, 1984).

The Middle Triassic Muschelkalk, divided into Lower, Middle and Upper Muschelkalk, has a total thickness of 200 m to 230 m. The succession is composed of alternating carbonates and evaporates (Schweitzer and Kraatz, 1982; Engesser and Leiber, 1991). These alternations are the results of sea-level-changes during their deposition in the epicontinental sea (Engesser and Leiber, 1991).

The Lower Muschelkalk shows a total thickness of approximately 75 m to 78 m and comprises carbonates, i.e. limestones, marly limestones, marls and dolomites, which were deposited under shallow marine conditions (Schweitzer and Kraatz, 1982; Engesser and Leiber, 1991). The thickness of Middle Muschelkalk rocks is varying but shows a maximum of 100 m (Engesser and Leiber, 1991; Eisbacher and Fielitz, 2010). These alternating carbonates and evaporites (dolomite, gypsum, anhydrite, rock salt) were formed under a shallow marine environment in a marine basin that repeatedly became isolated and experienced significant evaporation. Leaching of these evaporates has led to the aforementioned thickness variations, and only residual clay is commonly present (Engesser and Leiber, 1991). The 85 m to 100 m thick formation of the Upper Muschelkalk can be further subdivided into three main subunits, named as *Trochiten-Kalk* (mo1), *Nodosus-Schichten* (mo2) and *Semipartitus-Schichten* (mo3). They are characterized by micritic limestones, which are low on fossils, alternating with fossil-rich carbonates, marls and clay (Schweitzer and Kraatz, 1982; Engesser and Leiber, 1991). Deposition has been ascribed to a shallow marine environment characterized by changing water conditions (micritic limestones versus tempestites; Schweitzer and Kraatz, 1982; Engesser and Leiber, 1991).

3. Field studies

To obtain information on fault zone infrastructures, well exposed fault zones with distinct fault zone units are needed. The selected quarries, where the Muschelkalk rocks are crosscut by various fault zones, are located in the northern and southern part of the Kraichgau-Syncline (Fig. 1). The Nussloch-quarry is situated near the URG master-fault, whereas the Illingen-quarry shows the maximum distance of approximately 30 km to the graben margin. Due to the tectonic history of the study area, including changes in the regional stress field resulting in reactivations (cf., Sections 2. and 5.1.), the fault zones are of different types and show various

displacements (cf., Table 1, Section 5.1.). The damage zones of some main fault zones include minor faults, as is expected by progressive fault growth (e.g., Childs et al., 2009). In order to characterize the fault zone infrastructures, we determined the thicknesses and lithological features of the fault cores as well as the damage zone characteristics (damage zone widths and properties of the fracture systems within the damage zones; see below). According to previous studies we define the boundary between fault core and damage zone as the boundary between faulted rock (e.g., fault gouge or breccia, lenses, dragged bedding) and pronounced original bedding where the fracture density is higher than the background density (cf., Braathen et al., 2009; Bastesen and Braathen, 2010; Bastesen et al., 2013; Schueller et al., 2013).

Kinematically and mechanically, fractures can be distinguished in extension fractures and shear fractures, depending on their relative movement to the fracture plane (Fossen, 2010; Gudmundsson, 2011). Extension fractures show a relative movement normal to the fracture plane (opening/extension mode, for example joints and veins) and shear fractures in direction parallel to it (shear modes; eg., Twiss and Moores, 2007; Gudmundsson, 2011). Since there is not always the possibility to obtain clear evidence for fracture kinematics in the field, we use the general term fracture for a surface across which the rock has lost cohesion.

To determine the damage zone width, the fracture density distribution (number of fractures per unit length) normal to the slip surface was detected, if possible, in several limestone beds of these limestone-marl-alternations, using the scanline-method (e.g., Priest, 1981; Berg and Skar, 2005; Micarelli et al., 2006a). The selected limestone beds are well exposed and traceable over several meters. In rare cases of covered beds we used beds with comparable thicknesses for continued scanlines. Each scanline starts at the boundary of the fault core and damage zone (the fault core thickness was measured at this zero point) and runs towards the damage-zone-/host-rock transition of the hanging wall and footwall, except for the scanline across the Illingen oblique-slip fault (cf., Sections 4.1., 4.2.2.). Additional scanlines within the

undisturbed host rock give information on background fractures. We define the outer boundary of the damage zone as the point where the fracture density clearly decreases towards background fracturing (e.g., Childs et al., 2009; Schueller et al., 2013). Besides the fracture orientations (strike direction and dip angle), the properties of each fracture within the defined fault zone units were examined as follows.

One important fracture parameter in terms of reservoir permeability is the fracture aperture. Few open fractures with larger apertures may enhance the permeability, because the flow rate depends on the cube of the fracture aperture (cubic law; De Marsily, 1986; Odling et al., 1999) and fluid flow may be channeled along the widest parts of a fracture (Odling and Roden, 1997; Philipp et al., 2013, and references therein). We show the maximum values of fracture apertures, that is the maximum fracture dimension measured perpendicular to the fracture walls (Philipp et al., 2013). However, we have to consider that measurements under surface conditions are not directly applicable for permeability calculations for example due to uplift induced expansion and erosion as well as weathering effects such as karstification. It is intended that our measurements provide indications for fracture aperture distributions within fault zones, but no absolute values.

Additionally, it is necessary to distinguish between open fractures and fractures sealed with mineral precipitations. Open fractures include no filling material between the fracture walls (Nelson, 1985). We name fractures showing mineral precipitations, for example deposits of calcite or silica, mineralized fractures. They are indicators for past fluid flow, whereas they could act as barriers for recent fluid flow in potential geothermal reservoirs (Nelson, 1985; De Marsily, 1986; Philipp, 2012). Thus, the fracture orientations and distance to the fault core of mineralized fractures were noted during the field studies. Due to sealing of these fractures the fracture thickness was measured instead of fracture aperture.

Furthermore, the fracture system connectivity is of great importance in our investigation, because only interconnected fractures could form a hydraulically active fracture network

(Stauffer and Aharony, 1994; Odling et al., 1999; Ortega and Marrett, 2000; Micarelli et al., 2006a; Philipp et al., 2013). We distinguish between connected and unconnected fractures, that is, between fractures whose tips terminate against other fractures, and unconnected fractures with no visible connection. These observations indicate the degree of physical connection of the fracture system.

Additionally, we take the fracture vertical extension into account. First, the fracture length was investigated as the distance of a straight line connecting the two fracture tips in vertical direction (also referred to as fracture height). Second, we considered how far the fractures propagate through the mechanically layered rocks, distinguishing ‘stratabound’ and ‘non-stratabound’ fractures (Odling et al., 1999). Stratabound fractures are restricted to only one limestone bed. Non-stratabound fractures, however, expand across several beds and therefore may create a hydraulically relevant flow path between multiple layers.

4. Field results

In this section, first a short overview of the orientations of all analyzed fault zones and of the fracture systems within the quarries is presented. Second, detailed results of fault zone infrastructures and associated fracture system properties of selected, well exposed fault zones are shown to analyze their complex structures and discuss their most likely specific tectonic development.

4.1. Fault zone and fracture system orientations

We show the orientation of the fracture system (all fracture data of fault zones and host rock) as well as the fault zone orientations within the quarries Nussloch (NL), Illingen (IL), Knittlingen (KN) and Ittlingen (IT) (Fig. 2; the color code refers to the fault zone classifications in the discussion, Section 5.1.). Despite the Knittlingen-quarry exposes

additional fault zones, we only present results of three fault zones due to the best accessibility in the outcrop.

The analyzed fault zones are formed parallel to regional structures of the URG and the Kraichgau-Syncline in NNE-SSW- to N-S-direction, NW-SE-direction and E-W-direction.

The individual fracture systems are clearly affected by the fault zones: main fracture sets are formed parallel or subparallel to the fault zone strikes, except for the Knittlingen-quarry, where a wider scatter in fracture orientations occurs.

Since footwall and hanging wall show an asymmetric deformation behavior resulting in different fracture patterns within these fault blocks (e.g., Berg and Skar, 2005; Reyer et al., 2012), detailed fracture data are separated in fractures in footwalls versus fractures in hanging walls of the fault zones (Fig. 3; the color code refers to the fault zone classifications in the discussion, Section 5.1). The main fracture set is developed parallel to the fault zone strike in almost all hanging walls. In the footwalls, however, the fracture sets are formed either subparallel to or exhibit an angle of approximately 30° to the fault zone strike. These fractures may be shear fractures (Riedel shears) associated with the fault zone. Some of these fractures, however, may be not directly fault-related, but rather background fractures associated with the main regional stress field. Differing fracture orientations within the defined fault zone units are developed particularly in the Knittlingen-quarry.

Figure 4 shows the fracture system orientation within the fault zone in Illingen. Due to the steep dip of this fault zone, we distinguish between eastern fault block, western fault block and fault core only. The fracture systems in the eastern and western fault blocks contain main fracture sets parallel to main and minor (western fault block) slip surfaces. Fractures with differing orientation in the eastern fault block are interpreted as background fractures associated with main regional structures. The main fracture set in the fault core is different with strike NNE-SSW.

4.2. Detailed fault zone analyses

4.2.1. Nussloch

The steep-dipping fault zone cropping out in the Nussloch-quarry (northern Kraichgau; cf., Fig. 1) is hosted in parts of the entire succession of the Muschelkalk. The first slip surface (SP 1; NE) juxtaposes Middle Muschelkalk rocks, mainly residual clay and dolomite, and limestone-marl-alternations of the Lower Muschelkalk in the lower outcrop-level as well as Middle Muschelkalk rocks in the upper level. Another adjacent slip surface (SP 2; SW) juxtaposes these Middle Muschelkalk rocks and the Upper Muschelkalk (Fig. 5). A synthetic minor fault zone located in the hanging wall (Upper Muschelkalk) intersects with this main slip surface SP 2. The triangularly shaped area embedded between the slip surfaces of main and minor fault is highly fractured at their intersection (named as fractured zone, Fig. 5b). The up to 13 m wide fault core is embedded between the main slip surfaces and consists of inclined Middle Muschelkalk rocks and underlying Lower Muschelkalk rocks (Figs. 5 and 6). In general, this fault core comprises deformed rock, fault breccia and isolated host rock lenses, particularly at the fault core/hanging-wall-transition. In the Middle Muschelkalk part, gray colored residual clay is dragged downwards in an s-shape. Minor slip surfaces within the fault core displace the rocks at several locations. At the fault core-hanging-wall-boundary the fault core is characterized by red-colored, up to 1.5 m wide mineralizations (Fig. 6). The fracture density distribution normal to the fault zone was examined in several scanlines. The highest fracture density occurs at contact to the slip surface (Fig. 7). However, there is no decrease to background fracturing with rising distance to the fault core. We assume that the outer damage zone boundary is not reached in the analyzed fault zone section and that our measurements were exclusively performed within the damage zone. Two scanlines cut the minor fault zone within the hanging wall damage zone and therefore their minor damage zone as well (Fig. 7b).

4.2.2. Illingen

The steep fault zone in Illingen shows slight changes in strike-direction (see above; Fig. 8). The quarry provides the possibility to study both the fault core in the South (Figs. 8a and 8b) and one slip surface in the North (Fig. 8c). Various structures are hosted on the undulating slip surface exposed in the North such as slickenlines and slip fibers. Additionally we observed limestone beds rotated and truncated against each other (Fig. 8c). The fault core in the South, embedded within the two main slip surfaces, comprises fault breccias at contact to the main slip surfaces, limestone beds folded to an anticline in the upper center, flexures at contact to the western slip surface, and limestone lenses (Fig. 8a). Minor slip surfaces juxtapose the rocks at the bottom of the wall with a normal displacement of approximately 15 cm (Fig. 8b). The dip-direction and dip-angle of the bedding changes within the fault core, with a steeper angle towards the western main slip surface (Fig. 8b). Similar flexures are formed in the eastern fault block at contact to the slip surface, whereas the bedding in the western fault block is more or less horizontal. The western fault block is crosscut by one minor fault zone.

4.2.3. Knittlingen

The low-angle fault zone in Knittlingen with unknown displacement because of lacking visible marker horizons shows various deformation structures in hanging wall and footwall in particular (Fig. 9). The most conspicuous structure in the footwall is a synthetic minor fault. Between main and minor slip surface thin and softer layers are folded, but the thick and competent bed underneath is broken and shows a counterclockwise rotation. Another noticeable structure in the footwall is one water-bearing antithetic discontinuity, which intersects with the aforementioned minor slip surface. The hanging wall, where a flexure is formed, is less deformed than the footwall.

The fault core comprises various structures like lenses and both upwards and downwards dragged, tilted, and folded bedding. Other fault core parts are completely mineralized or comprise brecciated rock.

One outcrop-level beneath, where decimeter-thick limestone beds crop out, a differing deformation behavior is observable in the footwall. The competent beds are compressed, but not folded. In contrast, flexures occur in the hanging wall. The fault core in this fault zone part is brecciated and comprises discolored zones. Some limestone beds are dragged upwards in the fault core, similar to the upper section of this fault zone.

We determined the fracture density distribution normal to the fault zone (Fig. 10). Our results show no clear decrease to background fracturing with rising distance to the fault core. In addition to the high fracture density at contact to the slip surface an increased fracture density was detected at a distance of 2 to 3 m in the hanging wall.

4.3. Fracture connectivity

As mentioned in Section 3., the fracture connectivity is one important parameter in terms of reservoir permeability (Stauffer and Aharony, 1994; Odling et al., 1999; Micarelli et al., 2006a). We plot the fracture length versus fracture orientation (scale: 0°-180°; Fig. 11), and fault core distance [m] (Fig. 12) respectively, where we distinguish between connected (connected at either one or both tips) and unconnected fractures. Some fractures are marked by a star, because only the minimum length could be detected when one fracture tip was visible.

We plot the fracture length [m] of all fractures within the fracture systems vs. fracture orientation (Fig. 11a). In general, shorter fractures (up to a fracture length of 1 m) are more common within the quarries. Due to this huge number of comparatively shorter fractures, we show the data of fractures up to a fracture length of 1 m (Fig. 11b), in addition, to get a higher resolution on their fracture connectivity. The percentage of fractures with great length is

generally higher for fractures parallel or subparallel to major slip surfaces and to regional structures (i.e. URG, axis of the Kraichgau-Syncline).

Most of the fractures are unconnected, whereby especially shorter fractures formed parallel to the fault zones provide a better connectivity within the fracture system. The highest percentage of interconnected fractures, and fractures connected at both fracture tips in particular, occurs within the Nussloch fracture system.

To show the connectivity of the fracture system within the fault zones, we plot the fracture length [m] and connectivity vs. fault core distance [m]. Individual long fractures are formed up to 6 m distance to the fault core of the fault zone in Nussloch, whereby the fracture length decreases with distance to this unit. Very few fractures (up to 0.5 m in length) are connected at both tips in the hanging wall of this fault zone, mainly up to a maximum distance of 3 m to the fault core (Fig. 12a). In the footwall fewer fractures with lengths up to 0.3 m are connected at one fracture tip.

The fracture system within the fault zone in Illingen contains mostly unconnected fractures, apart from individual fractures in the eastern fault block (Fig. 12b). Within the separated fault zone units of the fault zone in Knittlingen some fractures show connectivity at one fracture tip (Fig. 12c). These fractures, however, do not exceed a fracture length of 0.2 m, with one exception in the footwall (0.6 m).

In general, the data show a decreasing fracture length with increasing distance to the fault cores but a better connectivity of fractures with lengths up to 0.5 m (Fig. 12). That implies an improvement of fracture system vertical connectivity based on these comparatively shorter fractures in the fault zone units, as mentioned above.

4.4. Fracture vertical extension

Fractures extending over multiple limestone beds (i.e., non-stratabound fractures) may increase the reservoir permeability across the mechanically layered Muschelkalk rocks in

vertical direction. Stratabound fractures, however, are restricted to one bed (cf., Section 3.; Odling et al., 1999). Therefore, we plot the percentage of stratabound to non-stratabound fractures determined in the quarries separately for the units fault zone and host rock and the same data in relation to the fault core distance of the detailed fault zones (cf., Section 4.2.; Figs. 13b, 13d, and 13f). Due to isolated limestone beds within the fault core of the fault zone in Illingen and a resulting rare dataset compared with the other outcrops, the fracture system within this fault zone is separated to eastern fault block, fault core and western fault block (Fig. 13d). In Figure 13 the fault zone types refer to the definitions in the discussion (Section 5.1.).

The percentage of non-stratabound fractures in the Nussloch-quarry is higher for all separated units, with a slightly increased value in the analyzed fault zone and a lowest value in the host rock of Upper Muschelkalk (HR mo, Fig. 13a). Within the fault zone, non-stratabound fractures clearly increase with proximity to the core zone (Fig. 13b). At the minor fault crosscutting the hanging wall of the main fault zone, the amount of non-stratabound fractures is enhanced in the minor fault hanging wall.

In contrast, the general percentages of stratabound fractures in Illingen and Knittlingen are higher (Figs. 13c and 13e), except for fractures within one fault zone in Knittlingen (FZ 3; Fig. 13e). The fault zone in Illingen contains a higher percentage of non-stratabound fractures within the eastern and western fault blocks, but a smaller value within the core zone of this main fault.

Within one fault zone in Knittlingen, described in detail in Section 4.2.3. (FZ 1), the percentage of stratabound fractures at contact to the fault core is high (Fig. 13f), particularly in the footwall. Non-stratabound fractures, however, increase in direction to the aforementioned antithetic discontinuity crosscutting the footwall (cf., Section 4.2.3.).

4.5. Mineralized and open fractures

We show the fracture aperture data to describe the fracture aperture distribution within the fault zones. Preferred fracture orientations and fracture locations for past fluid flow are highlighted by recording mineral-precipitations within the fracture system (cf., Section 3.). We plot the fracture aperture or thickness [mm] versus fracture orientation (Fig. 14, left) as well as the percentages of mineralized fractures (Fig. 14, center). Finally, we plot the fracture aperture or thickness [mm] in relation to the fault core distance (Fig. 14, right). In all plots we distinguish between mineralized and open fractures. Mineralized fractures with unknown thicknesses (e.g. due to only one visible fracture plane) are plotted with a fracture thickness of 0.1 mm in order to represent the fracture location in relation to the fault core distance. The fracture systems in the quarries Nussloch, Illingen and Knittlingen contain mainly open fractures. The highest amounts of mineralized fractures were observed in the host rock of the Upper Muschelkalk and within the damage zone of the main fault zone in Nussloch. In Knittlingen and Illingen a minor amount of mineralized fractures was detected, where the few mineralized fractures are developed mainly within the fault zones. In general, our data show a preferred orientation of fractures sealed with minerals parallel and subparallel to the analyzed fault zones and to regional structures like the URG, variscan and hercynian structures (Fig. 14), that is in NNE-SSW-, NE-SW- and NW-SE- direction. Fractures with comparatively larger apertures or thicknesses up to 4 mm (Illingen) are accumulated in these main directions as well. Several of these thicker fractures show mineral-precipitations, particularly in the Nussloch quarry (Fig. 14a). In all described fault zones the fracture apertures or thicknesses decrease with increasing distance to the slip surfaces. By contrast, no clear relation between mineralization and fault core distance becomes apparent. In Nussloch and Knittlingen (Figs. 14a and 14c) many fractures located close to the fault core show mineralizations, but also at distance up to a few meters. In the Illingen oblique-slip fault zones (Fig. 14b), however, only few fractures, located in the fault core, are mineralized.

5. Discussion

5.1. Kinematics and tectonic evolution of the fault zones

The described fault zones show different geometric features and dissect this area in different blocks. In this section, we aim at explaining the evolution of the analyzed fault zones, regarding to the different stress field phases and interpreting fault zone kinematics. Schumacher (2002) discusses the evolution of the URG within a changing regional stress field environment in detail and names four main evolution phases:

- 1.) Late Eocene: N-S- to NNE-SSW-oriented compression (σ_1 -direction: NNE) resulting in left lateral strike-slip. Primary ENE-WSW- and NNE-SSW- oriented faults were reactivated as normal faults or strike-slip faults, respectively.
- 2.) Early Oligocene: WNW-ESE- to E-W-oriented extension (σ_3 -direction: WNW) within the main rifting phase with regional normal faulting.
- 3.) Late Oligocene: NE-SW-oriented compression (σ_1 -direction: NE) resulting in right lateral strike-slip (also reactivation of URG-parallel faults as right lateral strike-slip faults).
- 4.) Miocene (to recent): NW-SE-oriented compression (σ_1 -direction: NW) resulting in left-lateral strike-slip.

Beside extensional and shear induced elements, structures indicating a compressional regime in the study area also are described in previous studies. Illies and Greiner (1978) for example mention primary normal faults of the eastern graben rim, which had been overprinted by younger reverse faults and small scale up-thrusts are described formed north of Karlsruhe (Ziegler, 1992).

The fault zones analyzed in the present study reflect the aforementioned stress field changes and are clearly related to the formations of main regional structures, in particular URG and Kraichgau-Syncline. Like the URG, the Kraichgau-Syncline consists of a block mosaic,

separated by various fault zones, caused by extension, left lateral strike-slip or compression within the stress field of the URG formation (e.g. Kleinschnitz, 2009, and references therein).

5.1.1. Nussloch

We define the Nussloch fault zone as a normal fault zone with a total displacement of at least 40 m, distributed on step faults. This extension structure is located close to the graben master fault and most probably part of a fault system described in literature: Kleinschnitz (2009) mentions a stepwise fault zone induced subsidence of the Kraichgau east of Nussloch. One of these fault zones crosscutting the Kraichgau east of Nussloch juxtaposes the Upper Muschelkalk and the Lower Muschelkalk formation. Both strike direction (NW-SE) and displacement coincide with the analyzed Nussloch normal fault zone. The stress field of this normal fault zone formation is in good accordance with the stress field characterized by left-lateral strike-slip and NE-SW-extension in Miocene (cf., Schumacher, 2002).

5.1.2. Illingen

Based on the flexures in the fault core and the eastern fault block at contact to the main slip surfaces of the Illingen fault zone (southern quarry-part) we assume a step fault induced normal displacement from western towards eastern fault block. Due to the exposed slickenlines which show a strike-slip and a dip-slip component (northern quarry-part) and the minor slip surfaces within the fault core (southern quarry-part) we define the Illingen fault zone as an oblique-slip fault zone. The aforementioned structures and the high deformation grade of the slip surface exposed in the North indicate also a reactivation of the fault zone. We assume that the tectonic elements within the Illingen quarry are affected by a strike-slip regime, but also by E-W-extension, probably caused by σ_1 oriented NNW-SSW, resulting in the formation of the main oblique-slip fault zone. Due to the orientation parallel to the URG, this fault zone can be linked to the regional stress field of the URG. Beside the normal dip-

slip component within the main oblique-slip fault zone another extension induced structure occurs in the formation of one NNE-SSW-oriented normal fault zone. We define a third fault zone as an ENE-WSW-oriented reverse fault zone due to exposed markers which indicate a reverse displacement and therefore a compression induced structure. The associated stress fields of fault zones formation and reactivation are in line with the regional stress field in late Eocene or Oligocene (cf., Schumacher, 2002).

5.1.3. Knittlingen

Both extension and compression structures are exposed in Knittlingen and indicate a complex local tectonic history. Compression induced structures, i.e. reverse faults and folds (particularly flexures) are the most prominent structures in this quarry.

The rock formation within the characterized fault zone (FZ 1) in Knittlingen shows a high deformation grade. We assume repeated slip events on the fault plane and a formation of this fault zone by fault linkage within these rocks characterized by alternating mechanical properties. Fault linkage could explain the variety in fault core characteristics along the fault plane (lenses, tilted bedding or fault breccia) (Bastesen et al., 2009; Childs et al., 2009; Bastesen and Braathen, 2010; Bastesen et al., 2013). Flexures in the hanging wall indicate a main upward movement of this fault block. Furthermore, flexure monoclines of softer limestone and marl beds as well as one broken and rotated competent bed hosted in the footwall are clearly caused by compression, where different mechanical properties of limestone and marl obviously have led to different deformation of the limestone beds.

However, it seems that this fault zone was subjected to an extensional regime to a minor degree since some fault zone parts locally show extension structures (downward tilted bedding at contact and within the fault core). We propose a partially reactivation of this fault zone due to changes in dip angle where some fault core parts (probably with lower dip angle) were reactivated first. However, compressional structures predominate and thus we

characterize this fault zone as reactivated reverse fault zone. Within this quarry, additional structures of compressive deformation occur in form of flexure monoclines (strike direction NW-SE), which show beginning fracturing and fault development along the axial surface (fold propagation fault).

Two other exposed fault zones (strike direction: NW-SE) show both a normal displacement and compressional structures like flexures or compressed limestone beds indicating a reactivation (inversion) of these primary normal faults.

A changing local stress field is common in regions characterized by a complex fault block structure due to rotation of σ_1 -direction at fault zones. The formation may be related to the regional stress field of the URG in Miocene (cf., Schumacher, 2002) with slight changes of the local stress field. It is, however, difficult to classify the local stress field at fault zone formation and reactivation. The fracture system, characterized by a wide scatter in fracture orientation, is affected by this complex local stress field as well.

5.2. Past fluid flow

5.2.1. Past fluid flow within the study area

Mineralized fractures and mineralizations within fault zones crosscutting the study area are described in several previous studies. Illies (1972) mentions tertiary mineral veins (e.g., barite, fluorite and various ore minerals), which are developed at both graben shoulders as consequence of mineralization through open fissures, but absent within the graben fill due to a differing stress regime. In addition, Eisbacher and Fielitz (2010) refer to NW-oriented fault zone and fractures, which are sealed by mineralizations.

Our data show that fractures formed in this NW-SE-direction are mineralized within the fracture systems of the studied quarries as well, particularly in the Nussloch-quarry.

Furthermore, mineralized fractures accumulate in directions parallel and subparallel to the graben master fault and may therefore be related to the graben formation.

In the present study the comparatively high amount of mineralized fractures within the Nussloch-quarry is conspicuous. We conclude that these mineralizations may be connected to the formation of the well-known Pb-Zn-deposit of Wiesloch (e.g. Walter, 2007; Kleinschnitz, 2009), which is located close to the Nussloch-quarry. This Pb-Zn-deposit was formed in context of the URG development, as hydrothermal metal-bearing fluids circulated through the fractures and faults (Kleinschnitz, 2009).

5.2.2. Past fluid flow with regard to fault zone permeability evolution

The permeability structure within fault zones and thereby associated fluid flow is changing during fault zone evolution and depends on their individual infrastructure (e.g., Caine et al., 1996; Agosta and Kirschner, 2003; Billi et al., 2003). The fault core of active faults zones may act as a conduit for fluid flow, if fractures or pores get interconnected during slip, whereas this unit acts as a barrier in inactive fault zones due to reduced grain sizes (cf., Section 1.; e.g., Sibson, 1994; Caine et al., 1996). Billi et al. (2003) discuss fault zone permeability development during their evolution in carbonate rocks in detail, including the following two main stages. First, they define a conduit stage, which precedes the formation of the fault core. When fracturing starts, the fault zone permeability increases and the fault zone acts as a self-enhancing conduit. In the second stage, the fault zone permeability structure is changing, due to the beginning of particle rotation and particle fracturing. The fine-grained matrix increases within the particle population and reduces the fracture connectivity and permeability (Billi et al., 2003; Micarelli et al., 2006b). As a result, the fault core starts to seal and may become a barrier for fluid flow. Fluid flow is limited to the fault damage zone at this stage, particularly in proximity to the fault core, where the rock is still highly fractured (Billi et al., 2003).

This evolutionary model of fault zone permeability is applicable to our study. The fault cores of all analyzed fault zones show mineralizations and therefore signs of fluid flow within this

540 fault zone unit, independently of their type, particularly the up to 1.5 m wide mineralizations
541 at the fault core-hanging-wall-boundary in Nussloch. Both fractures within the fault core
542 (Illingen oblique-slip fault zone) and the whole fault core unit of smaller scale fault cores
543 (Knittlingen reactivated reverse fault zone) are sealed by minerals as well. Additionally, red
544 colored areas and zones of discolorations indicate fluid flow within the fault cores in
545 Nussloch and Knittlingen.

546 During fault zone evolution, this fluid flow, but also a grain size reduction, led to sealing of
547 the fault cores and barrier formation within this fluid circulation system. As proposed by Billi
548 et al. (2003) we assume that fluid flow was then localized within the fault zone damage zones
549 characterized by an enhanced fracture density. In the present study several fractures are sealed
550 with minerals within this unit, particularly with orientations parallel and subparallel to the
551 fault zones.

552

553 *5.3. Fracture system characterization within the fractured reservoir*

554 In order to enable fluid flow in a fractured reservoir, the fracture system and the individual
555 beds have to be hydraulically connected (e.g., Odling et al., 1999; Ortega and Marrett, 2000;
556 Micarelli et al., 2006a, b; Reyer et al., 2012). Previous studies show enhanced percentages of
557 interconnected fractures within damage zones and an increase in fracture connectivity from
558 the protolith-damage zone boundary towards the fault plane (Micarelli et al., 2006b; Agosta et
559 al., 2010). Despite our data show that most of the fractures are not connected with other
560 fractures at fracture tips we conclude improved fracture vertical connectivity in proximity to
561 slip surfaces of the fault zones, particularly caused by comparatively shorter fractures up to a
562 length of 0.5 m. The Nussloch normal fault zone with a displacement of some tens of meters,
563 which was formed under an extensional regime in context of the URG and Kraichgau
564 tectonics, exhibits the best fracture connectivity within the damage zone fracture system of all
565 analyzed fault zones since fractures connected at both fracture tips are included in particular.

It has long been recognized that the average fracture density in thinner beds is typically higher compared with thicker beds due to the formation of a stress shadow (Hobbs, 1967; Narr and Suppe, 1991; Gross et al., 1995; Van der Pluijm and Marshak, 2004). In general, our data show a similar behavior, with highest fracture densities in comparatively thinner limestone beds. Figure 15 exemplary shows the bed thickness [cm] versus fracture density (number of fractures per meter) of all fracture data in Nussloch, separately for fault zone and host rock. In addition we observe that limestone beds with similar thicknesses show higher fracture densities within the fault damage zone compared with the host rock. As proposed in previous studies (Caine et al., 1996; Berg and Skar, 2005; Micarelli et al., 2006b; Reyer et al., 2012), we observed a further enhanced fracture density in proximity to the slip surface. Thus, the probability of the formation of interconnected fractures in horizontal direction increases in this fault zone part.

Our data generally show the significance of mechanical layering for fracture propagation and fracture arrest at contacts, as shown in several previous studies (Narr and Suppe, 1991; Odling et al. 1999; Gross and Eyal, 2007; Larsen et al., 2010; Reyer et al., 2012; Boro et al., 2013; Philipp et al., 2013; Afşar et al., 2014). Reyer et al. (2012), for example, propose that the number of stratabound fractures is generally higher in mechanically layered sedimentary rocks, which are characterized by abrupt lithological changes (Narr and Suppe, 1991; Gross et al., 1995), such as the Lower Muschelkalk of the North German Basin, compared with more homogeneous units. The mechanical layering of these limestone-marl-alternations affects the fracture propagation and fracture arrest respectively due to stiffness variations and stress field changes (Gross and Eyal, 2007; Larsen et al., 2010; Reyer et al., 2012). For example Larsen et al. (2010) and Philipp et al. (2013) describe the effects of fracture arrest at contacts such as stylolithes, zones of multilayers, welded layers, and cavities which induce a mechanical layering that does not coincide with clear lithological changes. In the limestone-marl-alternations of the Middle Triassic Muschelkalk, however, the mechanical contrasts match

with lithological contacts: stiff limestone beds alternate with soft marl layers. Despite this effect of mechanical layering is obvious, non-stratabound fractures may be formed as result of linkage processes of preexisting fractures induced by faulting (Agosta et al., 2010). Therefore we focus on the distribution of non-stratabound fractures in relation to the fault core distance for further reservoir characterization in the present study and summarize fracture data of all scanlines, neglecting the limestone bed thicknesses.

Our data of the Knittlingen-quarry show that the comparatively thick marl layers (~ 10 cm) which induce a strong mechanical layering clearly act as stress barriers for fracture propagation. Many fractures become arrested at contacts to marl layers due to the changing stress field, regardless of the fracture locations (close to the slip surface or at distance).

In both other quarries (marl thickness 0.5 to 2 cm) a better connectivity between multiple limestone beds is caused by non-stratabound fractures, particularly at contact to the fault core in the Nussloch-quarry, where the fractures propagate across the thinner marl layers in the more homogenous rock formation. Therefore we assume that the effects of mechanical layering on fracture propagation in fault zones are significant.

Philipp et al. (2013) propose that diagenetic processes (cementation, pressure solution, mechanical compaction) in reservoirs lead to stiffness homogenizations of adjacent layers where a formerly mechanically layered succession may behave mechanically as a single layer. Thus, this effect is of particular importance for fracture propagation and permeability in a fractured reservoir and should be taken into account.

In general our data show that the possibility of interconnected fracture formation increases with increasing fracture densities in proximity to the fault core, particularly in more homogenous rocks. The reservoir permeability is enhanced by the development of hydraulically active pathways across several beds (non-stratabound fractures) to a higher degree compared with the improvement caused by the formation of fractures interconnected at the fracture tips

The best fracture induced reservoir permeability in the present study is proposed for the Nussloch normal fault. The enhanced permeability in this normal fault is caused by a high percentage of non-stratabound fractures, which may provide a hydraulically active pathway across several limestone beds (e.g., Odling et al., 1999) and supported by improved fracture vertical connectivity.

5.4. Permeability implications on the analyzed fracture systems

Open fractures are of particular importance in terms of reservoir permeability. In the present study many fractures remained open. These open fractures are potential pathways for recent fluid flow in fractured reservoirs associated with the characterized fault zones.

As an extension of the cubic law (cf., Section 3.) we use calculations of the hydraulic conductivity k_f [m/s] for sets including parallel and open fractures [m/s] after Bear 1993 (Eq. (1)) to show fracture orientations of fractures which enhance the permeability of the fracture system:

$$k_f = \frac{\rho_f \cdot g}{12\mu \cdot L} (\sum_{i=1}^m b^3), \quad (1)$$

where ρ_f is the fluid density [kg/m³], g the acceleration due to gravity [m/s²], μ the dynamic viscosity [Pa s], L the profile length [m] and b the fracture aperture [m].

Since fracture data of surface measurements in the outcrop analogues are used for our calculations, for fluid reservoirs we have to consider that fracture parameters change with increasing depth, resulting for example in reduced fracture apertures and densities (Lee and Farmer, 1993). Therefore, we aim at highlighting fracture orientations with enhanced permeabilities, but no absolute values.

We show permeability calculations based on the surface measurements exemplary for the quarries Nussloch and Knittlingen. We conclude that increased fracture frequencies in the damage zones and larger fracture apertures parallel and subparallel to fault zone strike and to

regional structures like the URG and Variscan structures may lead to enhanced permeability compared with other orientations (Fig. 16). We propose that surface data may be used for estimations of fault zone characteristics at depth. Several fault zone and fracture system characteristics or at least relationships should be applicable to reservoir conditions. Also at depth the fracture density would be enhanced at contact to the slip surfaces. Furthermore we assume that the distribution of fractures with largest apertures at contact to the slip surface and parallel and subparallel to fault zone strikes remains the same. Thus, estimations on reservoir permeability are generally possible based on surface measurement in outcrop analogues. In order to obtain realistic permeability estimations it is essential to vary fracture system parameters such as aperture and density to adapt these parameters to reservoir conditions in further investigations. The received fracture data of the present study serve as a basis of future numerical models for example of fluid and heat transport in fault zones.

6. Conclusions

Based on outcrop analogue studies of eight fault zones crosscutting limestone-marl-alternations of the Middle Triassic Muschelkalk in the Kraichgau-Syncline (Southwest Germany) we conclude:

1. Fault zone formation and reactivation in the Kraichgau-Syncline is clearly affected by regional stress field changes of the Upper Rhine Graben development. Fault zones and associated main fracture sets have orientations similar to prominent regional structures, such as the NNE-SSW-oriented oblique-slip fault zone parallel to the URG or the NW-SE-oriented normal fault zone parallel to the step faults which induced the subsidence of the Kraichgau-Syncline.
2. Fractures extending across multiple limestone beds of the exposed limestone-marl-alternations may create pathways for fluid flow across these beds in the reservoir, but

different mechanical properties of limestone and marl obviously also affect fracture propagation. An enhanced fracture density and fracture connectivity of shorter fractures within the fracture system in the fault damage zones at contact to the fault core may improve reservoir permeability.

3. Increased fracture frequencies in fault damage zones and largest fracture apertures in direction of fault zone strike and of prominent regional structures may lead to enhanced permeability compared with other orientations. Fractures formed in these directions which are sealed by minerals as well as mineralizations within fault cores indicate hydraulic activity during fault zone evolution.
4. The fault damage zones in the Middle Triassic Muschelkalk may be potential drilling targets of geothermal wellbores in the adjacent Upper Rhine Graben although in many cases the hydraulic connectivity of the natural fracture network may need to be improved. Well-developed fault cores may be potential barriers for fluid flow in inactive fault zones.

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Figure Captions:

Fig. 1: Simplified geological maps (modified from Walter, 2007) of the Upper Rhine Graben (URG; left) and the Kraichgau study area (right). The locations of the quarries are marked by dark-gray dots (IL - Illingen; IT - Ittlingen; KN - Knittlingen; NL - Nussloch). The axis of the Kraichgau-Syncline is marked by a dashed line.

Fig. 2: Orientation of fracture systems and fault zones (n = number of fractures) in the quarries Nussloch (NL), Illingen (IL), Knittlingen (KN) and Ittlingen (IT). Left: Symmetrical Rose Diagram (10°-classes), the fault zones are plotted as lines. Right: Schmidt Diagram, equal area projection, lower hemisphere. The fractures are marked by poles (black), the fault zones by great circles and poles. Color code indicating fault zone type see key. These definitions refer to the reflections in the discussion (Sections 5.1.1. to 5.1.3.).

Fig. 3: Fracture orientations of the fractures in footwall and hanging wall of the fault zones (FZ) analyzed in Nussloch (NL), Knittlingen (KN), Illingen (IL) and Ittlingen (IT). Left: Symmetrical Rose Diagram (10°-classes), the fault zones are plotted as lines. Right: Schmidt Diagram, equal area projection, lower hemisphere. The fractures are marked by poles (black), the fault zones by great circles and poles. Color code indicating fault zone type see key. These definitions refer to the reflections in the discussion (Sections 5.1.1. to 5.1.3.).

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equal area projection, lower hemisphere. The fractures are marked by poles (black), the fault zones by great circles and poles in each case (gray).

Fig. 5: Field pictures of the analyzed fault zone in the Nussloch-quarry (SP = slip surface, also referred to as slip plane). a) Outcrop overview. View S. b) Fault zone overview, fault zone parts 1 to 3 are shown in detail in the lower section. View SE (b1 and b3) or to NW, respectively (b2). The trace of the minor fault is marked by a dashed line.

Fig. 6: Sketch and field picture of the analyzed fault zone in the Nussloch-quarry (view W). See person for scale. Outcrop overview: Picture location is displayed by the gray shaded ellipse, the fault zone trace by gray and black lines (dashed lines - assumed fault zone trace).

Fig. 7: Fracture density distribution normal to the main fault zone in the Nussloch-quarry. a) Data from all scanlines in the footwall up to 3 m (left) and hanging wall up to 5 m (right) distance to the fault core. b) Overview-picture of the hanging wall including one minor fault zone (left, view SE; scanline locations are traced) and fracture density distribution in the longest profiles 1 and 2 (up to 16 m). These profiles cut the minor fault zone in the SW (marked by the red bar) and therefore their damage zone. In the gray labeled zones the rock mass is destroyed or covered, not every fracture was detected individually.

Fig. 8: Overview of the main fault zone in Illingen: Trace of main and minor fault zones are displayed by lines in the outcrop overview (color code indicating fault zone type see key; these definitions are based on the reflections in the discussion in Sections 5.1.1. to 5.1.3.; dashed lines - assumed fault zone trace). a) Fault core at the southern quarry border (view S). b) Detailed sketch of the lower fault core part with lower hemisphere projection of the poles (bedding). c) Field pictures of the exposed fault plane in the northern outcrop part (view W).

Fig. 9: Overview pictures and sketch of the described fault zone (FZ 1) cropping out in the Knittlingen-quarry (view NW). The sketch shows the soft and thin folded layers as well as the broken and rotated competent bed.

Fig. 10: Fracture density distribution normal to the described fault zone (FZ 1) in the Knittlingen-quarry. a) Data from all scanlines in the footwall up to 3 m (left) and hanging wall up to 4 m (right) distance to the fault core. b) Overview-picture of this fault zone (left, view NW; scanline locations are traced; scale: see folding rule expanded to 1 m) and fracture density distribution in the longest profile (right, up to 8.5 m). In the gray labeled zones the rock mass is covered or destroyed, not every fracture was detected individually.

Fig. 11: Fracture connectivity of the fracture systems in the quarries Nussloch, Illingen and Knittlingen (color code see key; classified fracture types: percentage is shown for the entire dataset). Fracture length [m] vs. strike (scale: 0°-180°). a) All fracture data. b) Fracture data for shorter fractures up to 1 m length. The fault zone orientations are marked by a gray line. Fractures, from which only the minimum length was determined because only one tip was visible, are labeled with a star.

Fig. 12: Fracture connectivity of the fractures within the main fault damage zones (color code see key): a) Nussloch. b) Illingen. c) Knittlingen. In the gray labeled zone the rock formation is covered or destroyed, not every fracture was detected individually. The positions of fault core and minor fault zones are marked by dark-gray or by black dashed lines, respectively. Fractures, from which only the minimum length was determined because only one tip was visible, are labeled with a star.

Fig. 13: Percentage of stratabound vs. non-stratabound fractures. a) Fracture data of the Nussloch-quarry separated to the main fault zone (FZ), host rock of the Lower Muschelkalk (HR mu) and of the Upper Muschelkalk (HR mo). b) Fracture data determined normal to the main fault zone in the Nussloch-quarry (cf., Section 4.2.1.). c) Fracture data of the Illingen-quarry separated to FZ 2 (main fault zone), FZ 1, and FZ 4. d) Fracture data determined normal to the main fault zone (FZ 2) in the Illingen-quarry (cf., Section 4.2.2.) separated to eastern fault block (FB), fault core (FC) and western fault block. The percentage of fractures with no declaration in Illingen is marked by a shaded signature. e) Fracture data of the Knittlingen-quarry separated in FZ 1, FZ 2, FZ 3 and host rock (HR). f) Fracture data determined normal to FZ 1 in the Knittlingen-quarry (cf., Section 4.2.3.). The definition of stratabound and non-stratabound fractures is illustrated with a sketch (modified from Odling et al., 1999). The fault zone types refer to the reflections in the discussion (Sections 5.1.1. to 5.1.3.).

Fig. 14: Mineralized and open fractures: a) Nussloch. b) Illingen. c) Knittlingen. Left: Fracture aperture and thickness [mm] vs. strike. The fault zone orientations are marked by a gray line. Center: Percentage of mineralized fractures separated in fault zones and host rock (except for Illingen (b) due to the minor database). Right: Fracture aperture and thickness [mm] in relation to the fault core distance [m], the positions of fault core and minor fault zones are marked by dark-gray or by black dashed lines, respectively. The positions of mineralized fractures with unknown aperture are marked by open stars.

Fig. 15: Nussloch-quarry: Bed thickness [cm] vs. fracture density [m^{-1}], separately for fault zone and host rock.

Fig. 16: Based on surface measurements calculated hydraulic conductivity (k_f -value) [m/s] versus fracture orientation (scale: 0°-180°): a) Nussloch. b) Knittlingen. The fault zone orientations are marked by gray lines.

Tables:

Table 1: Analyzed fault zones. The fault zone types refer to the reflections in the discussion (Sections 5.1.1. to 5.1.3.).

Quarry	Number of fault zones	Fault zone type	Displacement
Nussloch (NL)	1	Normal fault zone with associated minor fault	~ 40 m, minor fault unknown
Knittlingen (KN)	1	Reactivated reverse fault zone	unknown
Knittlingen (KN)	2	Normal fault zone, reactivated as reverse fault	~ 4 m
Illingen (IL)	1	Oblique-slip fault zone with minor fault	Horizontal unknown, vertical ~ 0.15 m, minor fault unknown
Illingen (IL)	1	Normal fault zone	0.30 m
Illingen (IL)	1	Reverse fault zone	0.57 m
Ittlingen (IT)	1	Normal fault zone	~ 3 m

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