FRACTURE STRATIGRAPHY IN LOWER PALEOZOIC BEDROCK OF THE CENTRAL MIDCONTINENT, NORTH AMERICA

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ABSTRACT

Outcrop-based fracture mapping remains the best technique to provide insight into subsurface fracture characteristics and their hydrologic significance. Recent fracture mapping in exposures of relatively undeformed lower Paleozoic bedrock in the central midcontinent of North America has led to the recognition of stratigraphically controlled, and thus predictable, preferential termination horizons (PTHs) that can impact groundwater flow.

Fracture mapping at several outcrops of the carbonate-dominated Platteville Formation (Ordovician) in the Twin Cities Metropolitan area (TCMA) of Minnesota identified PTHs at the upper and lower contact of a 1.5 m shale and silt-rich dolomitic mudstone unit. The Jordan Sandstone (Cambrian) in the eastern TCMA has PTHs along contacts between 0.5-1 m thick sandstone beds at a consistent stratigraphic position within the lower part of meter-scale parasequences. Reconnaissance work at scattered Cambrian outcrops elsewhere in the region also suggests the presence of a PTH in the uppermost 2m of sandstone and shale in the Tunnel City Group. Fractures above and below PTHs in these examples typically cross multiple beds, with heights of a few to several meters. Each of the PTHs contain one or more features known to limit propagation of vertical fractures, including relatively weak rock strength compared to adjacent strata, the presence of ductile shale, or bed parallel macropore networks.

Some hydrologic characteristics of these stratigraphic units appear to reflect the subsurface hydraulic expression of PTHs. Our most comprehensive dataset links the uppermost PTH in the Platteville Formation to the preferential stratigraphic position of perched groundwater (commonly expressed as spring lines), and to significant head deflections in boreholes.

Our results are consistent with earlier fracture mapping of Silurian carbonate bedrock in eastern Wisconsin by Cooke et al. (2006) who also documented thick units with through-going fractures separated from one another by PTHs. These collective results indicate the lower Paleozoic bedrock in this region has a generally consistent, predictable fracture character across a wide spectrum of rock types and age. The correspondence to measurable hydraulic properties suggests promise for improved predictability of groundwater flow.

BACKGROUND

PREFERENTIAL TERMINATTION HORIZONS OF VERTICAL FRACTURES CAN HAVE SIGNIFICANT IMPACT ON GROUNDWATER FLOW

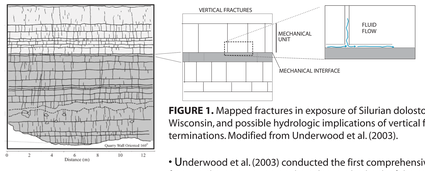

FIGURE 1. Mapped fractures in exposure of Silurian dolostone, eastern Wisconsin, and possible hydrologic implications of vertical fracture terminations. Modified from Underwood et al. (2003).

• Underwood et al. (2003) conducted the first comprehensive vertical fracture characterization on the Paleozoic bedrock of the central midcontinent and suggested that such termination horizons may lead to the development of high conductivity bed parallel macropore networks.

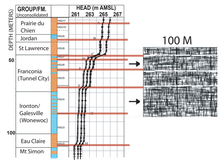

FIGURE 2. Hydraulic head profile for Cambrian and Ordovician bedrock strata near Madison, Wisconsin, and conceptualization of fracture characteristics. Modified from Meyer et al. (2008) .

• Meyer et al. (2008) used discrete interval head measurements to show that vertical changes in head occur across thin stratigraphic intervals

• They suggested that these key intervals of low vertical permeability correspond to horizons that limited the propogation of vertical fractures.

• Hydrologic investigations in Minnesota over the past 20 years (e.g. Runkel et al., 2013) have also shown that the groundwater system in lower Paleozoic bedrock is dominated by flow through fractures and bed parallel macropores.

• Over the past 5 years we have attempted to characterize vertical fracture patterns at a number of outcrops, in an effort to better predict subsurface groundwater conditions.

• Here, we summarize our in-progress work on the Ordovician Platteville Formation and Cambrian Jordan Sandstone in the Twin Cities Metro area (TCMA) (Fig. 3). This material builds on the results published previously by Anderson et al., (2011) and Runkel et al., 2014)

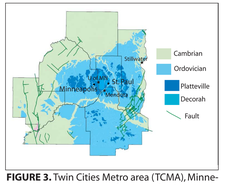

FIGURE 3. Twin Cities Metro area (TCMA), Minnesota, showing locations of outcrop fracture tracing summarized in this poster

FRACTURE MAPPING: PLATTEVILLE FORMATION (ORDOVICIAN)

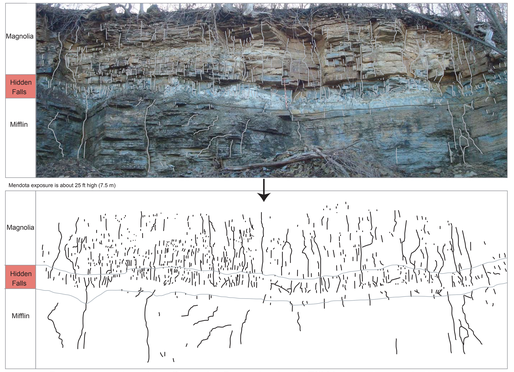

FIGURE 4. Fracture mapping of the Platteville Formation in the TCMA show that vertical fractures preferentially terminate along two ~0.5m stratigraphic intervals: at Hidden Falls-Magnolia contact strata, and in the lowermost Hidden Falls. Bed parallel macropores are common where the terminations within the Hidden Falls-Magnolia contact strata occur. Terminations in the lower Hidden Falls typically are gradational whereby fracture apertures narrow and become curvilinear as they terminate. Laboratory tests indicate a measurably weaker rock strength for the Hidden Falls member than for the members above and below it.

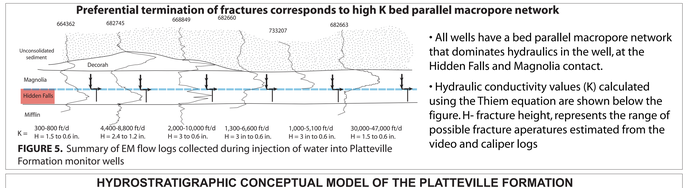

FIGURE 5. Summary of EM flow logs collected during injection of water into Platteville Formation monitor wells

• All wells have a bed parallel macropore network that dominates hydraulics in the well, at the Hidden Falls and Magnolia contact.

• Hydraulic conductivity values (K) calculated using the Thiem equation are shown below the figure. H- fracture height, represents the range of possible fracture aperatures estimated from the video and caliper logs

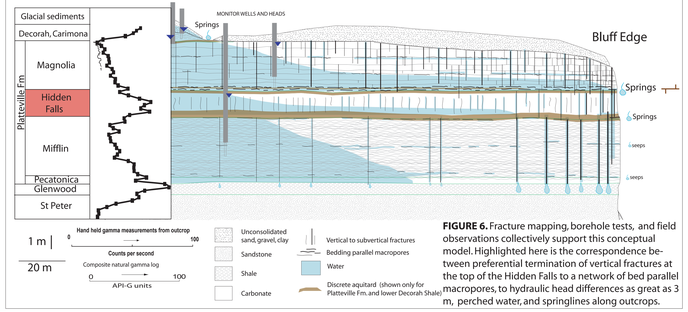

FIGURE 6. Fracture mapping, borehole tests, and field observations collectively support this conceptual model. Highlighted here is the correspondence between preferential termination of vertical fractures at the top of the Hidden Falls to a network of bed parallel macropores, to hydraulic head differences as great as 3 m, perched water, and springlines along outcrops.

• Fig. 11 shows in-progress fracture tracing results for the Platteville Formation at the University of Minnesota campus, Washington Avenue Bridge.

• Preliminary results indicate the vertical fractures preferentially terminate along two ~0.5m stratigraphic intervals: at Hidden Falls-Magnolia contact strata, and in the lowermost Hidden Falls (Fig. 11)

• Our goal is to link the fracture patterns in this outcrop, to hydraulic data in the nearby (500 m) Platteville monitor well shown in Fig. 12.

• The Platteville monitor well shows a large head deflection across the bed parallel macropore (BPM) network approximating the Hidden Falls-Magnolia contact (Fig 12). Another head deflection in the well, about 2 ft higher in the hole, corresponds in stratigraphic position to the dashed green line in Fig. 11, separating informal upper and lower Magnolia members.

• Bed parallel macropores are also present along the contact between the upper and lower Magnolia members, and our preliminary results indicate that it may also serve as an interface with a relatively high percentage of fracture terminations.

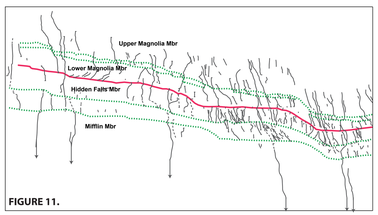

FIGURE 11.

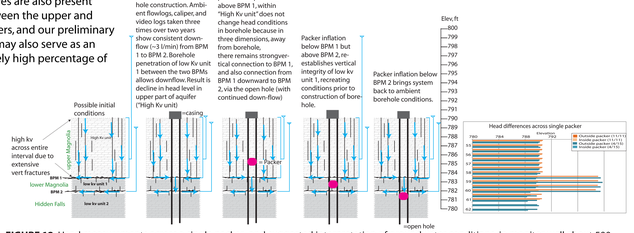

FIGURE 12. Head measurements across a single packer, and suggested interpretation of groundwater conditions in monitor well about 500 meters from outcrop in Figure 11. Poor vertical connectivity of fractures across the lower Magnolia interval separating BPM 1 from BPM 2 could account for the ambient flow conditions and head profile.

FRACTURE MAPPING: JORDAN SANDSTONE (CAMBRIAN)

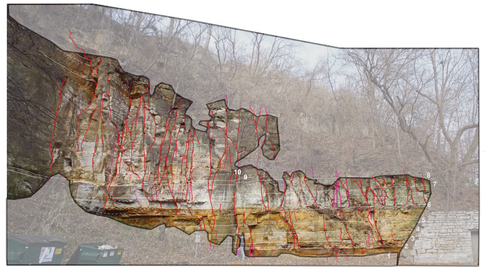

FIGURE 7. Stillwater, Minnesota. Jordan Sandstone outcrop with traced bed contacts (white) and vertical fractures (red). Gray shading denotes area too poorly exposed for fracture tracing.

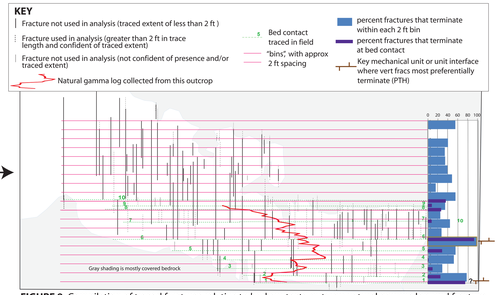

FIGURE 8. Compilation of traced fractures relative to bed contacts, outcrop natural gamma log, and fracture termination percentages calculated for the Stillwater outcrop shown in Fig. 7.

Fig. 8 shows the compilation of traced fractures relative to position of bed contacts.

• Bar graphs on the right depict calculated percentage of fractures that terminate within 2 foot bins, corresponding to the minimum thickness of most beds that can be traced across the length of these outcrops.

• We also calculated the termination percentage of fractures that meet each of the traceable bedding planes at an outcrop. For both of these analyses we used only fractures with trace lengths exceeding 2 ft.

• Note the high percentage of fracture terminations associated with bed contact 6. A second bed contact (contact 1) in the lowermost part of this exposure also has a high percentage of terminations, although an overall relatively lower density of fractures and limited lateral extent of exposure permit only 4 fractures to be traced to their intersection with this contact.

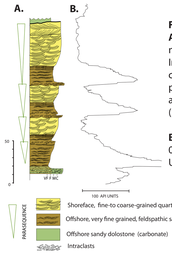

FIGURE 9.
A) Measured section of Jordan Sandstone, near Stillwater, MN (eastern TCMA). Intercalations of fine clastic and coarse clastic sandstone, representing stacked parasequences, are typical of lower Jordan and upper St. Lawrence strata regionally (Runkel et al., 2007; Runkel, 1994).

B) Borehole natural gamma ray log located 0.3 miles from measured section (MN Unique #448708).

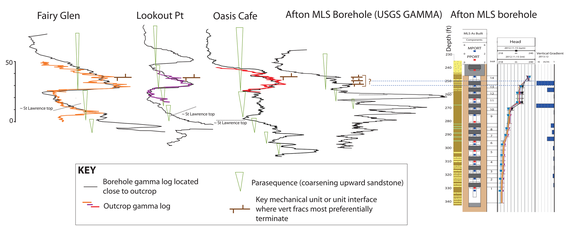

FIGURE 10. Correlation diagram of outcrop and borehole gamma logs and hydraulic head measurements, showing interpreted parasequences and key mechanical unit or unit interface where vertical fractures preferentially terminate.

• Fig. 10 shows a correlation of three localities near Stillwater, MN where we've conducted outcrop fracture mapping and outcrop gamma logging correlated with nearby borehole gamma logs.

• The fourth locality near Afton, MN is a Westbay instrumented borehole with discrete multi-level head data from the lower Jordan Sandstone, the St. Lawrence and the Tunnel City Group.

• Key mechanical units or interfaces where vertical fractures most commonly terminate (PTHs) align with the natural gamma signature within the coarsening upwards parasequence and correlate to significant head change in the Afton borehole.

The instrumented borehole at Afton was constructed in collaboration with Jessi Meyer and Beth Parker (and others) from the Centre for Applied Groundwater Research, University of Guelph (Runkel et al. 2014).

DISCUSSION: RELATIONSHIP BETWEEN BED PARALLEL MACROPORES (BPMs) AND VERTICAL FRACTURE TERMINATIONS

• Understanding the genesis, including timing, of fractures and bed parallel macropores could ultimately improve predictability of their distribution and thus provide a better understanding of groundwater flow.

• As shown in Figure 13, preferential termination horizons do commonly correspond to discrete intervals of BPM networks, as suggested by Underwood et al. (2003). A question, however, is whether the fracture termination horizons led to preferential development of BPMs, or whether BPMs developed prior to vertical fracturing and hindered fracture propagation.

• We suggest that BPMs are more likely to have preceded vertical fractures, and served as weak interfaces, than the inverse. BPMs in siliciclastic strata such as the Jordan Sandstone appear to have been formed early in burial history, prior to conditions necessary to produce vertical fractures (see adjacent poster by Runkel et al). BPMs in the Platteville Formation do not appear to be preferentially present, nor of greater dimensions, at vertical fracture terminations.

•The preferential termination of vertical fractures at horizons with abundant BPMs could in the subsurface be reflected by seemingly parodoxical hydraulic conditions whereby the highest horizontal conductivities in a strata succession may correspond (within centimeters) to the lowest vertical conductivies.

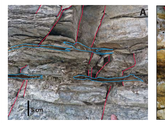

FIGURE 13. Examples of vertical fracture (red lines) terminations corresponding to stratigraphic positions with bed parallel macropores (blue lines) (Macropores are filled with fine-grained, unconsolidated, allochthonous sediment)

A) Platteville Formation. Vertical fractures terminate in an approximately one-half meter thick interval that contains bed parallel macropores (outlined in blue). Outcrop is Washington Avenue Bridge, Twin Cities, as shown in Figure 11 fracture map.

B) Jordan Sandstone. Vertical fractures terminate at an irregular bed contact that contains bed parallel macropores, underlined in blue.

CONCLUSIONS AND FUTURE RESEARCH

• Our results are consistent with earlier fracture mapping of Silurian carbonate bedrock in eastern Wisconsin by Cooke et al. (2006) in showing the presence of units with through-going fractures separated from one another by PTHs, indicating the lower Paleozoic bedrock in this region has in this respect a generally consistent, predictable fracture character across a wide spectrum of rock types and age.

•Our results also demonstrate that PTHs are correlatable (maintaining a consistent stratigraphic position) across distances of at least a few kilometers.

•The correspondence of PTHs to measurable hydraulic properties suggests promise for improved predictability of groundwater flow.

• We intend to improve our understanding of the link between detailed hydraulic head profiles and other borehole conditions to outcrop fracture attributes by improving our instrumentation of wells near bedrock exposures, in collaboration with Jessi Meyer and Beth Parker from the Centre for Applied Groundwater Research at the University of Guelph.

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