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Fault zone hydrogeology

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ABSTRACT

Deformation along faults in the shallow crust (<1 km) introduces permeability heterogeneity and anisotropy, which has an important impact on processes such as regional groundwater flow, hydrocarbon migration, and hydrothermal fluid circulation. Fault zones have the capacity to be hydraulic conduits connecting shallow and deep geological environments, but simultaneously the fault cores of many faults often form effective barriers to flow. The direct evaluation of the impact of faults to fluid flow patterns remains a challenge and requires a multidisciplinary research effort of structural geologists and hydrogeologists. However, we find that these disciplines often use different methods with little interaction between them. In this review, we document the current multidisciplinary understanding of fault zone hydrogeology. We discuss surface- and subsurface observations from diverse rock types from unlithified and lithified clastic sediments through to carbonate, crystalline, and volcanic rocks. For each rock type, we evaluate geological deformation mechanisms, hydrogeologic observations and conceptual models of fault zone hydrogeology. Outcrop observations indicate that fault zones commonly have a permeability structure suggesting they should act as complex conduit–barrier systems in which along-fault flow is encouraged and across-fault flow is impeded. Hydrogeological observations of fault zones reported in the literature show a broad qualitative agreement with outcrop-based conceptual models of fault zone hydrogeology. Nevertheless, the specific impact of a particular fault permeability structure on fault zone hydrogeology can only be assessed when the hydrogeological context of the fault zone is considered and not from outcrop observations alone. To gain a more integrated, comprehensive understanding of fault zone hydrogeology, we foresee numerous synergistic opportunities and challenges for the discipline of structural geology and hydrogeology to co-evolve and address remaining challenges by co-locating study areas, sharing approaches and fusing data, developing conceptual models from hydrogeologic data, numerical modeling, and training interdisciplinary scientists.

Contents

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1. Introduction

As the plumbing of the earth, fault zones in the shallow crust (<1 km) impact a suite of geological processes. Faults affect fluid flow patterns in groundwater aquifers (e.g., Levens et al., 1994; Mayer et al., 2007; Bense et al., 2008; Burbey, 2008; Folch and Mas-Pla, 2008), and hydrocarbon migration and entrapment in reservoir rocks (e.g., Aydin, 2000; Sorkhabi and Tsuji, 2005) as well as the safe storage of nuclear waste (Bredehoeft, 1997; Douglas et al., 2000; Mal'kovskii and Pek, 2001; Ofoegbou et al., 2001), and CO_2 sequestration (e.g., Shipton et al., 2004; Agosta et al., 2008; Dockrill and Shipton, 2010; Kampman et al., 2012; Tueckmantel et al., 2012b). Fluid expulsion and localized mineralization along faults can lead to the formation of economic mineral deposits (e.g., Deming, 1992; Garven et al., 1999; Person et al., 2008), and provides evidence of enhanced past fluid circulation along faults both on Earth (e.g., Mozley and Goodwin, 1995; Heynekamp et al., 1999; Caine and Minor, 2009; Balsamo et al., 2013) and on Mars (Treiman, 2008). Mineralization associated with fluid flow and water–rock interaction can impact the mechanical strength of faults, potentially affecting the character of fault slip in response to earthquakes in the deeper crust (e.g., Moore and Rymer, 2007; Carpenter et al., 2011). The specific impact of faults on groundwater flow in different geological environments is complex, diverse and often not well understood despite the relevance of understanding fluid flow around fault zones at shallow crustal depths which is important to numerous societal concerns.

The fundamental law of fluid flow through porous media, Darcy's Law, indicates that subsurface fluid flow is controlled by a combination of rock permeability and the hydraulic gradient within the rock mass. Examining deformation processes as well as the internal structure and architecture of fault zone structure using tools from structural geology is critical to obtain a primary understanding of the permeability structure of fault zones. However, hydraulic gradients around fault zones are strongly controlled by hydrogeologic processes such as rates of groundwater recharge forcing topography-driven flow, anthropogenic influences such as extraction of groundwater, and deeper processes like fluid flow driven by sediment compaction. Hence, examining hydraulic gradients present near fault zones and delineation of fluid flow paths in fault zones using tools from hydrogeology should also be central in a development of a comprehensive understanding of the role of fault zones in hydrogeology (Karasaki et al., 2008). Though there is a considerable body of research on faults and fluid flow in both hydrogeology and structural geology disciplines, there is limited evidence of an exchange of insights or integration between them.

We focus on fault processes and single-phase groundwater flow patterns in the shallow crust after fault deformation. At greater depths fractured rocks will contain predominantly saline groundwaters and/or hydrocarbon accumulations and density-dependent and multi-phase flow is beyond the scope of this review. At greater depths, seismogenic deformation and other deformation mechanisms beyond our scope are also more important. Although we do not discuss the impact of faults on flow in hydrocarbon reservoirs in much detail, in Section 5 we include hydrocarbon reservoir models which in many cases could be directly transferable to shallow single-phase groundwater systems. By focusing on fault zones post-deformation, we are excluding the role of fault evolution on fluid flow in active fault zones. For simplicity, in this paper we use the term rock for both lithified and unlithified materials. In the context of fault zone hydrogeology we consider a **fault zone** to be the volume of rock where permeability has been altered by fault-related deformation. The protolith is the undeformed geological material surrounding the fault zone.

Our objective in this paper is to propel research on fault zone hydrogeology forward by providing a comprehensive overview of the study of fluid flow in and around fault zones at shallow depths (<1 km) where surface and subsurface data is most abundant. We discuss fault zone hydrogeology as studied from a structural geological and hydrogeological viewpoint in Section 2. In Section 3 we discuss the geological processes and hydrogeological characteristics of fault zones derived from the study of rock outcrops, in a range of geological settings. Section 4 discusses the conceptual models of fluid flow in fault zones as derived from outcrop data. Section 5 reviews hydrogeological evidence of the impact of faults in a similar range of geological settings. Studies that have employed models as integrative tools to describe fluid flow patterns around fault zones are discussed in Section 6. Finally, we discuss different strategies to develop a more comprehensive and integrated framework for the investigation of fluid flow around fault zones in the shallow crust (Section 7). Throughout the text terminology is bolded when it is first defined.

2. Approaches to fault zone hydrogeology

Hydrogeologists and structural geologists use different methods and approaches to studying fault zone hydrogeology (Fig. 1). Explicitly reviewing the purpose, data required, limitations and advantages of each individual technique is beyond the scope of this paper but has been summarized in Table 1. Here we provide an overview of the different approaches and how these are impacted by data availability, field areas and scale.

Surface-focused studies, mostly by structural geologists, use techniques such as outcrop mapping of fault zone attributes, for example the length, orientation and aperture of fractures within the fault zone, the fault rock grain size and porosity, and permeametry to obtain the permeability of fault rocks (Fig. 1a). Outcrop data can be used in numerical flow models of fault zones (Section 6). From outcrop-based studies a set of conceptual hydrogeological models have been developed in the literature (outlined in Section 3.2) that suggest that faults act as barriers hampering fluid migration, as conduits propagating the movement of fluids or as more complex conduit–barrier systems (Caine et al., 1996; Aydin, 2000; Rawling et al., 2001; Bense and Person, 2006). However, direct hydrogeological evidence of the impacts of particular faults on fluid flow to test and refine these outcrop-based fault models is often lacking.

Subsurface-focused studies, often carried out by hydrogeologists, infer the hydrogeological behavior of fault zones from arrays of boreholes or springs usually without observing fault structure directly in outcrop (Fig. 1b). Often groundwater hydrologists need to be opportunists in the study of fault zones as groundwater monitoring networks are designed to characterize the hydrodynamics of aquifers as a whole without any specific focus on fault zones. Hence, closely spaced arrays of boreholes over fault zones are rare. However, the shape of the hydraulic head profile that might show steps or inflections in hydraulic

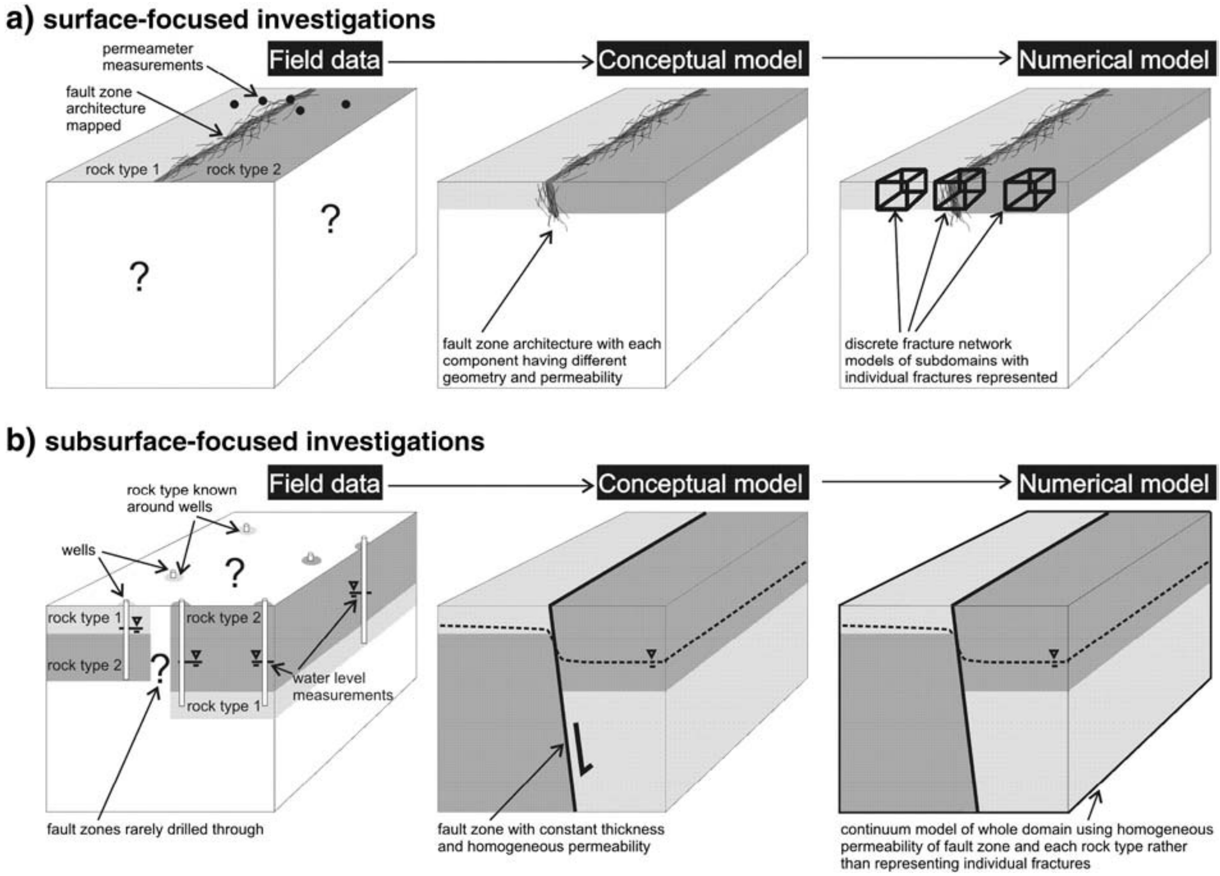

Fig. 1. Investigation of fault zone hydrogeology has often focused on (a) characterization of surface outcrops often by structural geologists or (b) by investigation of borehole data providing information on geology and direct hydrogeological evidence of the impact of faults on fluid flow. The source of field data leads to different conceptual models, numerical modeling assumptions and methods. Table 1 lists examples of studies employing the different modes of investigation and field methodologies. Surface investigations sometimes have a more three-dimensional surface exposure (i.e. at mine sites or in mountainous topography) and some sub-surface investigations include tunnels or underground mines.

gradient at fault zones can be used to infer the directions and rate of fluid flow at the fault zone (e.g. Haneberg, 1995; Bense et al., 2003a; Anderson and Bakker, 2008) and provide an indication of the hydrogeological behavior of a fault zone as a barrier or a conduit (Fig. 2a). Groundwater temperature, geochemistry and age (e.g., Bethke and Johnson, 2008; Leray et al., 2012) can constrain groundwater flow paths across fault zones in conjunction with hydraulic head observations (Fig. 2b and c). Boreholes can also be used for hydraulic testing with packer or pumping tests to enhance groundwater flow rates around fault zones to elucidate the fault zone hydrogeological structure (Anderson and Bakker, 2008). Sampling groundwater geochemistry, measuring hydraulic head, temperature and other parameters during pumping tests can result in detailed inferences on fault zone hydrogeological properties (Roques et al., submitted for publication).

Differences in the methodologies used by hydrogeologists and structural geologists is partly due to contrasts in the type of data available in field areas (Fig. 1). Dense networks of wells available to collect detailed hydrogeological evidence on fault behavior are typically found in developed areas where outcrops that are necessary for structural geological outcrop-based studies are usually sparse. Vice versa, where fault zones are well exposed in outcrop, a dense network of wells is often not available as these areas are generally less developed and/or the groundwater is not near the surface. Therefore, probably in part due to the differences in methods, data availability and field areas, we find that there is limited evidence of an exchange of insights or integration between hydrogeology and structural geological disciplines.

Each method used by structural geologists and hydrogeologists has a characteristic scale over which the method integrates observations (Fig. 3). Consequently, the use of the different methods results in faults being examined at various scales by the two disciplines. Generally, the methods used by structural geologists examine smaller integration scales of <0.01 m (microstructure) to e.g. 100 m (outcrop studies) whereas hydrogeologists often also infer fault hydrogeological behavior at larger integration scales of e.g. >10 km. Most of the methods used by hydrogeologists integrate over larger scales than the typical width of many fault cores (Section 3), which suggests that hydrogeological methods can only infer the effective hydrogeologic impact of fault zones rather than constrain the internal permeability structure of fault zones. Conversely, it may be difficult to elucidate a regional impact of faults on fluid flow from the smaller scale studies conducted by structural geologists.

3. Fault zone processes from surface-focused studies

3.1. Terminology and fault zone architecture

Structural geologists have described fault zones in outcrop in diverse settings (Fig. 4) such as poorly lithified sedimentary rock, for example basin fill sediments in the Gulf of Corinth Rift basin (Fig. 4a; Loveless et al., 2011), the Lower Rhine Embayment (Bense et al., 2003b), the Rio Grande Rift basin (Fig. 4b; Heynekamp et al., 1999; Sigda et al., 1999; Rawling and Goodwin, 2006; Caine and Minor, 2009), in southern Italy (Balsamo and Storti, 2010) and Austria (Exner and Grasemann, 2010), and glacial deposits in Denmark (Kristensen et al., 2008). In lithified sedimentary rocks, the Colorado plateau is a classic area of study where many researchers have focused efforts to determine fault hydraulic properties (Fig. 4c; Antonellini and Aydin, 1994, 1995; Jourde et al., 2002; Davatzes et al., 2003). Outcrops of regional scale

Table 1
Various approaches used by structural geologists and hydrogeologists to study fault zone hydrogeology.

Method	Purpose	Requirements and data	Comments	Literature examples
Structural geology				
Outcrop mapping	Map products of deformation and fault architecture	Field exposures; lithologic and structural data	Data limited to near-surface character of fault zones that might however be exhumed from deeper crustal levels	Lehner and Pilaar (1997), Caine and Forster (1999), Jourde et al. (2002), and Shipton et al. (2006a)
Fault rock mineralogy and geochemistry studies	Examine water–rock interactions	Cores or outcrop samples Mineralogy and elemental composition of fault components	Rock samples taken at a small scale might not be representative of larger scale processes	Evans and Chester (1995), Caine and Minor (2009), and Koukouvelas and Paoulis (2009)
Laboratory core tests	Permeability measurement	Rock samples	Rock samples small scale, not necessarily representative of larger scale average permeability, but provide direct measurements. Can be used to study permeability development with progressive strain	Evans et al. (1997), Ogilvie et al. (2001), Ngwenya et al. (2003), and Faoro et al. (2009)
In-situ permeametry (usually using mini air-permeameters)	Permeability measurement	Suitable (fresh, smooth) surfaces in outcrop	Potential of mapping spatial distribution of permeability across fault zones in detail	Antonellini and Aydin (1994), Sigda et al. (1999), Rawling et al. (2001), and Balsamo and Storti (2010)
Hydrogeology				
Drilling and borehole geophysics	Direct subsurface sampling and measurement of petrophysical properties	For example, geophysical logging of boreholes and/or inter-borehole tomography	Large range of techniques available. Translation of geophysical properties to hydrogeological properties can be problematic	Moretti (1998), and Ellsworth et al. (2005)
Flowmeter testing	Determine permeability and storativity of fault component or fracture(s)	Pressure or flow response measured in well	Allows to directly measure fluid fluxes	Davison and Kozak (1988), Martin et al. (1990), Hsieh (2000), and Le Borgne et al. (2006),
Pumping testing	Effective permeability measurement of aquifer	Pressure response measured in well field	Provides effective aquifer properties but without a delineation of flow paths	Shan et al. (1995), Marler and Ge (2003), Anderson and Bakker (2008), and Medeiros et al. (2009)
Mapping hydraulic head gradients	Identify flow discontinuities	Water levels in well field	Direct evidence of impact on hydraulic head but wells need to be very closely spaced at fault zones to resolve gradient in sufficient detail	Haneberg (1995), and Bense and Van Balen (2004)
Use of heat to characterize flow	Delineating of fluid flow paths	Distribution of temperature in aquifers	Direct evidence of flow paths but flow needs to be significant enough to disturb the background geothermal gradient	Fairley and Hinds (2004), Anderson and Fairley (2008), Bense et al. (2008), and Read et al. (2013)
Artificial and environmental tracers	Delineating fluid flow paths	Groundwater geochemistry	Direct evidence of fluid flow but the interpretation of geochemical data can be a challenge	Whiteman (1979), Abelin et al. (1991), Gascoyne et al. (1993), Rugh and Burbey (2008), and Leray et al. (2012)
Numerical modeling				
Discrete fracture network models	Integrating borehole and/or outcrop data, parameter estimation	3D distributions of fracture characteristics, hydraulic tests	Often only feasible at limited spatial scale (e.g. 10s of meters) and realistic representation of fractures requires large amount of data	Long et al. (1982), Caine and Forster (1999), Jourde et al. (2002), Caine and Tomusiak (2003), and Surrette and Allen (2007)
Continuum models	Integrating borehole and/or outcrop data, parameter estimation	Effective parameters	Challenge of a realistic inclusion of fault zones into the modeling routine	Oda (1986), Forster and Smith (1989), Lopez and Smith (1996), Bense and Person (2006), and Micarelli et al. (2006)

basement faults in the Rocky Mountains (Fig. 4d; Caine and Tomusiak, 2003) and Japan (Jefferies et al., 2006) have also been closely studied for their hydraulic properties. Cementation patterns caused by fluid circulation along faults for example seen on Spitsbergen Fault (Fig. 4e) have even been suggested as analogous to linear features seen on the surface of Mars (Fig. 4f; Treiman, 2008), thereby providing indirect evidence for past circulation of groundwater on another planet in our solar system.

Normal faults generally occur in extensional tectonic settings, reverse faults in compressional settings, and strike-slip faults where slip is horizontal. Normal and reverse faults typically have a dip of ~45–70°. The rock above the fault zone is called the hanging wall, the rock below the fault forms the foot wall. When reverse faults have a relatively shallow dip ($\ll 45°$) they are referred to as thrust faults. The reader is referred to textbooks on structural geology for further description of fault zone classification (e.g. Fossen, 2010). Fault zone permeability structures may be classified in a number of ways (e.g. Karasaki et al., 2008), including based on the type of displacement (normal, thrust/reverse and strike-slip). However, here we classify the conceptual models of fault zone hydrogeology primarily based on rock type. We choose this justification because the structural architecture of faults, and their resulting permeability structure and aquifer development, are strongly controlled by rock type (Section 3.2).

A first-order description of fault zones commonly includes a **fault core (FC)**, which is surrounded by a **damage zone (DZ)** (Fig. 5a). The fault core, as the zone of the most intense strain, is generally found in the center of the fault zone, and accommodates the majority of the displacement within the fault zone. The damage zone has secondary structures such as fractures, and minor faults extending into the foot-wall and hanging-wall, which take up the remainder of strain within the fault zone. In unlithified sediments, in which mixing of sediments can occur in the fault zone (discussed in Section 3.1), an additional zone, called the 'mixed zone' exists in between the damage zone and the fault core (Heynekamp et al., 1999). However, the use of a mixed zone, as a genetic term in the context of fault zone architecture, in the field description of faults has led to confusion (e.g., Evans and Bradbury, 2004) so we do not use the term in this paper but only distinguish a fault zone as to consist of a fault core and a damage zone.

In the FC–DZ framework a measurable fault thickness is defined perpendicular to the fault strike which is the sum of the fault core and damage zone thicknesses (Fig. 5b). The thickness of fault zones increases with fault throw or displacement (Knott et al., 1996; Sperrevik et al., 2002; Childs et al., 2007). This trend is relatively consistent for different types of faults (normal, reverse and strike-slip) in a range of rock types (Fig. 6). However, Evans (1990) and Faulkner et al. (2010) caution against over-interpretation of these trends as fault thickness–throw relationships are commonly plotted on log–log scales and show scatter over multiple orders of magnitude. The fundamental reasons underlying these observed relationships are still not well understood (e.g. Shipton et al., 2006b). While some modes of strain localization may

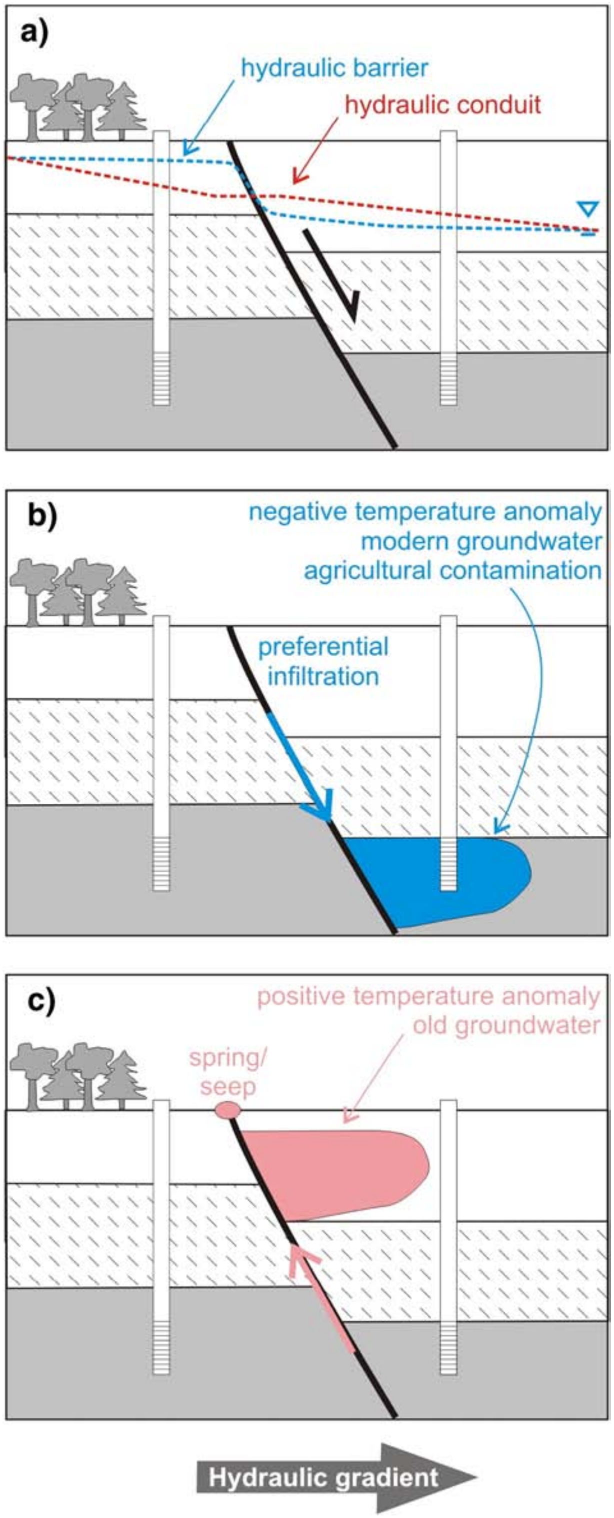

Fig. 2. Hydrogeologic tools to examine fluid flow around faults. (a) Hydraulic head maps can be derived from water levels measured in wells. Contours of mapped hydraulic head generally slope uniformly in unfaulted aquifers with homogeneous permeability. Faults acting as hydraulic barriers or conduits can be inferred from non-uniform gradients. The downward (b) or upward (c) direction and/or path of groundwater flow in fault zones can be further delineated using tracers such as temperature and other environmental tracers. Fluid movement can be driven by natural hydraulic gradients or groundwater abstraction.

be responsible for increasing fault thickness with increasing throw (Childs et al., 2009), inconsistencies in the definition of fault thickness in the field is also probably responsible for some of the scatter in data shown in Fig. 6 (Shipton et al., 2006b).

Assuming enhanced permeability due to fracturing in the damage zone and a low permeability fault core, a conceptual permeability model of a fault zone can be derived (Fig. 5d). In a widely-cited review paper by Caine et al. (1996), the geological FC–DZ model of fault zones is translated to a number of possible fault permeability structures as a function of the relative contributions of a low-permeability fault core and a high-permeability fractured damage zone (Fig. 5f). Field data (e.g. Savage and Brodsky, 2011) discuss how the proportion of fault core volume to that of the damage zone, evolves with increasing fault throw. Beyond the scale of an individual fault strand, the larger scale structure of faults can be segmented or otherwise complex (Fig. 5a; Childs et al., 1996; Walsh et al., 2003; Rotevatn et al., 2007; Bonson et al., 2007; Faulkner et al., 2010). As a result, fault zones in outcrop can display multiple fault cores, with overlapping damage zones (Fig. 5c). The density of fracturing can be plotted against distance along a scan line to identify the presence of a damage zone (Fig. 5d; Faulkner et al., 2010; Savage and Brodsky, 2011; Schueller et al., 2013). High fracture densities in these composite fault zones can be interpreted as a superposition of that of individual damage zones, as suggested by field observations (e.g. Savage and Brodsky, 2011). Where fault damage zones overlap, in cases of closely spaced fault zones, the permeability structure can be derived assuming superposition of individual fault zones (Fig. 5e). The structural heterogeneity provided by fault segmentation has a direct impact on the continuity and distribution of fault rocks. In this paper, however, we will consider the permeability distributions in individual fault zones and we will use the fault core and damage zone concepts as descriptors of a fault zone while also recognizing that these fault zones can be segments of a larger scale fault structure.

3.2. Impact of fault zone processes on permeability

The products of deformation processes accommodating strain in a fault zone can enhance or reduce the permeability within fault zones. We consider a first-order classification of such processes relevant for fault zone hydrogeology (Table 2) based upon whether a fault process increases (Section 3.2.1) or decreases permeability (Section 3.2.2) and indicate how the occurrence and impact of these varies for different rock types. Subsequently, in Section 3.2.3 we discuss a range of interacting, secondary or larger-scale processes that can reduce or enhance permeability such as compaction, tectonic stress and geochemical processes. These processes are highly relevant to understanding the permeability distribution and evolution in fault zones but are not constrained to occur solely within fault zones.

3.2.1. Fault zone processes that enhance permeability

3.2.1.1. Particulate flow in unlithified rock. In rocks with low cohesive strength, such as unlithified rock, the first stage of accommodation of tensile stress is via the formation of dilation bands (e.g. Du Bernard et al., 2002). Along **dilation bands** the grain fabric is disaggregated (Fig. 7a) but individual grains have not moved past each other to accommodate any shear offset along the band. Once offset occurs along dilation bands they are termed **shear bands** (Fig. 7b). Both shear and dilation bands are types of **deformation bands** (e.g. Fossen et al., 2007). The process of grains rolling and sliding past one another is usually referred to as particulate or granular flow (cf. Borradaile, 1981). Particulate flow will lead to a rearrangement of the pore network and thus impact permeability. The initial dilation could lead to a slight enhancement of permeability potentially up to one order of magnitude (Sperrevik et al., 2002; Bense et al., 2003b). Subsequent shearing and associated rotation of grains along deformation bands can introduce hydraulic anisotropy as observed in laboratory experiments producing shear bands in loose sediments (Fig. 7b; Arch and Maltman, 1990). Under greater confining pressures (greater burial depths) the breakage of grains (cataclasis) will increasingly occur along deformation bands.

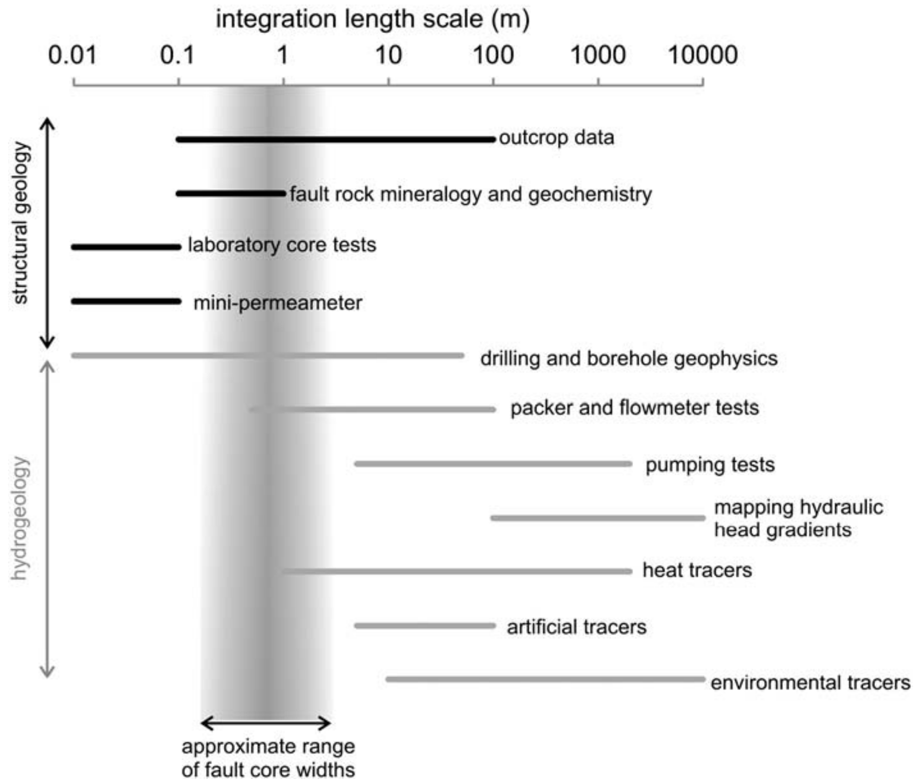

Fig. 3. The methods used in structural geology (black line) and hydrogeology (gray line) each have a characteristic length scale that they spatially integrate over, as shown here approximately.

Hence, only at shallow depths (e.g. <100 m) permeability in unlithified rock is usually not strongly impacted by fault zone processes, a distinct reduction in permeability may be possible at greater depths, which is discussed in Section 3.2.2.

Relatively little attention has been paid to the hydrogeological importance of permeable sands and gravels that are incorporated via particulate flow in fault zones instead of, or together with, low permeability beds such as clay and shale. However, the incorporation of sand along fault zones, together with or instead of clay beds, is well documented in the field (Lewis et al., 2002), and interpreted on seismic images (Koledoye et al., 2003). This process will often lead to an enhancement of permeability of a fault zone since beds of permeable material along the fault zone will form conduits for the migration of fluids along the fault zone, the efficiency of which depends on the continuity and thickness of this material (Bense and Person, 2006).

3.2.1.2. Fracturing and brecciation in lithified siliciclastic, crystalline and carbonate rock. In response to stress imposed on the rock, dilational fractures (Fig. 7a) with no shear displacement (called joints) occur in and outside fault zones in relatively strong rocks such as partially lithified low-porosity clastic rocks (e.g.; Balsamo et al., 2010), crystalline rocks and carbonate rocks (Berkowitz, 2002; Neuman, 2005). The mechanics of fracture initiation and propagation are beyond the scope of this review but are well described elsewhere (Pollard and Aydin, 1988; Aydin, 2000). For low-porosity (<10%) and permeability (10^{-15} m^2) rock, bulk porosity and permeability are primarily controlled by the fracture network properties. The network connectivity, that controls partly the permeability, depends on fracture density, fracture orientations and fracture length distribution (e.g. Hestir and Long, 1990; Bour and Davy, 1997). Permeability of fracture networks depends both on connectivity of fracture networks and the fracture aperture distribution (Long et al., 1982; Brown and Bruhn, 1998; Faybishenko et al., 2000; de Dreuzy et al., 2001, 2002). Using a simple parallel plate model to represent fractures, it was shown that the cube of the aperture is a good approximation of their permeability (Snow, 1969: Kiraly, 1971; Witherspoon et al., 1980; Zimmerman and Bodvarsson, 1996). Thus, individual fractures with a moderate (~100–250 μm) aperture can still control local permeability. Near fault zones the fracture density and connectivity typically increases significantly (Fig. 5). Therefore the bulk rock permeability near fault zones is generally larger than that of the protolith. For example, permeability measurements indicate an increase in effective permeability by 2–3 orders of magnitude relative to granite and gneiss protolith in the East Fork thrust faults in Wyoming, USA (Evans et al., 1997).

Brecciation is a prominent fault process in low-porosity settings such as within crystalline rocks, and carbonates (Sibson, 1977; Sibson, 1986). **Breccia** is fault rock composed of angular, coarse-grained fragments that formed via high-density fracturing (brecciation), which are embedded in a fine-grained matrix, and where the matrix does not make up more than 30% of the total rock volume (Sibson, 1977; Woodcock and Mort, 2008). Breccia is often uncohesive when formed in the upper few kilometers of the crust. As with the development of joints, fracturing leading to breccia formation in fault zones will, at least initially, cause an enhancement of permeability. This can amount to up to four to five orders of magnitude (Walker et al., 2013). Cementation of the pore space created by brecciation, or a grinding of the brecciated rock with further displacement along the fault zone, will in turn lead to a strong reduction in permeability.

3.2.2. Fault zone processes that reduce permeability

3.2.2.1. Particulate flow, sediment mixing and clay smear in unlithified rock. Particulate flow was discussed above as a process to potentially lead to subtle enhancements of permeability along shear bands. However, when fault displacements are higher than bed thickness, particulate flow can result in the mixing of unlithified rock of different grain sizes,

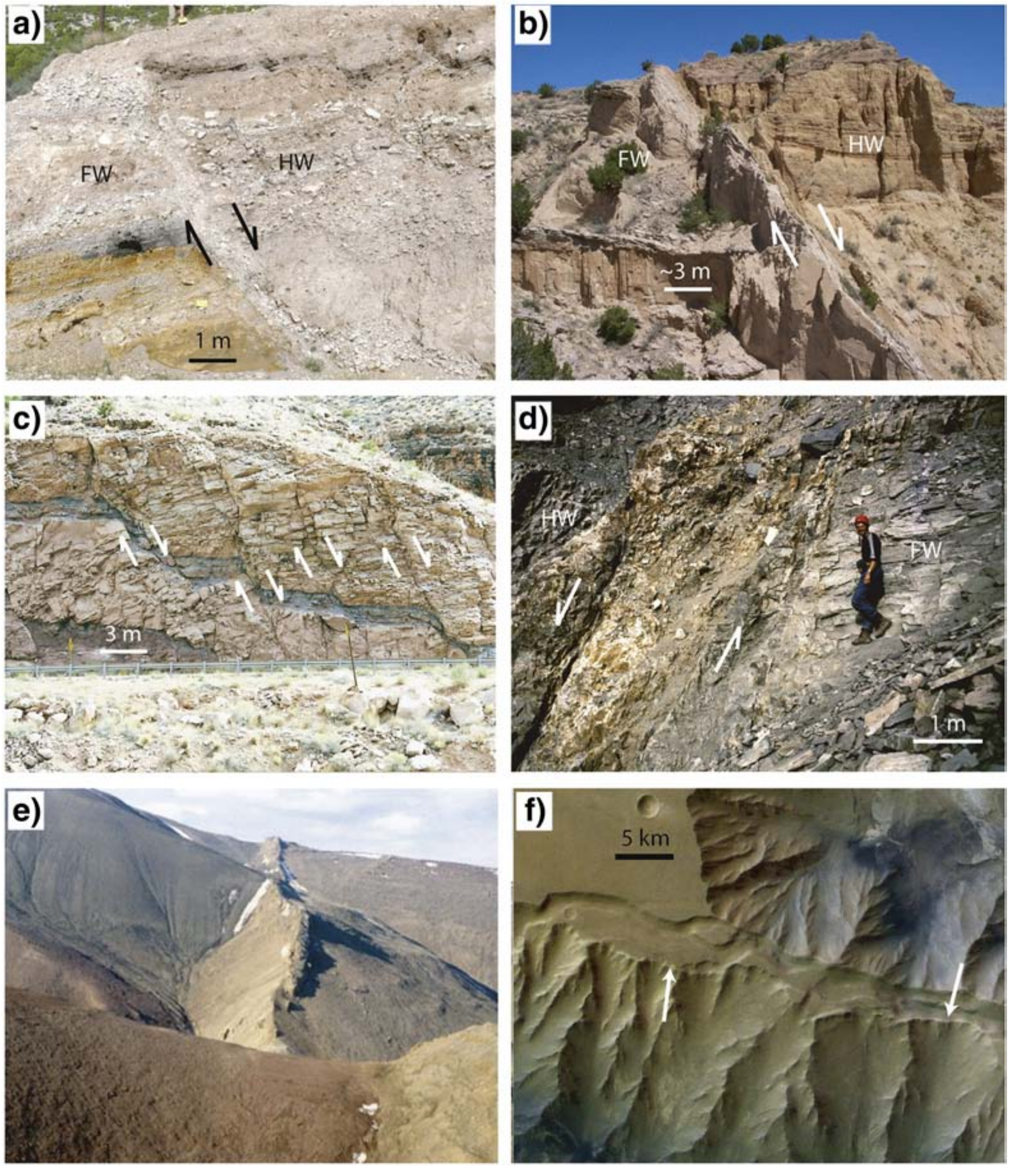

Fig. 4. Fault zones in a variety of geologic settings. HW = hanging wall; FW = foot wall; arrows in (a–d) indicate the direction of movement along the fault. (a) Fault offsetting unlithified gravels in the Gulf of Corinth, Greece. (b) San Ysidro fault zone cross-cuts unlithified, siliciclastic sediments in the Rio Grande rift, New Mexico, USA (from Caine and Minor, 2009). (c) Shale entrainment along minor faults in sand–stone sequences, in the damage zone of the Moab Fault, southern Utah, USA; (d) Fault 6, Traill Ø, East Greenland truncating interbedded sandstones and shales. (e) Quartz-cemented, mineralised fault of the Billefjorden Fault Zone, Austfjorden, Spitsbergen. (f) High-albedo features on the surface of Mars (indicated by the arrows), which have been interpreted (Treiman, 2008) as cemented fault zones analogous to the one shown in (e).

at the grain-scale as well as at the scale of sedimentary beds. Tectonic sediment mixing in fault zones generally leads to a reduction of permeability (Heynekamp et al., 1999; Faerseth, 2006; Rawling and Goodwin, 2006; Caine and Minor, 2009; Balsamo and Storti, 2011). The physical mixing of sediments with contrasting grain-size distributions can be expected to result in a more poorly sorted sediment mixture than any of the source beds, and for this reason sediment mixing leads to the effective reduction of pore space and permeability in the fault zone. The degree to which permeability is reduced as a result of sediment mixing in unlithified rock will depend on the contrast in permeability between the end-member beds, and whether particulate flow is to any extent facilitated by grain breakage, which adds an additional reduction in average grain-size of the mixture. Heynekamp et al. (1999) report a reduction in permeability of up to six orders of magnitude as compared to the original sand bed, where sandy clay form in the fault zone as a result of mixing between sand and clay beds along the Sand Hill fault zone in New Mexico, USA. The latter study further illustrates that mixing, from relatively homogeneous source beds, causes strong permeability heterogeneity in the fault zone because of incomplete mixing. In addition to permeability heterogeneity, an anisotropy of permeability can be expected to be present in fault zones as a result of rotation of bladed sediment grains. Grains aligning preferentially with the main fault dip have been observed in both lab-experiments on loose sands (Arch and Maltman, 1990), and in naturally faulted sediments ranging from sand (Bense et al., 2003a,b; Fossen et al., 2007) to gravels (Loveless et al., 2011). At the grain scale, the increased tortuosity of fluid flow paths across the fault as a result of the re-alignment of oblate grains in the direction of the fault dip results in permeability anisotropy so that perpendicular to the shear zone, permeability can be up to two orders of magnitude lower than along it (Arch and Maltman, 1990).

Where clay minerals are present in the rock matrix phyllo-silicate framework bands will develop (Fig. 7c) along which platy clay minerals

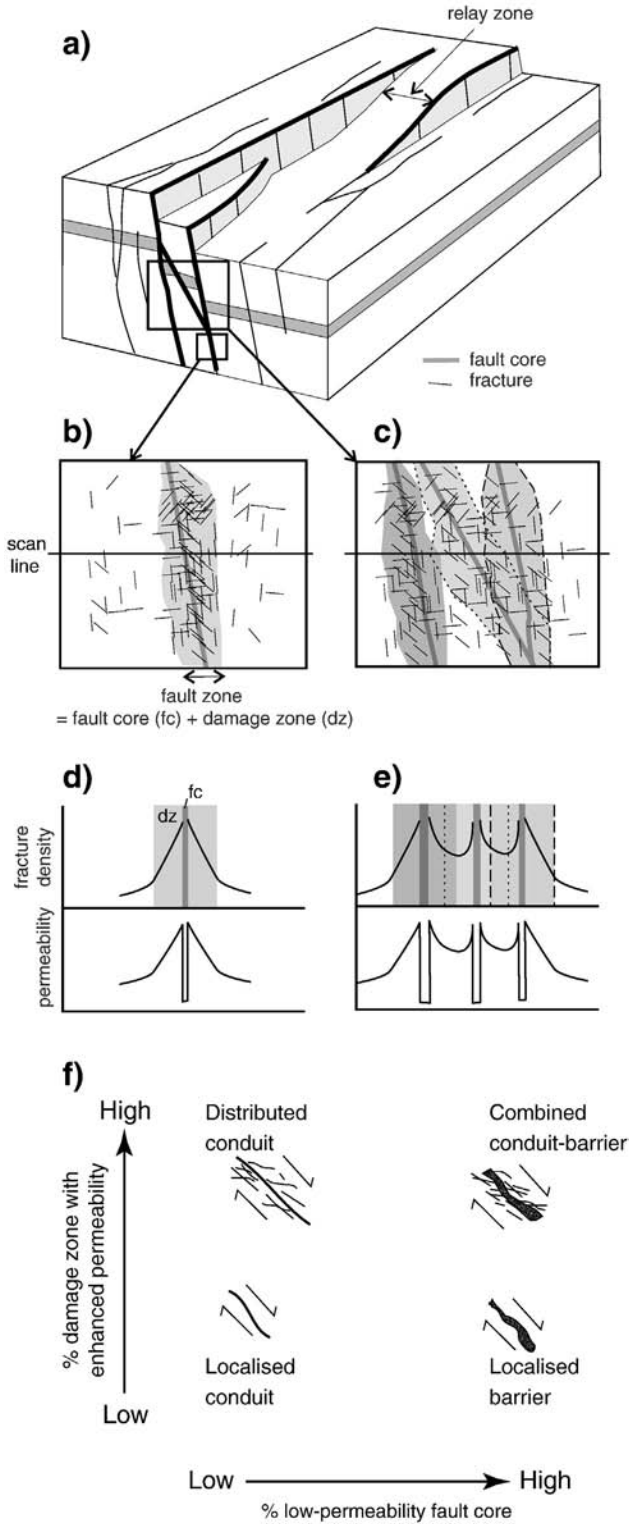

Fig. 5. (a) Block diagram showing aspects of the three-dimensional normal fault zone such as a relay zone from Childs et al. (2009). Fault zone width has been defined (b) as the combined width of the fault core and damage zone for faults with a single core (Chester and Logan, 1986; Caine et al., 1996) or (c) as the distance between the outer slip surfaces belonging to the same fault structure where multiple strands of high-strain material enclose lenses of fractured protolith (Faulkner et al., 2004, 2010). Fracture density and permeability for a crystalline bedrock lithology for a single fault zone strand (d) and multiple fault zone strands (e) (for other models see Fig. 9 and Section 3.2), modified from (Faulkner et al., 2010). (e) A description of fault behavior based on the proportion of fault core to damage zone, from Caine et al. (1996).

orient in the direction of the fault zone and will so facilitate the sliding of grains past one another possibly reducing grain breakage (e.g. Fossen et al., 2007). Clay smears often develop along fault zones cutting through clay beds (Figs. 4c and 7c). The mechanisms and parameters controlling the continuity of clay smears (Lehner and Pilaar, 1997; Aydin and Eyal, 2002; Eichhubl et al., 2005) and shale smears (Lindsay et al., 1993; Davatzes and Aydin, 2005) entrained along fault zones have been the focus of a substantial body of research. The focus on clay smear exists mainly because of their potential to form effective seals for hydrocarbon migration (e.g., Yielding et al., 1997; Sorkhabi and Tsuji, 2005), and to effectively block across-fault fluid flow (Bense and Van Balen, 2004), compartmentalizing reservoirs and aquifers. Clay smears have been described in stratigraphies characterized by unlithified rock consisting of sand–clay alternations (Yielding et al., 1997) as well as in predominantly carbonate rocks (Ferrill et al., 2004; Bonson et al., 2007; Bourouis and Cornet, 2009). Experimental work using ring-shear apparatus (e.g. Sperrevik et al., 2002), sand-box (Schmatz et al., 2006) and numerical modeling using discrete element approaches (Egholm et al., 2008), has attempted to elucidate the mechanisms and geological parameters controlling the thickness and continuity of clay-smear. Ring-shear experiments (Sperrevik et al., 2000) suggest that the competence contrasts arising between clay and sand units during sediment burial, exert an important influence on the continuity of clay-smears that develop.

3.2.2.2. Cataclasis in unlithified and lithified rock. Cataclasis is the pervasive brittle fracturing and comminution of grains (Engelder, 1974; Chester and Logan, 1986; Blenkinsop, 1991; Davis and Reynolds, 1996). In lithified rock with relatively high primary porosity (>15%) such as sandstone, displacement along deformation bands (shear joints) is commonly accommodated through cataclasis, replacing particulate flow that usually dominates deformation in soft-sediments (Fig. 7b). Cataclastic deformation band networks in lithified sandstones have been the focus of a very substantial body of literature (e.g. Fowles and Burley, 1994; Shipton and Cowie, 2001; Schultz and Siddharthan, 2005; see Fossen et al., 2007 for a review). While particulate flow occurs near the ground surface in unlithifed rock, at greater depths rock is stronger and cataclasis becomes the dominant deformation process at some point. However, at intermediate depths particulate flow can be accompanied by cataclasis in which case the deformation process has been called facilitated- or dependent particulate flow (Borradaile, 1981; Rawling and Goodwin, 2003). Facilitated particulate flow characterized by grain flaking has been observed in unlithified sedimentary rock only buried to a few hundreds of meters (Heynekamp et al., 1999; Sigda et al., 1999; Rawling and Goodwin, 2003; Balsamo and Storti, 2010; Balsamo et al., 2010, 2013). Moreover, the effectiveness of cataclasis occurring in unlithified sedimentary rock, varies as function of grain composition; relatively weaker grains such as feldspars can be entirely crushed while stronger quartz grains show low-intensity cataclasis characterized by the flaking of grains rather than their entire disintegration by crushing (Heynekamp et al., 1999; Exner and Grasemann; Loveless et al., 2011; Exner and Tschegg, 2012). Sediment grain-size distributions allowed Rawling and Goodwin (2003) to show how the efficiency of cataclasis along deformation bands in partially lithified quartz-dominated sediments is greater for relatively large grain-sizes than for finer sediment. Major near-surface rupturing associated with earthquakes at depth may result in the occurrence of cataclasis under relatively low confining pressure in loose sediments where normally particulate flow would dominate as the mode of deformation (Cashman et al., 2007; Doan and Gary, 2009; Balsamo and Storti, 2011). However, occurrence of fluid overpressure in rapidly subsiding sedimentary rocks can potentially lead to substantial reduction in rock strength as a result of which particulate flow might dominate over cataclasis as the deformation mechanism in granular rock to depths much larger than 1 km.

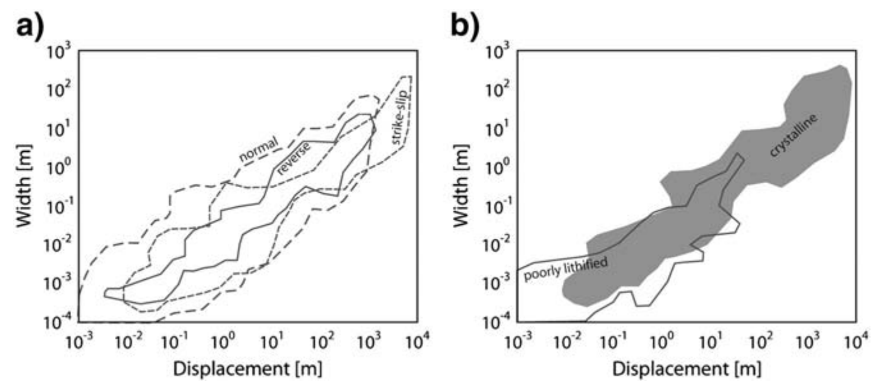

Fig. 6. The relationship between fault thickness (width) and fault throw (displacement) for different fault types (a) and between lithified and unlithified sediments and crystalline rock (b) shows similar trends. Lines and shading covers range of observed data for each fault type. Diagrams are based upon data presented in Childs et al. (2009).

Where particulate flow is accompanied by cataclasis a permeability reduction along slip surfaces of 1–3 orders of magnitude has been reported (Fig. 8; Sigda et al., 1999; Rawling et al., 2001; Balsamo and Storti, 2010; Ballas et al., 2013; Balsamo et al., 2013). Permeability along cataclastic deformation bands in lithified sandstones with low clay-content is typically reduced more strongly by 4–5 orders of magnitude, as compared to undeformed sandstone, which is demonstrated by many field- and laboratory permeability tests (e.g. Antonellini and Aydin, 1994; Fisher and Knipe, 2001). Permeability along cataclastic deformation bands is often anisotropic with the largest reduction in permeability perpendicular to the band (Antonellini and Aydin, 1994; Sigda et al., 1999). Currently, the controls on the magnitude and spatial variability of the permeability reduction along deformation bands is still the focus of a substantial research effort (e.g. Torabi and Fossen, 2009).

3.2.3. Interacting, secondary or larger-scale processes that either reduce or enhance fault zone permeability

In addition to the fault processes that impact the permeability of fault rocks described above, a suite of other geological processes and conditions can have a significant impact on the development of fault permeability and architecture. Here we focus on the main processes relevant to the shallow crust, (1) the role of compaction and cementation of unlithified rock, (2) dissolution and cementation in fracture networks, and (3) regional stress field impacting fracture permeability.

3.2.3.1. Compaction and cementation of unlithified rock. Compaction and cementation of sediments in subsiding sedimentary basins generally leads to porosity loss (e.g. Bethke and Corbet, 1988) and a reduction in permeability (Bense and Person, 2006). Rate of sedimentation, sediment compressibility, and permeability will control rates and magnitudes of mechanical compaction during burial of the rock (Bethke and Corbet, 1988). The influence of compaction and cementation on fault-related permeability structures can be two-fold. Firstly, permeability patterns formed by deformation at shallow depth will be overprinted by permeability changes as a result of compaction and cementation at larger depths (e.g. Milliken et al., 2005). The compressibility of the sediment, which is governed in part by rock strength, is likely to be influenced by shallow diagenetic and tectonic processes where for example disaggregation leads to a loss of cohesion. Consequently, the impact of compaction on permeability of faulted sediments can be variable: permeability contrasts can either become homogenised when porosity loss is greater in the protolith than along deformed rock, or enhanced when compaction and cementation preferentially reduces permeability along shear bands (Fossen et al., 2007). Secondly, compaction and cementation strengthens the rock which causes, as discussed above, the dominant deformation mechanism to shift from particulate flow to cataclasis or jointing with increasing depth. Field measurements of permeability of fault rocks formed in compressible clastic sediments thus reflect the effects on permeability of both compaction and deformation (Fisher and Knipe, 2001). Bense and Person (2006) described permeability loss due to faulting in combination with compaction (but not cementation) as a function of volumetric clay content mimicking the observed range in permeabilities of faulted unlithified and lithified rocks associated with various deformation mechanisms as reported in the literature (Fisher and Knipe, 2001; Sperrevik et al., 2002).

3.2.3.2. Dissolution and cementation in fracture networks. Fluids carrying reactive solutes circulating through fault zones potentially enhance or reduce permeability as a result of water–rock interaction (e.g. Zhang et al., 2008). Whether precipitation of minerals into pore space occurs (cementation), or rock dissolution occurs depends on the specific geochemical conditions such as rock composition, solute concentrations, temperature, and rates of advective solute transport via fluid flow (e.g. Appelo and Postma, 2005). Moreover, the enhancement or reduction of pore space provides a strong feedback mechanism on the conditions for water–rock interaction to progress or slow down. For example, if a requirement for cementation is that sufficient solutes are provided via advective fluid and permeability is reduced via cementation, a negative feedback mechanism will be in operation. Given the correct conditions, fracture networks surrounding fault zones can become fully cemented, but this is by no means always the case (Micarelli et al., 2006; Kim and Sanderson, 2009). Regardless of whether such cementation happens, new generations of fractures can develop with further stress imposed on the rock (Roberts and Stewart, 1994; Geraud et al., 2006; Benedicto et al., 2008). This cyclic process leads to the formation of characteristic crack-seal breccias (cf. Ramsay, 1980; Woodcock et al., 2007; Kampman et al., 2012). Enhanced permeabilities may prevail along active faults if the opening and formation of fractures is more rapid than the sealing mechanism via cementation (Riggs et al., 1994; Constantin et al., 2004). Although fluid–rock interaction as described above is a typical feature of carbonates which are relatively easy to dissolve, geochemical, geomechanical and outcrop observations suggest that fluid flow and chemical reactions are often important to fault development and growth in crystalline rock as well (Chester and Logan, 1986; Evans, 1988; Bruhn et al., 1994; Chester, 1995; Hickman et al., 1995; Wintsch et al., 1995). Laboratory and field evidence show that quartz is commonly dissolved and re-precipitated in fault cores which can reduce their permeability by several orders of magnitude (Chester and Logan, 1986; Evans, 1988). Feldspars often react with slightly acidic pore water to produce phyllo-silicate which are volume–loss reactions that reduce the rheological strength and permeability of the central fault core (Evans, 1988; Goddard and Evans, 1995; Wintsch et al.,

Table 2
Processes that impact the permeability of fault zones in different rock types. Cells with bold citations or single asterisk (*) implies process is common for the lithology; italic citations or double asterisk (**) implies process is uncommon but possible; and blank cells implies rare. Representative examples of studies that describe the geologic structure are included

Process	Product	Unlithified to poorly lithfied rock	Siliciclastic sedimentary rock	Carbonate sedimentary rock	Crystalline rock	Volcanic rock
Primary fault processes that enhance permeability (section 3.2.1)						
Particulate flow	Disaggregation bands, dilation bands, sand smear	**Du Bernard et al. (2002)**, and **Bense et al. (2003a,b)**, and **Exner and Graseman (2010)**	**	**	**	**
Fracturing	Shear fractures, joints	*Balsamo et al. (2010)*	*Eichhubl et al. (2009)*	**Roberts and Stewart (1994)**, **Agosta and Kirschner (2003)**, and **Ferrill et al. (2004)**	**Martel, 1990**, and **Caine and Tomusiak (2003)**	**Gray et al., 2005**
Brecciation	Breccias	*Caine and Minor (2009)*	*Hippler (1993)*; *Eichhubl et al. (2009)*	**Roberts and Stewart (1994), and Billi (2005)**	**Bruhn et al. (1994), and Caine et al. (2010)**	**Gray et al. (2005)**, and **Kaven and Martel, (2007)**
Primary fault processes that reduce permeability (section 3.2.2)						
Particulate flow	Sediment mixing; dilation	**Heynekamp et al. (1999)**, and **Rawling and Goodwin (2006)**	**	**	**	**
Phylosilicate smearing	Phylosilicate band	Fulljames et al. (1997)	**Antonellini and Aydin (1994)**; **Knipe (1997)**		**	**
	Clay smear	**Lehner and Pilaar (1997)**, and **Bense and Van Balen (2004)**	**Lindsay et al. (1993)**, and **Egholm et al. (2008)**	*Ferrill et al. (2004)*; *Bonson et al. (2007)*	**	**
Cataclasis	Cataclastic deformation bands	*Sigda et al. (1999)*, *Sigda and Wilson (2003)*, and *Cashman and Cashman (2000)*	**Aydin and Johnson (1978)**, and **Antonellini and Aydin (1994, 1995)**	*Storti et al. (2003)*; *Rath et al. (2011)*	**	*Wilson et al. (2003)*
	Cataclasite, ultracataclasite	**	**Labaume et al. (2001)**, and **Tueckmantel et al. (2012a)**	**Agosta and Kirschner (2003)**; **Micarelli et al. (2006)**	**Chester and Logan (1987)**	*Walker et al. (2013)*
Brecciation/ cataclasis	Fault gouge	**	**Engelder (1974)**, and **Gibson (1998)**	**Ferrill and Morris (2003)**, and **Benedicto et al. (2008)**	**Chester and Logan (1987)**, and **Schulz and Evans (2000)**	**Gray et al. (2005)**
Secondary and other geological processes that can either reduce or enhance permeability (section 3.2.3)						
Fluid flow controlled dissolution & cementation	Solution cavities or incomplete precipitation (e.g., vugs)	**	**	**Micarelli et al., (2006)**; **Kim and Sanderson (2009)**	**	**
	Crack-seal veins or breccia	**	**	**Roberts and Stewart (1994)**	**Walker et al. (2012)**	
	Veins, concretions and localised precipitation	*Mozley and Goodwin (1995)*, and *Balsamo et al. (2013)*	**Eichhubl et al. (2009)**	**Bastesen and Braathen (2010)**; **Matonti et al. (2012)**	**Bruhn et al. (1994)**; **Schulz and Evans (2000)**; **Person et al. (2008)**	**Person et al. (2008)**
Pressure solution	Solution band	**	*Knipe (1993)*, and *Gibson (1998)*	**Peacock et al. (1998)**		
	Stylolites	**	**	**Tondi et al. (2006)**, and **Agosta et al. (2012)**	**	**
Sediment infilling	Sediment infill	**	**	**Roberts and Stewart (1994)**, and **Ferril and Morris (2003)**	**	**Walker et al. (2012)**
Fault growth	Relay ramp, segment boundaries, asperities, juxtaposition of lithologies at the fault zone	**Rawling and Goodwin (2006)**, and **Loveless et al. (2011)**	**Childs et al., (1996)**; **Watterson et al., (1998)**; **Mailloux et al (1999)**	**Benedicto et al. (2008)**, and **Bastesen et al. (2009)**	**Bruhn et al. (1994)**	*

1995). Phyllo-silicate formation could transiently enhance or redistribute fluid flow.

3.2.3.3. Regional stress field impacting fracture permeability. The aperture of fractures and therefore fracture transmissivity, is very sensitive to pressure and to the stress conditions in the rock (Guéguen and Palciauskas, 1992). This is one of the reasons, with a possible decrease of fracture density with depth, that explains the decrease of permeability with depth often observed in the first hundreds of meters in crystalline rocks (Ingebritsen and Manning, 1999; Gleeson and Novakowski, 2009). Field evidence over the past decades (e.g. Barton et al., 1995), shows how in active, or recently active areas, faults networks appear to be more permeable, as evidenced by higher hydrocarbon production rates at those locations. The most permeable fractures are generally assumed to be those which are most closely oriented in the direction of the largest horizontal stress. However, Barton et al. (1995) nuances this view by proposing that it is those fractures that undergo a high ratio of shear to normal stress which are most likely to be hydraulically conductive. The latter model is confirmed by Hennings et al. (2012), who show that the number of critically stressed fractures is the best indicator of hydrocarbon reservoir performance, as a proxy for the fracture network permeability.

4. Conceptual geological models of fault zone hydrogeology

In fault zo\nes in which a fault core and a damage zone are well developed, the FC/DC concept provides a convenient framework to describe the hydrogeological characteristics of fault zones (Fig. 5f; Caine et al., 1996). The permeability structure of a fault zone can be derived from outcrops by combining a map, cross-section or 3D model of architectural

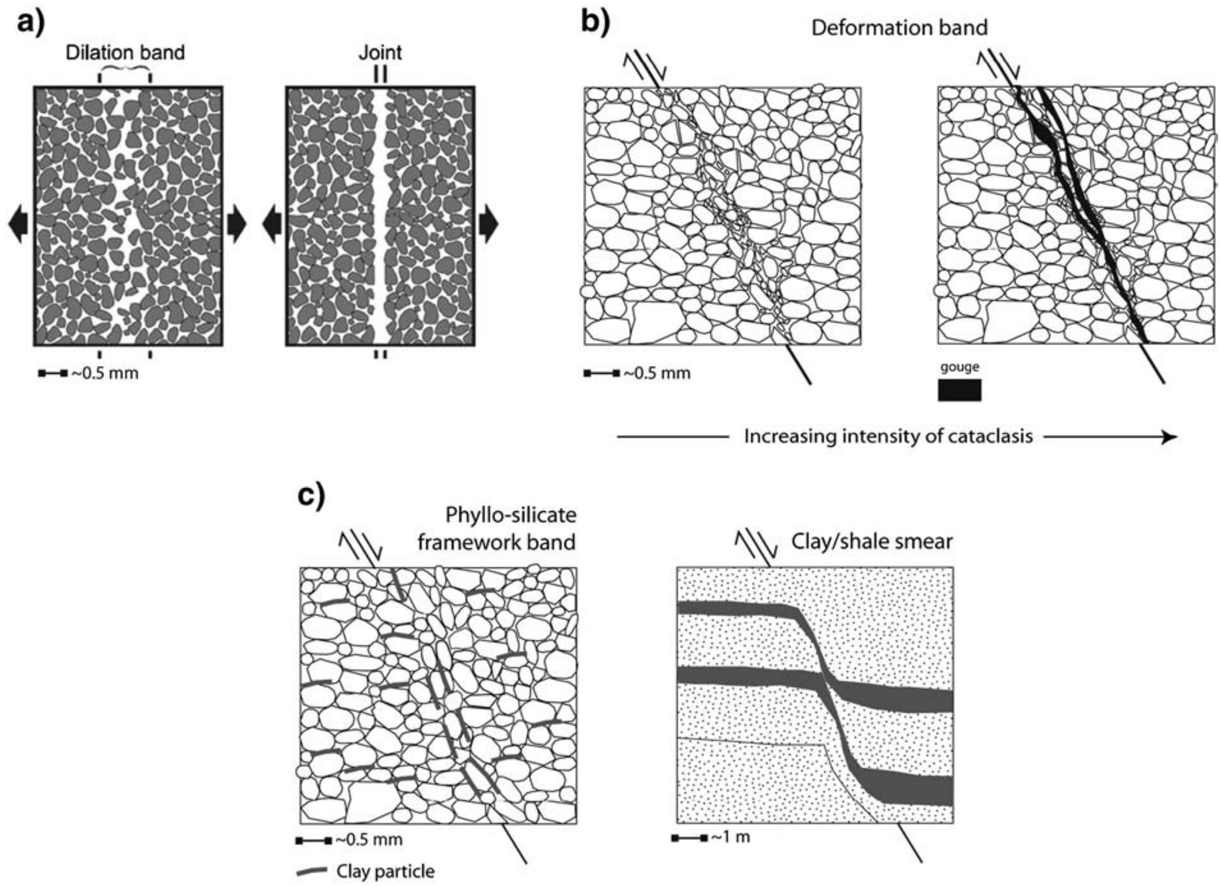

Fig. 7. Deformation mechanisms in clastic rock. (a) Formation of dilation bands in unlithified rock, and joints in lithified rock (from du Bernard et al., 2002). (b) Facilitated particulate flow, as low-intensity cataclasis, and cataclastic deformation bands forming gouge. (c) Clay within the rock matrix reduces the occurrence of cataclasis along deformation bands, and phyllo-silicate framework bands develop at the grain scale while at the scale of sedimentary beds clay units will fold along the fault plane to form clay smears.

components with the permeability of each fault zone element. Idealized models of fault permeability structures have been proposed from field observations of faults, over a range of magnitudes in fault throw and in different geological settings (Caine et al., 1996; Aydin, 2000; Rawling et al., 2001). The promise of such generic fault zone hydrogeology models is that they have generic applicability in areas with similar geological

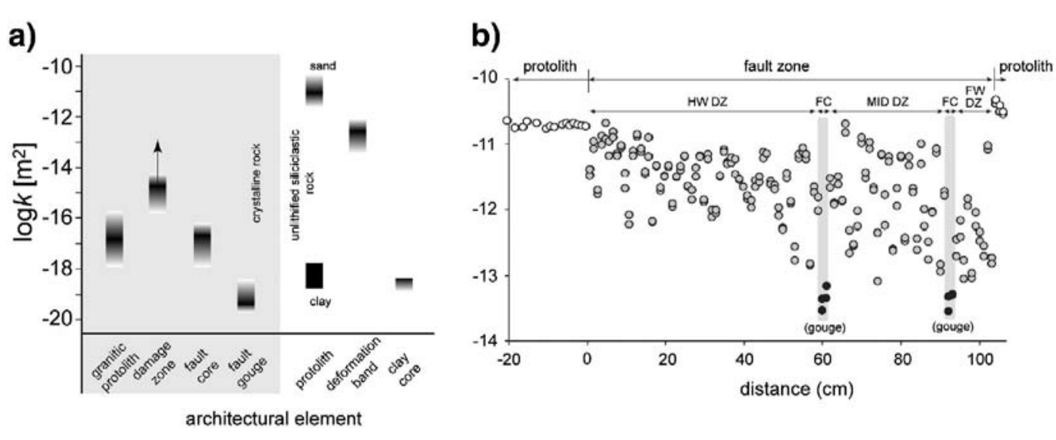

Fig. 8. (a) Example of observed permeability contrasts between architectural elements making up fault zones in crystalline rock, and unlithified siliciclastic rock (modified from Rawling et al., 2001). Gray shading within each box represents the spread in observed values where the black hue represents the median value. The arrow towards high permeability values for damage zones in crystalline rocks represents the possibility of the presence of open fractures in such settings. Measurements of permeability on protolith clay units were too few to be represented as a distribution in the data set underlying this figure. (b) Permeability data collected across a small fault zone (throw ~20 m) in unlithified rock dominated by sand (Figure from Balsamo and Storti, 2010) in the Crotone Basin in southern Italy (HW = Hanging Wall; FW = Foot Wall). The undeformed sediment has a relatively homogeneous permeability distribution. In the damage zone (DZ), cataclastic deformation bands occur along which permeability is reduced by one to two orders of magnitude leading to strong hydrogeological heterogeneity. In the fault core, more intense cataclasis leading to the formation of gouge causes permeability to be reduced further by almost four orders of magnitude as compared to the protolith.

parameters such as the lithology and geology of the protolith, and effective stress (the total overburden pressure reduced by the fluid pressure).

4.1. Unlithified- and lithified siliciclastic rock

In unlithified siliciclastic rock the smearing and drag of sand- and clay-beds along the main fault plane results in relatively consistent fault architectures as apparent when different outcrop studies are compared (e.g. Lehner and Pilaar, 1997; Eichhubl et al., 2005; Rawling and Goodwin, 2006). With increasing fault displacement a layered structure of clay and sand smears often develops (Fig. 9a). Bense and Person (2006) argue that in faults where cataclasis does not play an important role in reducing permeability at near surface depths in sandy sediments, the smearing of both clay and sand along the main fault plane is an important mechanism to generate a strongly anisotropic fault core in which the sand seams will act as along-fault conduits while the clay smear will strongly hamper across fault flow. Any damage zone in this kind of scenario will not have a strong impact on the fault hydrogeological structure as permeability along deformation bands in unlithified rock will be hardly affected. Based upon these considerations, faults in unlithified siliciclastic rock, in which cataclasis is minimal are likely to behave as combined conduit–barrier systems as a result of the strongly anisotropic nature of the fault core (Fig. 9a), which will be further enhanced by grain rotation (Loveless et al., 2011).

When cataclasis does play an important role, however, any sand incorporated in the core might be impacted by cataclasis and, hence, have a significantly reduced permeability. Empirical relationships in faulted high-porosity sediments suggest that permeability in the fault core rapidly decreases up to 2–3 orders of magnitude in the first 5–10 m of displacement, and then decreases at a slower rate in relation to further displacement (Balsamo and Storti, 2010). Also, cataclastic deformation bands developing in the damage zone will reduce permeability there (Fig. 8b). A range of faults along which shale is entrained in the fault core, and complex deformation band networks have formed in the damage zone and the fault core, have been described in detail on the Colorado plateau (Davatzes and Aydin, 2005; Shipton et al., 2006a) and the Rio Grande Rift Basin (Heynekamp et al., 1999). In the absence of open-fracture networks, this type of fault is thus likely to behave as an efficient barrier to fluid migration (Fig. 9b; Rawling et al., 2001).

4.2. Crystalline rock

Fault cores in crystalline rocks are commonly zones of fault gouge and breccia (Evans and Chester, 1995; Caine et al., 1996; Evans et al., 1997). Fault cores often display anastomosing slip surfaces and occasionally deformation bands (Hancock, 1985; Evans, 1988). Flanking the fault core is typically a damage zone, characterized by a high density of fractures (Fig. 4d; Caine et al., 1996; Chester and Logan, 1986). The fault core and damage zone are surrounded by protolith of relatively undeformed rock that may contain joints not primarily related to the fault zone, but exists as a 'background' deformation pattern. While laboratory and in situ permeability experiments suggest that often the damage zone has a larger permeability than both the fault core and the protolith, the permeability in each domain is internally anisotropic (Forster and Evans, 1991; Caine and Forster, 1999). However, the permeability contrast between components is much greater than the anisotropy within components suggesting that inter-component contrast controls the bulk anisotropy of the system (Caine et al., 1996). Laboratory permeability tests of orientated samples show that the damage zone is usually a high permeability conduit parallel to the fault plane while the core is a low permeability barrier parallel and perpendicular to the fault plane (Chester and Logan, 1986; Caine et al., 1996). Each of four end-member architectural styles (Fig. 9e) is thus associated with a characteristic permeability structure which varies with the percentage of the fault thickness taken up by the relatively low permeability FC and the higher permeability DZ. In this scheme, the ratio of damage zone width to total fault thickness quantifies the description of fault architecture. In principle faults in these settings are thus thought of as to a degree behaving along continuums between four end members: conduit–barriers, distributed conduits, localized barriers or localized conduits (Fig. 5f; Caine et al., 1996).

4.3. Volcanic rock

As a result of the wide variety of volcanic rocks ranging from unwelded tuffs, to welded tuffs and solidified lava, the fault zone hydrogeology models that will be applicable to volcanic rocks will thus be wide-ranging.

For fault zones in unwelded, stratified tuffs a fault zone hydrogeology model similar to that for unlithified siliciclastic rocks has been described (Evans and Bradbury, 2004). In welded, crystallized tuffs other conceptual models have been proposed (Wilson et al., 2003; Gray et al., 2005; Riley et al., 2010), which show that generally fault zone hydrogeological architecture in this geological setting is comparable to that of faults described in crystalline rocks. Hence, the main fault processes are brecciation in the fault core, and fracturing in the damage zone which can be accompanied by mineralization. In particular, Gray et al. (2005) classifies the architecture of fault zones found in welded tuffs around Yucca mountain, Nevada into four groups based upon the shift, with increasing fault throw, in the relative thickness of the damage zone and fault core making up the entire thickness of the fault zone, similar to the model described by Caine et al. (1996) for crystalline rock (Fig. 9d).

A conceptual model for the development of fault permeability architectures in basalt sequences was proposed by Walker et al. (2013) largely based upon outcrop evidence from the Faroe Islands. This work shows that faults in basalt are likely to behave as conduit–barrier systems in an analogous way to many faults in crystalline rock. Walker et al. (2013) report how fault permeability along well-developed fault cores is strongly reduced through cataclasis and the growth of authigenic clay-minerals, while in the damage zone fracture networks can, if well connected, maintain a relatively high permeability promoting along-fault fluid flow. However, as Walker et al. (2013) point out, during the initial stages of fault zone development the conduit behavior of the fault zone is likely to dominate. Overall, however, the fault zone permeability model as proposed for these faults is very similar to that of crystalline rocks as discussed above (Fig. 9c).

4.4. Carbonate rock

While dissolutional weathering often dominates carbonate rocks, primary fault deformation mechanisms are largely similar to those in crystalline rocks and siliciclastic rocks in which fracturing and cataclasis play important roles impacting permeability (Stewart and Hancock, 1991; Roberts and Stewart, 1994; Cello et al., 2000; Ferrill and Morris, 2003; Storti and Billi, 2003; Doan and Cornet, 2007; Benedicto et al., 2008; Bastesen et al., 2009; Matonti et al., 2012). Fine grained sediment may also be washed into the fault core through cavities (Ferrill and Morris, 2003). Because of the importance of water–rock interaction in carbonate systems the permeability structures of faults in carbonate rocks can be expected to be transient, heterogeneous and anisotropic (Agosta et al., 2007; Agosta, 2008). The presence of uncemented fracture networks, breccia and dilatational jogs provides conduits whereas the formation of fine-grained cataclastic fault rocks, the smearing of clay into the fault core and the mineralization of fracture networks reduces the permeability of the fault zone. The permeability structures of fault zones in carbonate rocks are thus likely to be similar to those described above for crystalline rock and form to varying degrees conduit–barrier systems through the potential of fluid-flow conduits through a fracture dominated damage zone flanking a low permeability fault core (Fig. 9d). However complex the permeability structure along faults in carbonates might be as a result of deformation, when dissolutional weathering creates significant high-permeability pathways these may

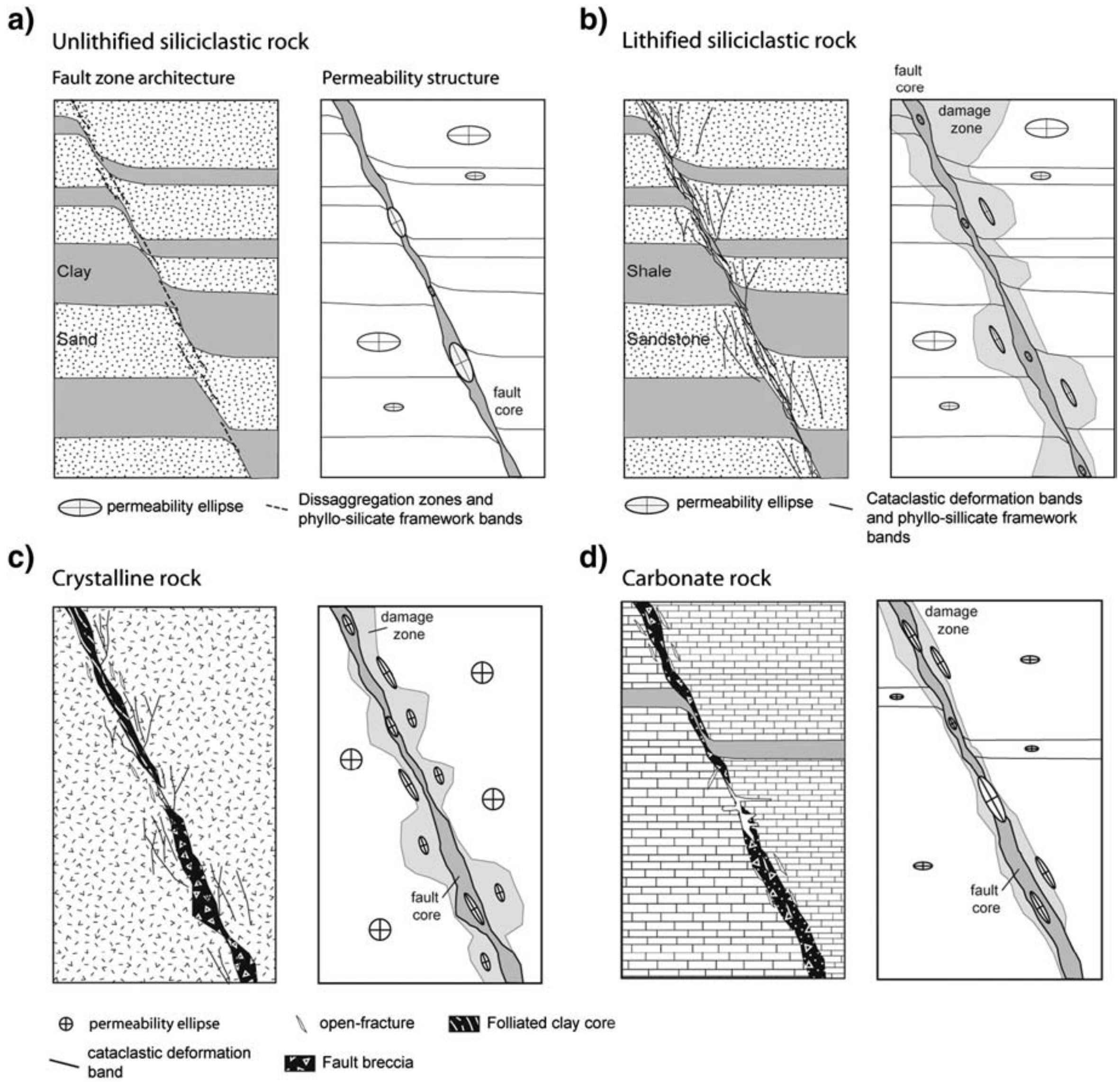

Fig. 9. Fault architectures are commonly described in terms of a fault core (FC) and a damage zone (DZ) flanking the fault core into the footwall and hanging wall. (a) Fault architecture and associated conceptualized permeability structures in faults dominated by soft-sediment deformation at relatively shallow depths (partially after Heynekamp et al., 1999), and (b) within lithified sedimentary rocks in which cataclastic deformation plays a dominant role. Fault architecture and associated conceptualized permeability structures in (c) crystalline rocks and (d) carbonate rock.

well dominate over the secondary permeability patterns induced by deformation related to fault zone processes.

5. Hydrogeological evidence of the impact of faults on fluid flow

The variety of fault models discussed in the previous sections, are primarily inferred from outcrop descriptions and permeability measurements from the field and laboratory (Fig. 1a). The testing of these models for their hydrogeological use needs field evidence of the hydrogeological impacts of these fault zones (Fig. 1b). Here we also divide faults into distinct lithological categories despite the observation that, often, faults crosscut and/or juxtapose multiple lithologies which makes describing and studying these fault zones more complex.

5.1. Unlithified- and lithified siliciclastic rock

Clastic sedimentary rocks often have relatively high bulk rock permeability (>10^{-14} m^2) and porosity (>15%), and are important loci of groundwater and hydrocarbon reservoirs. Often fault zones in sedimentary aquifer systems are apparent by significant differences in hydraulic head in groundwater aquifers (Bense and van Balen, 2004) or fluid pressure as observed in hydrocarbon reservoirs (Sverdrup et al., 2003) on either side of a fault zone, indicative of anomalously high hydraulic gradients across the fault zone itself.

The impact of faults as barriers may become apparent when groundwater abstraction takes place either for mine-dewatering or water supply purposes. In the loosely unlithified sediments of the Lower Rhine Embayment (LRE), Germany, extensive groundwater withdrawal takes place and hydraulic head differentials across faults occur of up to ~120 m. In addition, data from this area illustrate the potential effects of discontinuities such as relay zones to strongly impact fluid flow patterns in faulted aquifers. The differences in water table elevation on either side of faults in unlithified sediments often result in contrasting vegetation characteristics when shallow water tables are found upstream of the fault zone while downstream water tables are deeper (Bense and Kooi, 2004; Mayer et al., 2007). Outcrop studies in the LRE indicate the presence of clay/shale along fault planes, possibly in combination with cataclastic deformation (Lehner and Pilaar, 1997), which suggests that these faults would impede lateral groundwater movement. Anomalously high hydraulic gradients across fault zones are indeed commonly interpreted as being indicative of a low fault permeability so that the fault acts as a baffle to groundwater flow (Haneberg, 1995).

While in the LRE the presence of clay smearing, as observed in outcrop, seems to provide a good explanation for the barrier properties of faults as inferred from hydraulic head data, often such direct links between structural geological and hydrogeological fault properties are not so directly made. For example, hydraulic head data collected by Medeiros et al. (2009) around a fault zone dominated by cataclastic deformation bands in a sandstone aquifer show that, although permeability measurements on deformation bands show that the permeability of individual deformation bands is reduced by almost five orders of magnitude compared to the host rock, there seems to exist a mostly uninterrupted hydraulic communication between either side of the fault zone as observed during a pumping test. Structures in the fault zone cause open fluid flow pathways that by-pass the low-permeability deformation bands. Mayer et al. (2007) on the other hand, reports water table drops of ~80 m across the Mission Creek Fault, California, cutting through alluvium dominated by gravel in which clay-smearing along the fault plane is unlikely to occur. In the latter case, rotation of oblate pebbles along the fault plane might introduce sufficient reduction in permeability perpendicular to the fault to explain the high hydraulic head gradients.

Although an analysis of hydraulic heads can give an indication to what extent a fault might form an effective barrier to lateral groundwater flow, natural tracers for groundwater flow such as salinity, temperature and other geochemical parameters are essential to provide additional information on the presence and nature of fluid flow paths across fault zones (Fig. 2). For example, in the LRE thermal anomalies occur in the aquifers flanking the Rurrand Fault which can only be explained by significant along-fault up- and down welling of groundwater and subsequent sideways migration into the aquifer (Bense et al., 2008). Presumably, the transport of groundwater along the fault plane occurs through sand lenses and possibly continuous drags of sand in the fault core in combination with the presence of clay smear contributing to strongly anisotropic flow.

Along the coast of the Gulf of Mexico, hydraulic head observations seem to indicate that the Baton Rouge Fault in unlithified Quaternary siliciclastic sediments hampers lateral fluid flow while hydrogeochemical analyses suggest that the brackish to saline water occurring along the Baton Rouge Fault in shallow aquifers has migrated upward along the fault plane by several hundreds of meters (Stoessel and Prochaska, 2005; Bense and Person, 2006). Along the Baton Rouge Fault the abstraction of water in shallow aquifers provides the driving hydraulic head gradient needed for the up coning of deeper groundwater along fault zone. In the deeper parts of the Gulf of Mexico basin offshore upward fluid flow is driven by ongoing sediment compaction (Harrison and Summa, 1991) and, possibly analogous to the system along the Baton Rouge Fault is the upward flow along faults of hydrocarbons resulting in oil-seeps found at the seabed offshore in the Gulf of Mexico (MacDonald et al., 2000). Uniquely, in the Gulf of Mexico, the migration of pockets of over pressurized fluids along faults has been monitored directly using time-lapse seismic tomography (Haney et al., 2005).

Further evidence indicating the importance of along-fault flow in siliciclastic aquifers is illustrated by paleo-fluid flow patterns and inferences of its evolution through geological time as function of basin development derived from, for example, oxygen-isotopic analysis of calcite cements along block-bounding faults in California (Boles et al., 2004), diagenetic elongate carbonate concretions associated with faults in poorly lithified sediments in south Italy (Balsamo et al., 2013), and mineralogical analysis of cements along faults in New Mexico (Caine and Minor, 2009). Other examples are the distribution and geochemistry of clay and iron precipitates along faults in sandstones in Nevada that allowed to reconstruct fluid flow patterns and permeability structures of deformation band networks and fault zones (Lansing Taylor and Pollard, 2000; Eichhubl et al., 2004), and in poorly lithified sandstones in the Paraiba Basin in Brazil the distribution of iron-oxide concretions allowed to infer the dynamics of groundwater flow as controlled by fault structure and permeability (Balsamo et al., 2013).

5.2. Crystalline and volcanic rock

Crystalline rocks such as igneous and/or metamorphic rocks (here, we do not focus on other types of crystalline rocks such as evaporites) generally have low porosity and permeability and are therefore not classed, generally, as good aquifers or reservoirs. Volcanic rocks can have high primary porosity and permeability (e.g. basalts), but often do not (e.g. tuffs). However, crystalline and volcanic rocks are important to siting of nuclear waste disposal sites and locally important for water resources, in particular where secondary processes such as faulting and fracturing play a role in enhancing the rock's permeability. While crystalline and volcanic rocks may deform by different fault processes resulting in different structures (see Sections 4.2 and 4.3) they often outcrop together or are within close proximity, so we describe the hydrogeological evidence together.

In mountainous settings, faults in the basement metamorphic and igneous rocks often are the loci of spring systems with elevated temperatures which, often in combination with evidence from silica-chemistry (Andrews et al., 1982; Ferguson et al., 2009), are indicative of relatively deep circulation along fault zones. Examples of such systems in crystalline rock are found in the Coastal Mountains of British Columbia (Forster and Smith, 1988; Forster and Evans, 1991; Grasby and Hutcheon, 2001). The well-documented distribution and variation of temperature of springs along fault zones in the Northwestern Great Basin, USA provide perhaps the clearest evidence that faults in crystalline and volcanic rock can be conduits allowing fluid circulation (Fairley and Hinds, 2004; Anderson and Fairley, 2008). The discharge of water at or near the boiling point in springs at this site is indicative of rapid, upward advective transport along preferential flow pathways of enhanced permeability (Curewitz and Karson, 1997; Anderson and Fairley, 2008).

While such thermal anomalies indicate that faults behave as along-fault conduits, other hydrogeologic, hydrologic and remote sensing data suggest that faults in crystalline terrain can be effective hydraulic barriers (Marler and Ge, 2003; Gleeson and Novakowski, 2009; Illman et al., 2009). Lineaments in the Canadian Shield were interpreted by Gleeson and Novakowski (2009) to be low permeability faults acting as hydraulic barriers to across-fault flow using well yield data, remote sensing and numerical modeling, but it is uncertain whether the structures are also vertical barriers. Numerical modeling suggests a reverse fault in crystalline rock in the southern Rocky Mountains of Colorado, USA is a barrier to lateral groundwater flow (Marler and Ge, 2003). Recent geophysical data from the same fault is interpreted to indicate conduit–barrier behavior at the meter to tens-of-meters scale (Ball et al., 2010). Detailed artificial tracer and hydraulic testing data from a thrust fault in Virginia, USA also suggests that faults in crystalline rock can be combined conduits and barriers (Seaton and Burbey, 2005; Rugh and Burbey, 2008). Artificial dye tracers applied at the surface traveled >100 m along the fault within weeks (Rugh and Burbey, 2008), yet, hydraulic test data suggest that the fault is a low permeability barrier. A new hydraulic tomography cross-hole testing method at a proposed nuclear depository site in Japan showed low permeability zone and compartmentalization effects (Illman et al., 2009).

There are other field examples that show that faults may be highly permeable and may represent valuable groundwater resources, particularly in granitic basement. Some field studies have shown that gently dipping fault zones may be highly productive (Seaton and Burbey, 2005; Le Borgne et al., 2006; Liou et al., 2010; Ruelleu et al., 2010; Leray et al., 2013). A multi-disciplinary field experiment (Roques et al., submitted for publication) recently investigated in detail the hydrogeological character of a sub-vertical fault zone in crystalline bedrock in Brittany (France). The field site was selected because of high well yields during drilling (100 m^3/h) related to a main permeable fault zone, encountered below 100 m. The fault zone was characterized both in natural conditions and during a 9-week large scale pumping test carried out at a pumping rate of 45 m^3/h. High-resolution flow logs allowed identification of fracture connectivity and preferential flow paths while dye tracer tests at different depths allowed estimation of transfer times and groundwater fluxes between the main compartments. Results suggest that the sub-vertical fault acts as the primary hydrogeological link between aquifers (Roques et al., submitted for publication). In natural conditions, deep groundwater flows along the fault zone towards aquifers in shallow weathered bedrock and alluvial sediments. During pumping, sub-vertical groundwater fluxes are reversed. Field-based insight on the hydraulic functioning of this kind of fault zone has important implications for groundwater resources and protection.

Regional-scale faults in crystalline and volcanic rock have been examined in detail by nuclear waste repository research and the risk of faults forming fluid flow pathways in otherwise low-permeability rock. For example, multiple low-angle thrust fault zones cross-cut massive and sparsely fractured crystalline rock of the Lac du Bonnet batholith in the Canadian Shield. Hydraulic tests and geochemical tracers indicate that faults are connected kilometer-scale conduits that control regional groundwater flow and discharge (Gascoyne, 2004). However, the permeability distribution within the fault zones is highly heterogeneous at a meter- to kilometer-scale (Davison and Kozak, 1988). High angle normal faults cut the volcanic rocks of Yucca Mountain, a proposed geologic repository for high-level nuclear waste located in southern Nevada (Bredehoeft, 1997; Fabryka-Martin et al., 1997; Flint et al., 2001; Painter et al., 2003). Bomb pulse isotopes, which were highly elevated in the atmosphere during above ground nuclear weapons testing in the Pacific Ocean in the early 1960s, were found in fault zones (Flint et al., 2001). The presence of these isotopes indicates groundwater water that is <40 years old and supports the conceptual model of deep, rapid and preferential infiltration along these faults (Flint et al., 2001).

5.3. Carbonate rock

Fine-grained carbonate rocks often have low primary porosity but fracturing and subsequent dissolution can cause large enhancements of permeability resulting in carbonate rocks often being considered aquifers or reservoirs. More than in any other lithology, faults cutting through carbonate rocks will often be dominated by secondary dissolution and precipitation processes altering the permeability structure almost continuously. As a result, in the literature faults in carbonate rocks have been reported to display a very wide range of hydrogeological behaviors; from significant barriers where secondary cementation or smearing of low permeability material occurs, to effective conduits where dissolution along fault and fracture planes dominates. For example, high hydraulic head gradients across a fault in a carbonate aquifer in Southern Italy provide evidence for the barrier-like behavior of faults (Celico et al., 2006), analogous to observations in siliciclastic aquifers. Similar borehole data across the Aigion fault zone, Greece, show a pressure differential of 0.5 MPa across the fault plane, indicating that a major hydraulic barrier exists between the carbonate aquifer on either side of the fault plane (Giurgea et al., 2004; Micarelli et al., 2006; Doan and Cornet, 2007).

Springs and outflows often occur along faults in carbonate rocks (Bredehoeft, 1997; Giurgea et al., 2004; Celico et al., 2006; Billi et al., 2007; Magri et al., 2010). One noteworthy example of a fault related thermal spring emerging from carbonate rocks is the Bath hot spring in southwestern England (Andrews et al., 1982). These springs have been interpreted to represent emerging flow from within the fault zone itself, implying that the fault zone acts as a conduit (Billi et al., 2007) or below the fault zone implying that the fault zone acts as a barrier (Giurgea et al., 2004; Celico et al., 2006). An analysis of pumping tests in a fractured carbonate aquifer carried out by Allen and Michel (1999) show a mixed influence of both permeable fracture networks and barriers along faults cutting through a carbonate aquifer in Ottawa, Canada. A similar conduit–barrier behavior of faults in carbonates has been inferred by Breesch et al. (2009) who reconstructed a paleo-fluid flow history along reverse faults, based upon detailed petrographic and geochemical analyses of calcite filled fracture networks in Triassic and Cretaceous carbonate strata of Northern Oman. In this study, determinations of oxygen isotope ratios on calcite cements and circulation depth constraints provided by fluid inclusion thermometry suggest that saline formation waters migrated syn-tectonically during contraction of the basin along a major fault acting as a conduit, but at the same time the fault hydraulically compartmentalized the basin.

Geochemical data have indicated that fracture networks parallel to fault planes divert fluid flow along the fault zone rather than across it (Maslia and Prowell, 1990; Ferrill and Morris, 2003; Ferrill et al., 2004; Geraud et al., 2006; Bushman et al., 2010). On the other hand, Ferrill et al. (2004) found fluid flow paths in the faulted Edwards Aquifer, Texas, crossing from the foot wall to the hanging wall and back to the footwall.

6. Modeling fluid flow in fault zones

In fault zone hydrogeology numerical models are used to evaluate the potential impact of fault zones on fluid flow patterns. The primary challenge is how to represent and parameterise the complex hydrogeological structure of fault zones into such fluid flow simulations (Garven et al., 1999). The approach taken to model fluid flow in fault zones, depends on the amount of detail required in the calculated flow paths and hydraulic head distributions which relates to the practical aim of the modeling exercise (e.g. water resources management, design of nuclear waste repositories), but also on the type of aquifer in which the faulting occurs and the type of deformation occurring along the fault zone. The spatial scale considered by a model evaluation is an important decision when modeling. A fundamental concept in hydrogeology relating to scale, is the representative elementary volume (REV) which can be defined as the smallest volume over which a measurement can be made that will yield a value representative of the whole (Bear, 1972). Below the REV, the spatial variability of parameters such as porosity and permeability is too large for the material to be satisfactorily represented by a continuum with an averaged property assigned to it. If flow paths and fluid fluxes at a scale below that of the representative elementary volume need to be known, individual features, such as fractures, should be represented in models (Fig. 1a), which is often accomplished using a discrete fracture network (DFN) modeling approach, whereas above the representative elementary volume, the material can be treated as a continuum (Fig. 1b) for which an implementation of effective properties over larger volumes is reasonable.

Hydrogeological models on a scale larger than a few tens of meters are usually continuum models using effective properties for discrete domain features defined, often based upon the fault core/damage zone schematisation of fault zones. This approach is often taken for models of fluid flow along fault zones in sedimentary basins considering regional scale (~10–100 km, Forster and Evans, 1991; Person et al., 1996; Micarelli et al., 2006; Magri et al., 2010) and more local (~1–5 km) groundwater flow systems (e.g. Folch and Mas-Pla, 2008). In such models, the thickness of a fault zone, outlining the fault zone as a hydrogeological unit, is a crucial parameter which is directly controlling the rate of fluid mass – and associated solute – and heat fluxes in the fault zone (e.g. Haneberg, 1995; Roberts et al., 1996; Bense and Person, 2006). Continuum models can explicitly describe variations in fault width, the juxtaposition pattern of aquitards and aquifers at the fault zone (Mailloux et al., 1999; Bense and Person, 2006), and the three dimensional structure of fault zones (e.g. Micarelli et al., 2006). Other examples of continuum models of fault zone hydrogeology include finely-gridded models of a fault in a sand–shale sequence to analyze the effect of varying fault permeabilities on fluid flow patterns and pressure compartmentalization in hydrocarbon reservoirs in the Gulf of Mexico (Matthaï and Roberts, 1996), and models of hydrothermal flow in carbonate rocks along the west-coast of Turkey (Magri et al., 2010). Leray et al. (2013) studied the productivity of permeable fault zones for water supply purposes. Using a simple numerical approach, they showed how the productivity of fault zone for groundwater resources depends on the fault hydraulic properties as well as the geometrical characteristics of fault zones, and in particular the dip of fault zones. Continuum models at the outcrop scale have also been used to calculate effective fault zone properties like permeability anisotropy and the impact of small scale internal structure of fault zones on such properties (e.g. Jourde et al., 2002; Lunn et al., 2008).

In contrast to continuum models that represent the bulk permeability of a fault zone or fault zone components, discrete fracture network (DFN) models, originally developed to simulate flow and transport in fractured bedrock (see reviews by Berkowitz, 2002; Neuman, 2005), represent the shape, orientation, length and aperture of fractures (which is related to permeability), and connectivity of fracture networks. DFN models can directly incorporate detailed and realistic geometric and hydraulic data of fracture networks measured at the outcrop and/or in boreholes, but often fracture networks and properties are generated in the DFN based upon statistical properties equivalent to those observed in the field. DFN models have been used to quantify the effective permeability of individual fault components within outcrops of basement rocks dominated by fracturing (Caine and Forster, 1999; Caine and Tomusiak, 2003). Where appropriate, geostatistical evaluations are used both in DFN models as well as in continuum models to condition fault zone attributes such as fault rock permeability (e.g. Lopez and Smith, 1996; Fairley, 2009), and distribution, shape, and continuity of fault zone elements (e.g. Lunn et al., 2008). Continuum modeling and DFN models can be combined in the simulation of the permeability structure of fault zones. In this approach, key faults and fractures can be located explicitly in the model domain, while geostatistical simulation of fracture networks is carried out using a DFN. In hybrid modeling schemes, fracture focused flow can be considered using a DFN and linked to a continuum flow model to describe diffuse flow in the rock matrix. For example, Jeong et al. (2004) present a typical example of hybrid fault zone models, in that case with application to the evaluation of radionuclide transport across fault zones in prospective nuclear waste repositories.

Empirical approaches to estimate fault zone hydraulic properties have been used mostly in the hydrocarbon industry. Some of these have been demonstrated to be applicable in fault zone hydrogeological studies. For example, Bense and Person (2006) adapted the widely-used Shale Gouge Ratio (SGR) methodology (e.g. Yielding et al., 1997; Childs et al., 2007) in which the estimated clay-content of faults is used as a proxy for the fault's sealing capacities and reduction in across-fault permeability, to model groundwater flow paths across anisotropic fault zones. Manzocchi et al. (1999) shows how an estimated fault thickness and fault permeability, based upon clay-content derived from SGR, are used to calculate a transmissibility multiplier which is a factor to reduce the hydraulic communication between grid blocks at a fault zone. The computational flexibility and efficiency of this approach are evident (Fisher and Jolley, 2007; Manzocchi et al., 2008, 2010). However, flow in the fault zone itself cannot be considered in the same way as hydrogeological continuum models of fault zones can. The potential of empirical techniques to develop fault zone permeability models is further exemplified by the fault facies methodology (Fredman et al., 2008; Braathen et al., 2009), developed in the hydrocarbon industry. The fault facies approach can be used to geostatistically model permeability structures, as a continuum, of a fault zone conditioned as function of a large number of geological parameters, believed to be key to control fault permeability structure, such as strain distribution, rock strength and lithology, using a data base of outcrop observations.

7. Towards interdisciplinary fault zone hydrogeology

Our objective is examining the hydrogeological character of fault zones by reviewing the sometimes contrasting approaches, data and interpretations of structural geologists and hydrogeologists. Surface-focused studies generally led by structural geologists and subsurface-based studies led by hydrogeologists are both inherently located in a specific location yet the two different disciplines largely focus on different field areas (Fig. 1) and use different methods (Table 1) that integrate over different scales (Fig. 3). Currently, there is a dearth of studies where detailed models of geologically-derived permeability architecture are directly co-located with robust hydrogeology data on flow patterns along and across the same fault zones. This final section reviews the controls of fluid flow around faults, summarizes the contribution of the two disciplines, and then discusses synergistic opportunities and the importance of the emerging field of fault zone hydrogeology for both scientific problems and societal concerns.

7.1. Controls on fluid flow around fault zones

Darcy's Law of fluid flow through porous media states that fluid flow rates are the product of permeability and hydraulic gradient (Section 1). The nature of fluid flow around fault zones is thus directly influenced by geological deformation processes (Section 3.1) and the ensuing permeability structure and thickness of fault zones (Section 3.2). The organization and tone of this review as well as our analysis of the body of literature in both structural geology and hydrogeology, tacitly implies that at shallow crustal depths (<1 km) geologic processes impact hydrogeology more than hydrogeological processes impact geologic processes. This is not true at greater crustal depths where fluid pressures significantly impact the rate and location of fault processes and seismicity (Sibson et al., 1975; Flemings et al., 2002; Fulton and Saffer, 2009; González et al., 2012). However, at shallow depths fault processes are not as dependent on fluid pressures, which implies that it is easier to predict hydrogeological properties from structural geologic data rather than vice versa.

The orientation and magnitude of the hydraulic gradient are another primary control on rate and direction of fluid flow in and around fault zones. The same fault zone can behave as a barrier for across-fault flow and a conduit for fault-parallel flow primarily because of the inherent anisotropic nature of fault zones. This can be visualized by examining any of the cross-sections of permeability architecture in Fig. 9. When fluid flow parallel to the strike of the fault zone is significant, the fault would be regarded to act as a conduit. However, even in the absence of a low-permeability fault core, in such a scenario across-fault fluid flow is severely restricted because groundwater flow paths will not cross the fault zone. As a result of which, it is not possible to determine that the fault zone acts effectively as a barrier in that direction. For fault parallel fluid flow to be enhanced, hydraulic gradients need to be maintained in that direction. Significant vertical hydraulic head gradients can occur naturally in areas of groundwater recharge and discharge, and in aquifer systems in which overpressures at depth are generated by sediment compaction. Anthropogenic influence, such as groundwater extraction for water-supply or mine-dewatering to enable open-pit mining will lead to enhanced hydraulic gradients. Often the permeability architecture of fault zones is less obvious in hydraulic head maps under natural hydraulic gradients but becomes easier to study when perturbed by groundwater extraction.

It is important to consider the scale of investigation on the controls of fluid flow around faults. At a small-scale, individual products of deformation such as discrete fractures or deformation bands may control fluid flow whereas at larger scales the permeability architecture in combination with regional hydraulic gradients control fluid flow patterns. Groundwater abstraction enhancing hydraulic gradients will allow the characterization of the groundwater system at a larger scale. Highly permeable fault zones will allow the diffusion of pressure over large scales, especially in host rocks of relatively low permeability (Leray et al., 2013; Roques et al., submitted for publication). It is also important to consider the appropriate scale of analysis and the suitable approach for modeling complex fault zone hydrogeological processes (Section 6).

7.2. The tale of two disciplines

To date, the contribution of structural geology and hydrogeology to the study of fault zone hydrogeology can largely be told as the tale of two disciplines. Although we realize that in applied hydrogeology or in industry settings a more synergistic practice between hydrogeology and structural geology might be focused on fault zone hydrogeology, the currently available conceptual models of fault zone hydrogeology as published in the scientific literature are mostly carried out by structural geologists. These models consist of a description of the structure and heterogeneity and anisotropy of permeability introduced by deformation in fault zones, as summarized in Fig. 9. These conceptual models suggest that faults in various settings act as either pure barriers or conduits to fluid flow, or as complex conduit–barrier systems in which preferential or enhanced flow along the fault plane should occur while across-fault flow is impeded (Fig. 5e). Yet, these conceptual models are largely not substantiated with co-located hydrogeological data in the same fault zones.

Hydrogeological studies have successfully observed the rate and direction of fluid flow around fault zones but have derived few if any conceptual models of fault zone hydrogeology for different geologic and hydrologic settings. Part of the reason that hydrogeological studies have not derived conceptual models may be that at shallow crustal depths geologic processes impact hydrogeology more than hydrogeological processes impact geologic processes. Although hydrogeological studies have not derived conceptual models of fault zone hydrogeology, hydrogeological data are crucial for testing conceptual models developed in surface-focused studies. 'Testing' conceptual fault permeability models with subsurface hydrogeological data is often hampered by a limited understanding of three-dimensional fluid flow patterns and processes driving fluid flow which is crucial.

Important conclusions can be derived from the hydrogeological evidence of the impact of faults on fluid flow (Section 4). Hydrogeological observations show a broad qualitative agreement with the permeability structure of fault zones derived from outcrop observations. We caution, however, that no fault zone seems to have been studied from both equally detailed geological and hydrogeological perspectives. Nevertheless, no description of the impact of a fault zone on hydrogeology is complete without the perspective from both hydrogeology and structural geology combined. For example, a fault zone which would be described as a 'localized conduit' (Fig. 5f) as a characterization of the fault permeability structure may impede across-fault flow depending on the hydraulic gradients. Equally, a fault described as a 'localized barrier' will focus groundwater flow in a fault-parallel direction just outside of the fault zone. In this framework, generalized descriptions of fault permeability structure such as provided in Fig. 5f (Caine et al., 1996) and Fig. 9 cannot be used to qualify fault zone hydrogeological behavior without consideration of the fault zone's hydrogeological context.

7.3. The future tale of one inter-discipline?

To gain a more integrated, comprehensive understanding of fault zone hydrogeology, we foresee numerous synergistic opportunities and challenges for the discipline of structural geology and hydrogeology to co-develop. We imagine that the study of 'fault zone hydrogeology' could evolve like 'hydrostratigraphy' has evolved by combining approaches, data and interpretations of sedimentary geologists and hydrogeologists. There may be challenges with finding co-located field areas (Section 2), scale issues (described above) and historic disciplinary biases. However, we focus on the opportunities of (1) co-locating study areas; (2) sharing approaches and fusing data; (3) developing conceptual models from hydrogeologic data; (4) numerical modeling; and (5) training interdisciplinary scientists.

(1) Co-locate study areas to better use hydrogeologic data to test conceptual models derived from surface-focused studies. This would involve targeted drilling and installation of boreholes near well-studied outcrops as well as examining outcrops along strike in the same or similar structure as well-instrumented well fields. Such well monitoring fields could be located near mining sites, and or temporary excavations where in many cases very strong hydraulic gradients are caused by groundwater extraction.
(2) Better integrate approaches and fuse data from structural geology and hydrogeology and use tools from other disciplines such as geophysics, petroleum geology and mine hydrogeology. Section 2 and Fig. 3 suggest that the methods used by structural geologists examine smaller integration scales than the methods used by hydrogeologists. A central question is how data obtained at smaller outcrop scale or from boreholes, which will always only provide a limited sample of the characteristics of a fault zone as a whole, can be used to predict hydrogeological behavior at a larger scale. And there is some overlap in scales that could be further exploited. For example outcrop data is often derived at similar scales as borehole tracer tests that employ a range of artificial tracers (e.g. Dorn et al., 2012) or heat (e.g. Read et al., 2013). Another promising avenue is using tools from other disciplines such as geophysics to examine fault zone hydrogeology. The ongoing development of new hydrogeophysical characterisation techniques (e.g. Ferré et al., 2009) will lead to new geophysical tools to complement current ones such as geoelectrical and seismic investigations, to apply in fault zone hydrogeology.
(3) Hydrogeological studies have derived few, if any, generalized models of fault zone hydrogeology for different geologic and hydrogeologic settings, and we suggest that this is an important future research direction. Important questions for this future research direction could be: can generalized and transferable models of fault zones be developed only from hydrogeologic data? Or how can larger-scale hydrogeologic data be used in conceptual models primarily developed from smaller-scale structural geology data (Fig. 3)?
(4) Numerical modeling can be a useful tool for integrating geological and hydrogeological data from specific locations, testing conceptual models and forward-modeling predictions. Numerical models are typically derived for a specific scale or purpose (Fig. 1) and telescoping models from outcrop-scale discrete fracture modeling to regional-scale grid-based continuum modeling could examine fundamental processes over a variety of scales. The construction of two- and three dimensional numerical fluid flow models honoring, to varying degrees, fault permeability architecture as observed in the field, has resulted in a variety of approaches and emphases to include fault zones (Section 6). Although many studies qualitatively link the hydrogeological behavior to geological fault zone models, there are very few studies that report a more detailed quantitative evaluation of model validity using, for example, groundwater flow paths and residence times. Forward-modeling of fault zone hydrogeological properties based upon geological parameters in areas where field exposures of fault zones are lacking seems especially important since this could stimulate a more multi-faceted hydrogeological data analysis and focus data collection. Moreover, such integrated studies will lead to the formulation of more specific field experiments which can be carried out to improve such predictions. Post-audit of model predictions has been shown to yield surprising insights to the robustness of model conceptualisation (e.g. Bredehoeft, 2005) and to focus such efforts on models of fault zone hydrogeology could be a fruitful exercise to improve our understanding of fault zone hydrogeology.

(5) One necessity for the future of fault zone hydrogeology is more integrated and interdisciplinary training. Few practitioners or academics are formally trained at a graduate level in both hydrogeology and structural geology. Formal training in this way can transform how one approaches an inherently interdisciplinary problem. This training could include targeted workshops and colloquia for graduate students and early-career scientists as well as new, interdisciplinary graduate programs.

This interdisciplinary approach of fault zone hydrogeology could contribute to our understanding of important scientific problems and societal concerns surrounding the safety of groundwater resources, nuclear waste repositories, and CO_2 sequestration. Hence, a better understanding of deformation processes, permeability structure, and a more reliable forecasting of fluid flow rates and directions in and around fault zones are crucial both for the emerging field of fault zone hydrogeology as well as society.

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