



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.

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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 CO₂ 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

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