Proposed wellbore re-entry to measure stress orientations and geophysical properties for earthquake hazard and minerals characterization in Minnesota

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Overview

Despite its importance for characterizing seismic hazards, the state of stress is poorly understood in much of the Upper Midwest and Great Plains. A project is in development to re-enter and log inactive boreholes in Minnesota to determine stress orientations, rock properties, and other geophysical parameters. This effort will also involve geophysical logging of previously obtained core samples.

Motivation: Stress data are very limited in the Upper Midwest

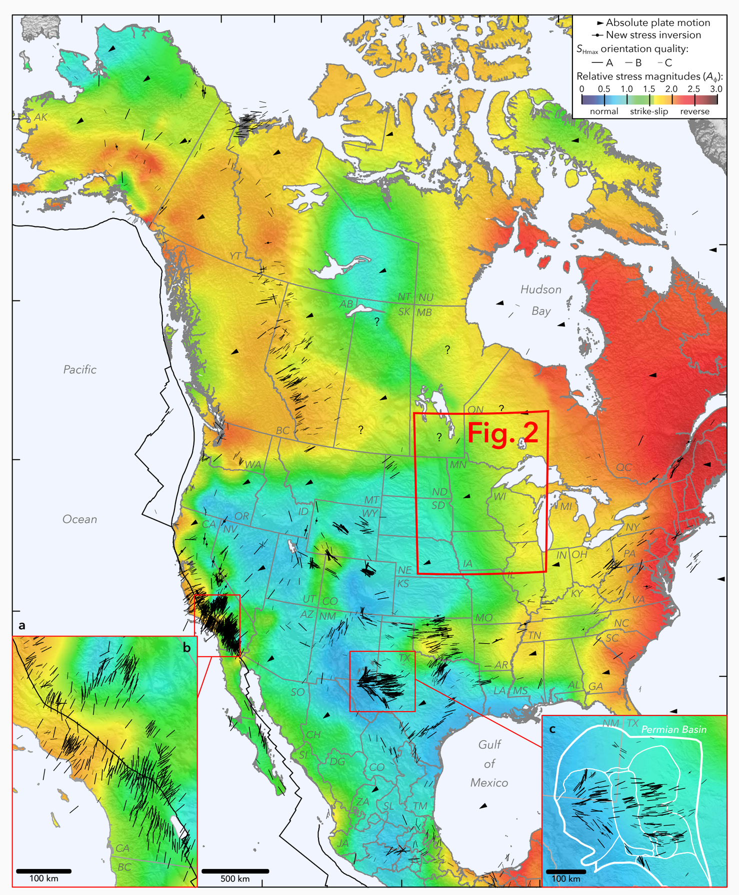
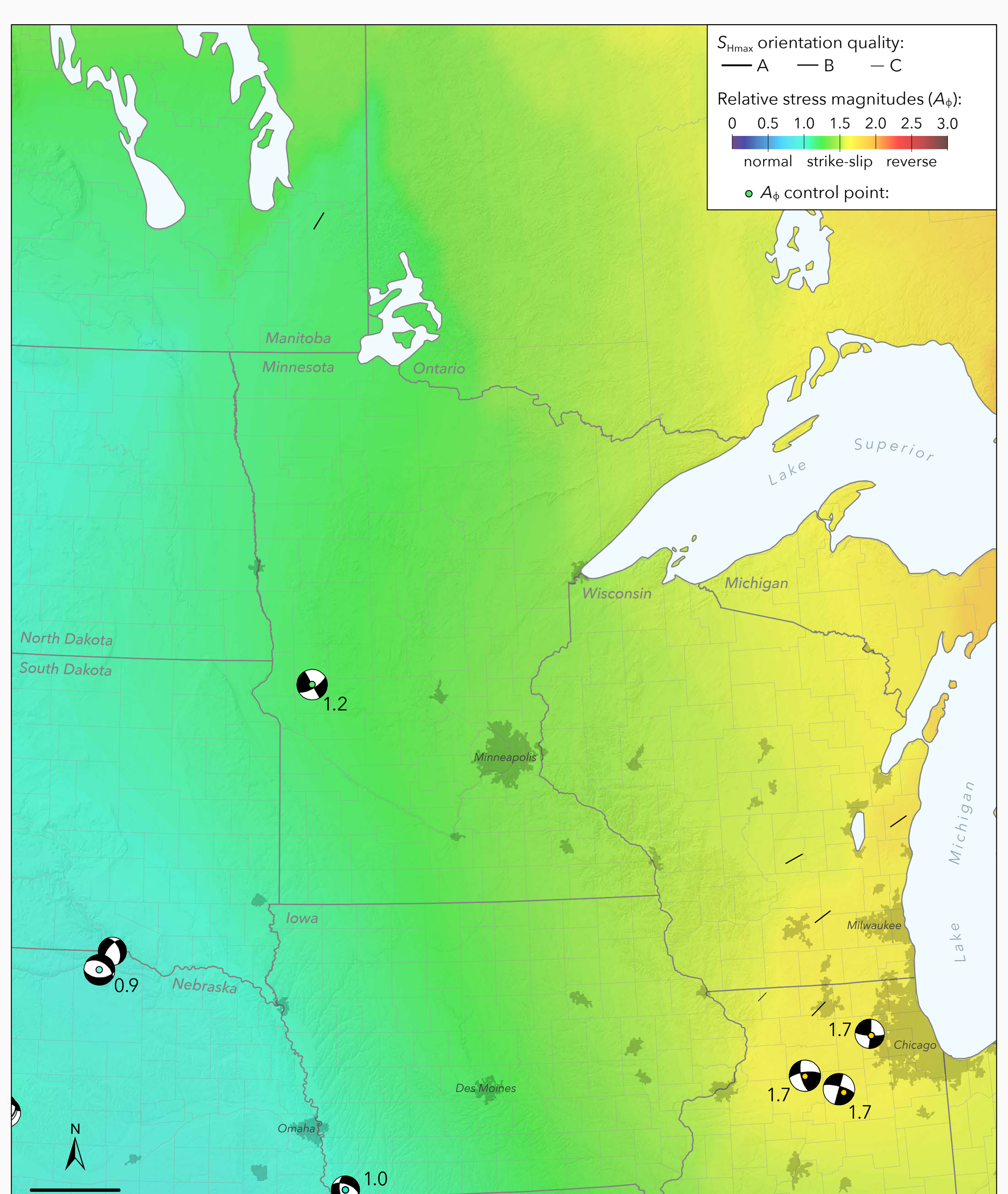


Figure 1 *(right)*
State of stress in North America (Lund Snee & Zoback, 2020). Black lines are S_{Hmax} orientations, mostly from wellbore measurements or aligned microseismic events defining hydraulic fractures. The background depicts the style of faulting using the A_ϕ parameter (Simpson, 1997).

Figure 2 *(below)*
State of stress in the Upper Midwest (after Lund Snee & Zoback, 2020, 2022). Focal mechanisms are from Saint Louis University (Herrmann et al., 2011). Map extent is shown on Fig. 1.

- The state of stress (Fig. 1) determines which faults are most likely to produce damaging earthquakes.
- Like natural earthquakes, induced seismicity usually occurs on the most favorably oriented faults (e.g., Lund Snee & Zoback, 2016; Skoumal et al., 2019).
- Knowing only the orientation of the maximum horizontal principal stress (S_{Hmax}) and the relative stress magnitudes (faulting regime, A_ϕ) is sufficient for most purposes.
- Very little stress information is available in Minnesota and throughout the Upper Midwest (Fig. 2).
- Seismicity rates are low in this area, but damaging earthquakes can be induced by changes in fluid pressure.
- Minnesota contains large population centers, two nuclear power stations, and other critical facilities (Fig. 3).
- We plan to re-enter inactive boreholes (Fig. 3) to determine the state of stress and other geophysical data.



Log inactive boreholes for stress, lithology, and geophysical parameters

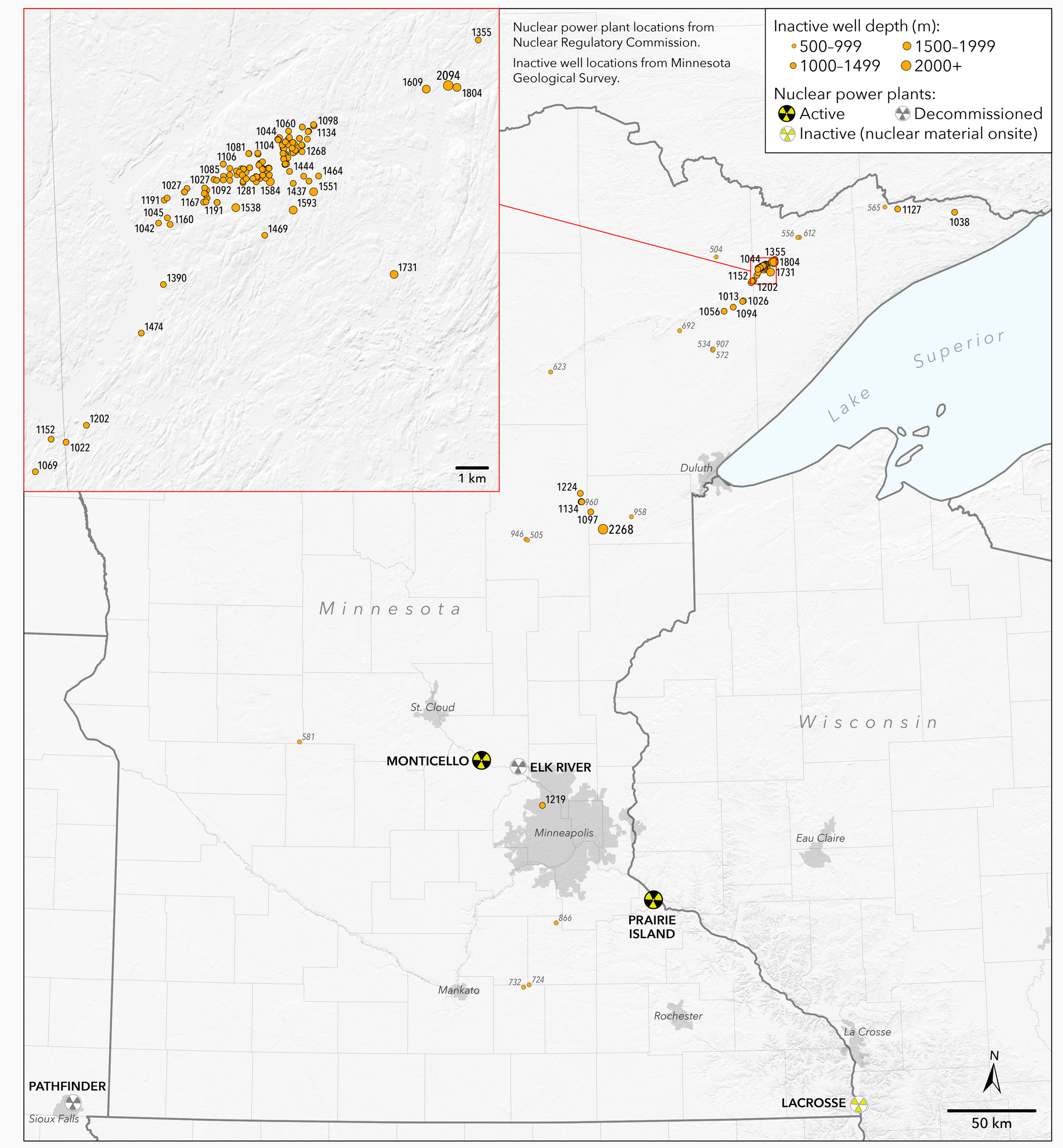


Figure 3 *(above)*
Map of inactive boreholes in Minnesota with depths ≥ 500 m (orange dots), from the Minnesota Geological Survey. Many are candidates for re-entry.

- The State of Minnesota maintains a database of inactive wells (Fig. 3). About 184 with depths >1 km are candidates for stress measurement. Such deep boreholes will also be valuable for seismic site characterization.
- Re-entering existing wells is a cost-effective way to obtain high-quality stress data (~$25–70k for 5–7 wells).
- S_{Hmax} orientations can be readily measured in boreholes using image logs.
- In subvertical wells, borehole breakouts form perpendicular to S_{Hmax} and drilling-induced tensile fractures form parallel to S_{Hmax}.
- Logging tools will include:
  - An acoustic micro-imager to obtain oriented images of the wellbore wall;
  - Standard wireline logging tools: Full-waveform sonic, formation resistivity, natural gamma, fluid temperature/resistivity, and 3-arm caliper for identifying in-hole hazards.

Log previously obtained drill core

- The Minnesota Geological Survey and Department of Natural Resources (MN DNR) maintain extensive drill core libraries (Fig. 4).
- Geophysical measurements will be obtained on core from selected wells distributed across the state (not necessarily from the boreholes to be re-entered).
- Measurements to be collected include unconfined compressive strength (Fig. 5) and ultrasonic P- and S-wave velocities (Fig. 6) at surface conditions (measurement at borehole conditions is possible at greater cost).

Figure 4 *(right)*
Photo of core at the Minnesota Geological Survey.

Figure 5 *(below right)*
Photo of rock mechanics test system (MTS) at the University of Minnesota for rock strength measurements of drill core.

Figure 6 *(below left)*
Photo of oscillator at the University of Minnesota for wave speed measurements of drill core.

Determining fault sensitivity for natural and induced seismic hazards

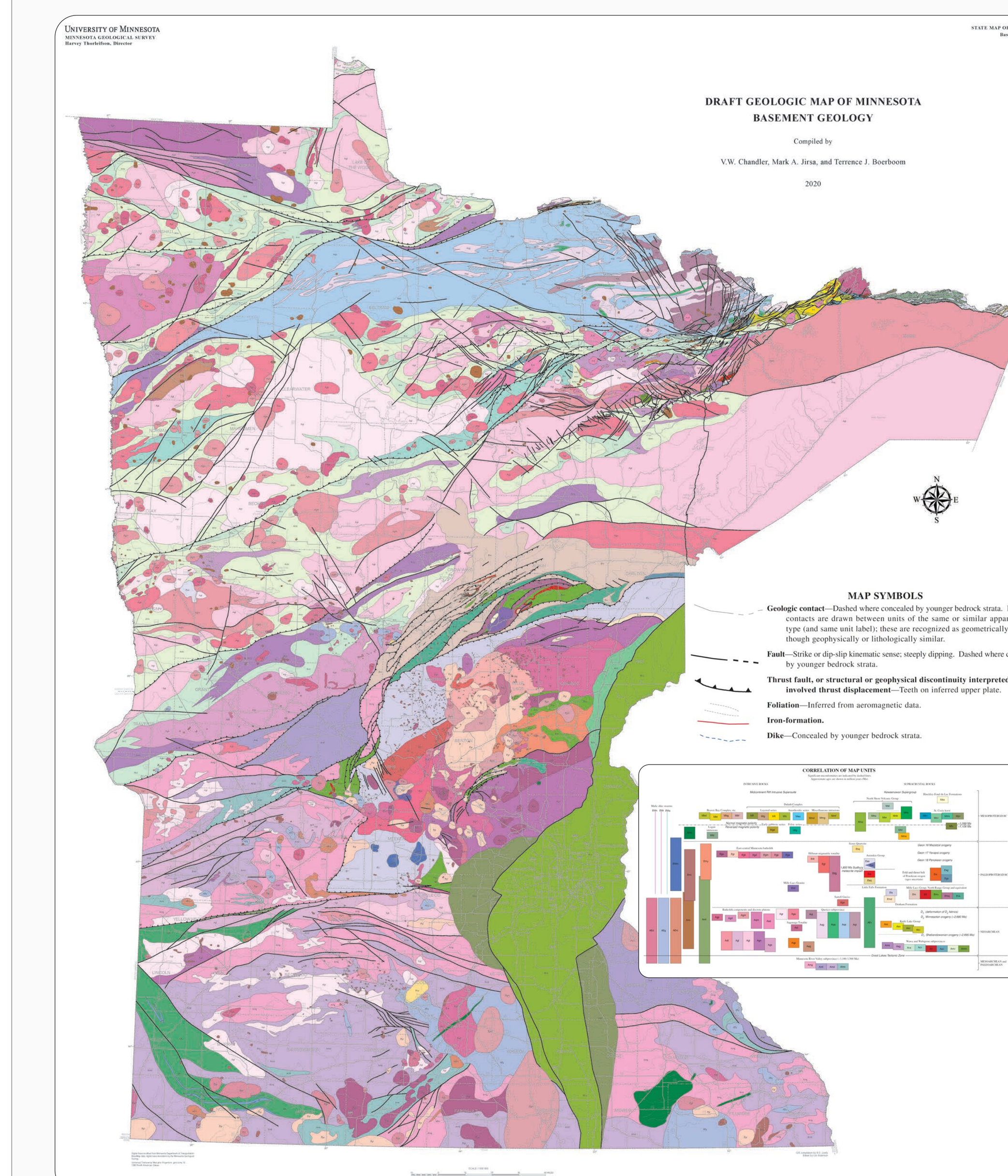


Figure 7 *(left)*
Draft, updated geologic map of the crystalline basement of Minnesota by the Minnesota Geological Survey (Chandler et al., 2020). Black lines are faults. Dikes are not shown. Full legend and description of map units are available from Jirsa et al. (2012).

- Recently, the Minnesota Geological Survey released an updated map (Fig. 7) of major faults and geologic units in the crystalline basement (Chandler et al., 2020).
- Earthquakes are most likely to occur within the crystalline basement (i.e., below the sedimentary cover).
- By mapping S_{Hmax} orientations and the style of faulting (A_ϕ), it will be straightforward to determine which of those faults are most likely to cause earthquakes in today's stress field and their sensitivity to fluid pressure perturbations (Fig. 7).
- This analysis can be done probabilistically; e.g., using Fault Slip Potential (FSP) software (Walsh et al., 2017).
- The data and analysis will be beneficial for characterizing induced seismicity hazards at potential sites for low-temperature geothermal development or energy or carbon storage.

Additional applications

- Well log data will be used to determine near-surface seismic velocities for earthquake ground motion prediction.
- Image logs will also be used to determine orientations of natural fracture populations.
- Fluid content and temperature will be logged to support groundwater modeling and low-temperature geothermal energy development.
- Lithologies and rock properties in boreholes and core will be valuable for mineral resource exploration, seismic hazard analysis, prospecting for carbon/energy storage and low-temperature geothermal energy.

References

Chandler, V.W., Jirsa, M.A., and Boerboom, T.J. (2020). Draft geologic map of Minnesota basement geology. Minnesota Geological Survey, scale 1:500,000.

Herrmann, R.B., Benz, H.M., and Ammon, C.J. (2011). Monitoring the earthquake source process in North America. *Bull. Seismol. Soc. Am.*, 101:2609–2625.

Jirsa, M.A., Boerboom, T.J., and Chandler, V.W. (2012). Geologic map of Minnesota: Precambrian bedrock geology. Minnesota Geological Survey State Map Series S-22, scale 1:500,000, https://conservancy.umn.edu/handle/11299/101466.

Lund Snee, J.-E. and Zoback, M.D. (2016). State of stress in Texas: Implications for induced seismicity. *Geophys. Res. Lett.*, 43(19):10,208–10,214, doi:10.1002/2016GL070974.

Lund Snee, J.-E. and Zoback, M.D. (2020). Multiscale variability of the crustal stress field throughout North America. *Nat. Comms.*, 11(1951):1–9, doi:10.1038/s41467-020-15841-5.

Lund Snee, J.-E. and Zoback, M.D. (2022). State of stress in areas of active unconventional oil and gas development in North America. *AAPG Bull.*, 106(2):355–385, doi:10.1306/08102120151.

Simpson, R.W. (1997). Quantifying Anderson's fault types. *J. Geophys. Res.: Solid Earth*, 102(B8):17909–17919.

Skoumal, R.J., Kaven, J.O., and Walter, J.I. (2019). Characterizing seismogenic fault structures in Oklahoma using a relocated template-matched catalog. *Seismological Res. Lett.*, 90(4):1535–1543. doi:10.1785/0220190045.

Walsh, F.R., III., Zoback, M.D., Pais D., and Weingarten M. (2017). FSP 1.0: A Program for Probabilistic Estimation of Fault Slip Potential Resulting From Fluid Injection, Stanford Center for Induced and Triggered Seismicity.

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