Unraveling the history of ultra-deep fractures in sedimentary basins

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In the past half-decade unprecedented opportunities have arisen for extracting information about the origin and persistence of fracture porosity from fracture samples. Even in largely open fractures, localized cement deposits and fluid inclusion assemblages accumulated during fracture growth provide unique records of fluid composition and temperature. With burial history or cement accumulation models these records can yield evidence of the timing and rate of fracture formation.

Here we unravel the history of fracture in the ultra-deep Lower Cretaceous Frontier Formation sandstones using core samples from two wells in the Madden field, Wyoming (Figure 1). The Madden structure is an east-west trending anticline discovered in the 1960s (Brown and Shannon, 1989). The Big Horn 2-3 was an early deep delineation well. In 1992, shortly after retrieving the core we describe, the Big Horn 3-36 well blew out and caught fire; subsequently gas was produced at a rate of about 5 MMcfd, testifying to the efficacy of open fractures as fluid conduits in these low porosity sandstones.

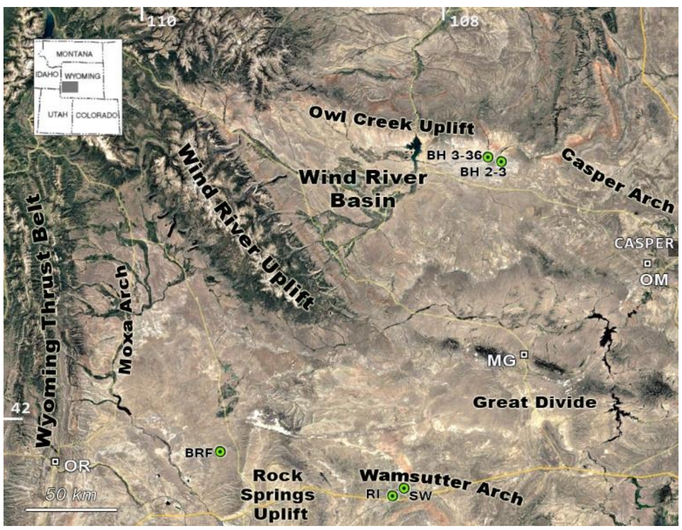

Figure 1. Location of deep 'Bighorn' BH 3-36 and 2-3 cores in Wyoming. RI, SW and BRF are other core locations (shallower depths) and OR, MG, and OM are outcrop locations of fractured Frontier Formation being compared with subsurface data.

Our samples are from depths of 6240 to 6244 m. Frontier sandstones are dominantly litharenites to sublitharenites, with average composition of 64% quartz, 6% feldspar, and 30% lithics, although more quartz-rich facies are locally present. Opening-mode fractures are aligned at a high angle to beds and thus have steep dips. Fractures are lined and locally bridged with quartz deposits (Figure 2). Overall apertures of the fractures we mapped are 400-700 µm. As in other moderately-deeply buried sedimentary rocks, isolated bridges of cement deposited during fracture opening in otherwise open fractures have rod or pillar-like shapes that are typically oriented normal to, and connect opposite, opening-mode walls.

Bridges contain wall-rock fragments and cement arranged in crack-seal texture that records repeated cracking and local cement accumulation along fractures within the bridges as well as zoned, non-crack seal quartz. Each crack-seal increment, called a 'gap deposit' to distinguish them from the overall fracture of which they form a part, is typically marked by a fluid inclusion assemblage trapped along the gap deposit centerline (Figure 2).

Gap deposit thicknesses normal to fracture walls in more shallowly buried sandstones typically range from less than 1 µm to more than 1 mm, but commonly are less than 20 µm (avg. ca. 10 µm)(Laubach et al., 2004). But gap sizes in our deep samples are wider, with many in the range of 40 µm. Cross-cutting relations documented by mapping cement textures, allows the relative time sequence of fluid inclusion assemblages to be documented. Quartz deposits that span between fracture walls are separated by porous fractures having thin quartz lining (rinds) or these areas or residual void space may be filled with calcite.

Preliminary fluid inclusion results show that FIAs record a wide range of temperatures from about 140°C to 260°C or more, and have a fairly narrow salinity range that is mostly less than 2 wt% NaCl. The high temperature of fracture formation likely accounts for the wide sizes of quartz gap deposits, since temperature is a main control on spanning potential (Lander and Laubach, 2015). Assuming measured temperatures reflect burial depths, for typical Rocky Mountain region burial histories for the Frontier Formation (i.e. Laubach et al., 2016), our FIA results imply that fractures grew over tens of millions of years. Although further analysis is needed, both wells may contain a temperature gap (ca. 170-210°C) that could mark a hiatus in fracture growth. A hiatus in fracture widening was documented in fractures from the Frontier Formation in the Green River Basin from depths of 4538 to 4547 m (Laubach et al., 2016).

Fracture mineralogy and textures were documented using transmitted light petrography and cathodoluminescence (CL) imaging obtained with a Zeiss Sigma High Vacuum Field Emission SEM with an Oxford X-Max 50 Silicon drift detector (SDD) and a Gatan MonoCL4 system specifically configured for large-area mosaic SE, BSE, EDS, and CL imaging. The SEM was operated at 12–15 kV and at large sample currents for panchromatic and color CL imaging. For microthermometry we used a USGS-style gas flow heating/freezing stage mounted on an Olympus microscope equipped with a 40× objective (N.A.=0.55) and 15× oculars.

In agreement with previous results from other sandstones (e.g., Fall et al., 2015) our results show that fractures in sandstones can grow over long time periods and retain porosity at great depth (>6 km) and high temperature (>170°C) for tens of millions of years.

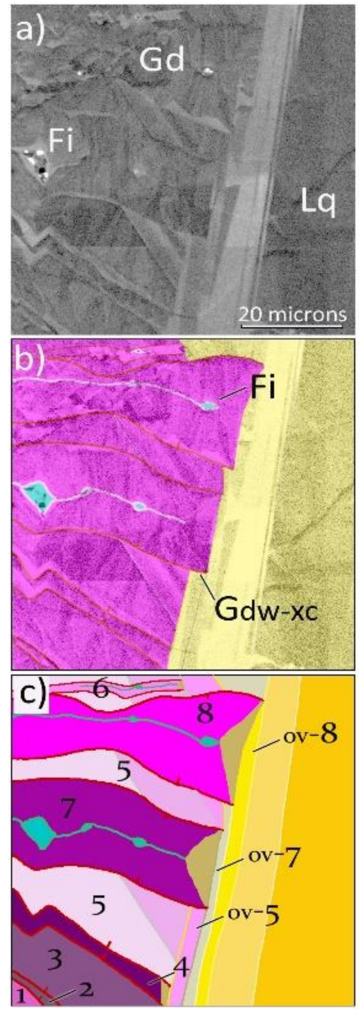

Figure 2. SEM-CL (a), (b) and map (c) of edge of bridge deposits showing crack-seal texture. Gd; Gdw-cx gap deposits and crosscutting relations. Lq, non-crack seal quartz. FIA locations marked by blue color in(c). Numbers indicate sequence of gaps and overgrowths.

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