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Full Length Article

Lessons learned from the Youngstown, Ohio induced earthquake sequence from January 2011 to January 2012

A.P. Morris [a,*], D.A. Ferrill [a], G.R. Walter [a], A.M. Price [a], K.J. Smart [a], R.J. Skoumal [b], M.R. Brudzinski [c], B.S. Currie [c]

[a] Southwest Research Institute, Culebra Road 6220, San Antonio, TX 78238-5166, USA
[b] United States Geological Survey, Earthquake Science Center, 345 Middlefield Rd, Building 3A, RM 113, Menlo Park, CA 94025, USA
[c] Department of Geology and Environmental Earth Science, Miami University, Oxford, OH 45056, USA

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ABSTRACT

The Youngstown earthquake sequence of 2011 is one of the clearest examples of inadvertently induced seismicity for which detailed documentation is available. In this paper, we investigate (i) likely stress states in the vicinity of the injection well, (ii) a range of likely permeability scenarios, and (iii) relatively simple methods by which induced seismicity can be evaluated and mitigated. We use relocated hypocenters from the seismic sequence to construct a basement fault structure, which is then used to serve as a reference surface within the basement, and on which we calculate the effects of pore pressure changes induced by the injection activities of the Northstar #1 injection well. We also deduce an in situ (pre-injection) strike-slip stress regime, where $\sigma_2 \approx \sigma_3$, and it is consistent with both recent earthquake data and published stress estimates for the region. If the reactivation characteristics of the basement are known or assumed, a critical or threshold slip tendency can be determined and the basement faults can be analyzed for the likelihood of reactivation in a perturbed pore pressure field. Comparison of well injection pressures and simulated pore pressure perturbations within the basement below the injection well indicates that permeability anisotropy is necessary to generate sufficient pore pressure perturbation to induce fault reactivation. Simulations of the well's injection history show that our estimate of in situ stress state, coupled with a highly anisotropic permeability structure, can generate sufficient pore pressure perturbation on the inferred basement structure to cause reactivation, potentially slipping an area of approximately 4×10^5 m^2.

1. Introduction

The earthquake sequence in Youngstown, Ohio, recorded over a 12-month period from January 2011 to January 2012, included approximately 130 seismic events with Richter magnitudes ranging from 0.68 to 4 (Skoumal et al., 2014; Holtkamp et al., 2015). Details of this seismic sequence, including *b* values and magnitudes versus time distributions are given in Skoumal et al. (2014; see their Figs. 2 and 3). Over the same time period and within 1 km vertically and horizontally of the majority of these events, the underground injection control (UIC) Class II Northstar #1 injection well (Fig. 1) was actively injected with saline wastewater (Kim, 2013). Because of the temporal and spatial association of these seismic events with the wastewater injection, these earthquakes have been attributed to the pore pressure perturbation generated by the fluid injection in the Northstar #1 injection well (Holtkamp et al., 2015). This induced seismicity began within days after the initiation of wastewater injection, increased in frequency and magnitude over elapsed time, and migrated from east to west and downward along a narrow zone approximately 1 km long (Skoumal et al., 2014; Holtkamp et al., 2015) (see Fig. 1). The sequence culminated in a magnitude 4.0 event on 31 December 2011, for which Kim (2013) determined the focal mechanism.

The Northstar #1 injection well was drilled vertically through approximately 9000 ft (2743 m) of near-horizontal sedimentary rocks of the Mississippian Cuyahoga Formation near the surface to the Cambrian Conasauga Group and into the Precambrian crystalline basement (Ohio Department of Natural Resources, 2012;

* Corresponding author.
E-mail address: amorris@swri.org (A.P. Morris).
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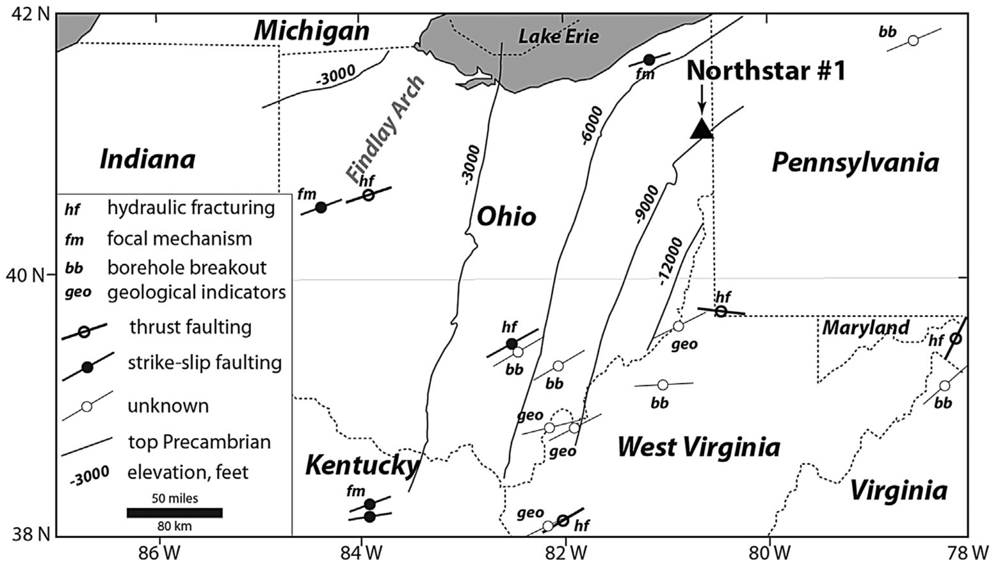

Fig. 1. Map of Ohio and adjacent region showing the location of the Northstar #1 injection well, the elevation of the top of the Precambrian basement in feet (Bayley and Muehlberger, 1968; Ohio Department of Natural Resources, 2012), and the orientations of the maximum horizontal stresses, as determined from a variety of data sources (Helmholtz Centre Potsdam, 2009).

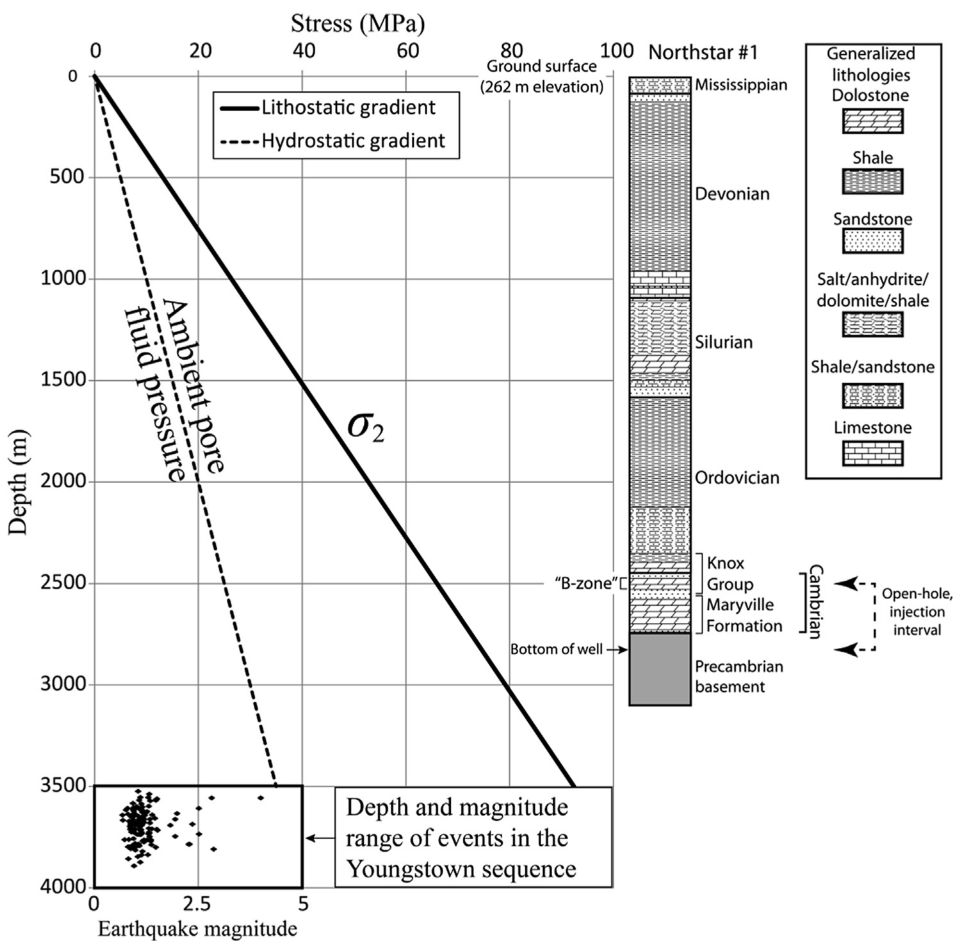

Fig. 2. Stratigraphy reported within the Northstar #1 injection well (Ohio Department of Natural Resources, 2012; Holtkamp et al., 2015), stress versus depth profile at the Northstar #1 injection well, as well as the depths and magnitudes of seismic events in the 2011–2012 Youngstown sequence.