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Identification of reactivation and increased permeability associated with a fault damage zone using a multidisciplinary approach

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ABSTRACT

We evaluate the fault damage zone associated with a reactivated long-strike length, small-offset normal fault in the Permian Cedar Mesa Sandstone, southeastern Utah. This fault is characterized by a single slip surface and a 9-m wide damage zone containing deformation bands and veins. Field observations include cross-cutting relationships, permeability increase, rock strength decrease, and ultraviolet-light-induced mineral fluorescence within the damage zone. These field observations, combined with the interpreted structural diagenetic sequence from petrographic analysis, suggest a deformation history of reactivation and several generations of mineralization. All deformation bands and calcite veins fluoresce under ultraviolet light, indicating fluid pathway connectivity and a shared mineralization history. Pre-existing structures act as loci for younger deformation and mineralization events, so this fault and its damage zone illustrate the importance of the fault damage zone to subsurface fluid flow.

We model a simplified stress history to understand the importance rock properties and variations in differential and effective mean stress have on the structures within the damage zone. The moderate confining pressures, possible variations in pore pressure, and porous, fine-grained nature of the Cedar Mesa Sandstone produces a fault damage zone characterized by enhanced permeability and mineralization.

1. Introduction

Fault-zone architectural components and their associated effects on permeability act as a primary control on fluid flow in the upper brittle crust (Knipe, 1993; Mozley and Goodwin, 1995; Caine et al., 1996; Evans et al., 1997; Rawling et al., 2001). Fault-zone architecture refers to the nature and geometry of the fault core, damage zone and protolith, which can be lithologically heterogeneous and structurally anisotropic (Caine et al., 1996). Spatial variations in the permeability of the fault damage zone, and fault core create conduits and/or barriers for fluid flow in faulted rocks (Aydin, 1978; Aydin and Johnson, 1978; Antonellini and Aydin, 1994; Aydin and Eyal, 2002; Lothe et al., 2002; Davatzes et al., 2003; Johansen and Fossen, 2008). Understanding sub-seismic fault damage zones is critical to understanding fluid flow in oil and gas production and sequestration operations for nuclear and chemical waste storage or CO_2 sequestration scenarios. Consequently, we examine a small-offset, long-strike length normal fault so as to characterize a field example of a damage zone with evidence for multiple generations of mineralization due to dilatancy at moderate confining pressures in a fine-grained porous sandstone.

In this paper, we examine the mineralization of a fractured fault-damage zone and propose a stress history using a uniaxial strain model in a normal Andersonian tectonic stress orientation. The damage zone of this fault provides evidence for the localization of stress and re-activation of pre-existing structural discontinuities, as well as increased permeability and subsurface fluid flow. We use traditional field and petrographic investigative methods, and introduce a novel method of ultra-violet light illumination to document the presence and connectivity of veins within the fault damage zone. We describe a diagenetic sequence and propose a stress history based on rock properties, which supports failure in a dilational regime, resulting in enhanced permeability and subsequent mineralization within the damage zone.

2. Geologic setting

Located on the White Canyon Slope in the upper Lake Powell region, SE Utah, are several steeply dipping (78°–90°), northwest-striking normal faults near Hite Crossing, Utah (Figs. 1–3).

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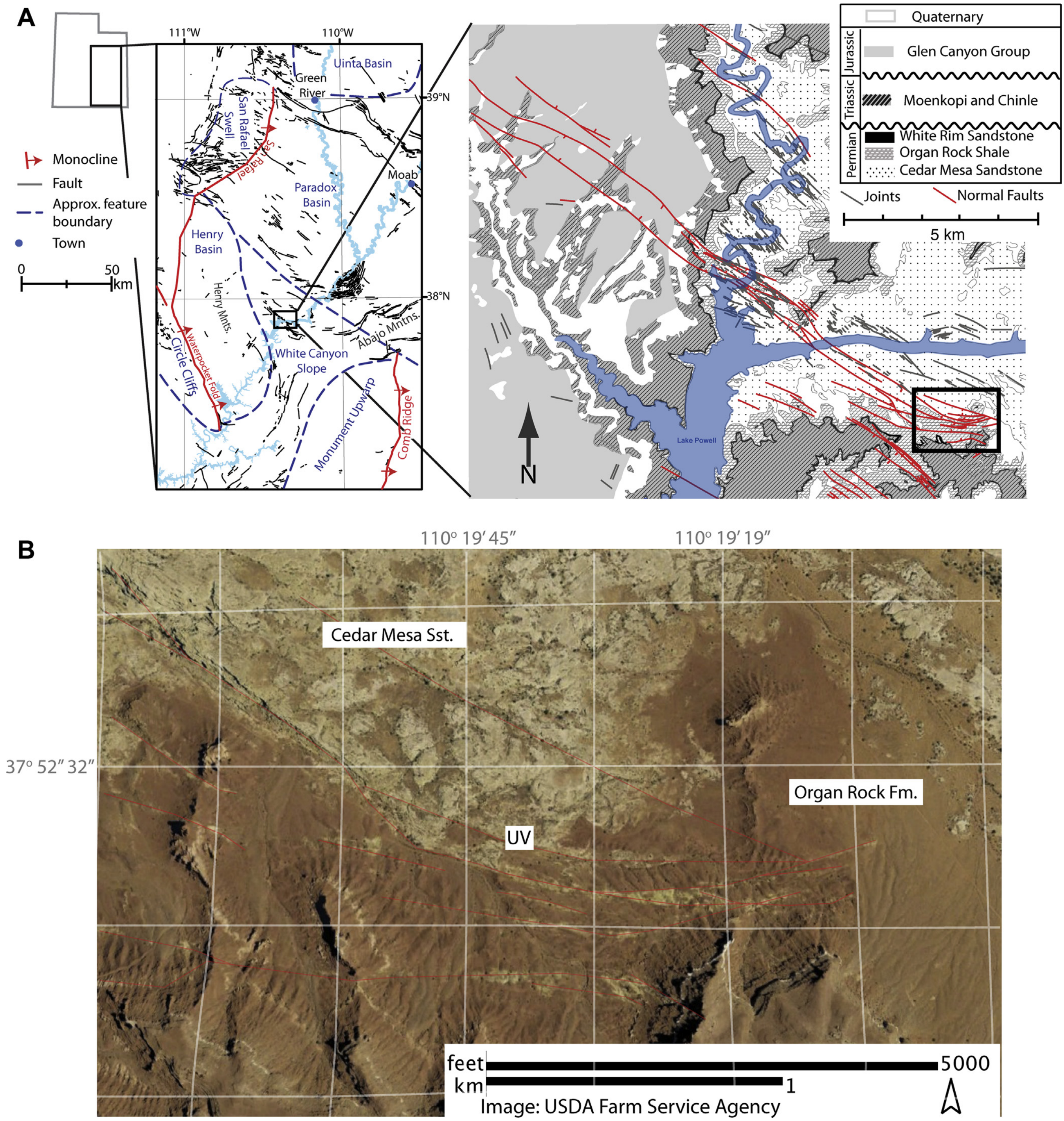

Fig. 1. A) Location and tectonic elements of the Colorado Plateau, modified from Kelley, 1955 and Condon, 1997 with geologic base map of the study area modified from Willis (2012). B) Google Earth imagery of study area showing landscape-scale bleaching in the Organ Rock Formation and location of fault damage zone with UV-light induced fluorescence evaluated in this study, labeled (UV). Note bleaching along fault traces within the Organ Rock Formation.

Accessible outcrop exposures lie in Glen Canyon National Recreation Area near the confluence of the Dirty Devil and Colorado Rivers. The faults cut the Permian Organ Rock Formation and the underlying Cedar Mesa Sandstone of the Cutler Group (Willis, 2012). The Organ Rock Formation is 60–80 m (196–262 ft) thick in the study area and consists of reddish-brown interbedded siltstone, mudstone and fine to medium-grained sandstone (Willis, 2012). The underlying Cedar Mesa Sandstone is a light-gray to orange, cross-bedded, fine-grained quartz arenite with an overall thickness of 300–365 m (1000–1200 ft) bed sets within the Cedar Mesa Sandstone range from 1 to 15 m (3.28–49 ft) thick. Deposition of the Cedar Mesa Sandstone occurred dominantly within eolian systems but interbedded siltstones represent depositional environments associated with transient streams, small rivers, and/or floodplains (Loope, 1985; Langford and Chan, 1988; Anderson et al., 2003; Willis, 2012).