Modeling pressure response into a fractured zone of Precambrian basement to understand deep induced-earthquake hypocenters from shallow injection

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Abstract

Analysis of the spatiotemporal distribution of seismic events in Youngstown, Ohio, from previous studies has revealed that the seismicity was triggered by injection during January through December 2011 into a brine-disposal well (North Star #1 well). Investigation of the hypocenters of induced earthquakes, which were substantially deeper than the injection zones in the well, brings the question of how pore pressure could migrate more than a kilometer below the injection zone into the Precambrian basement rock to cause induced seismicity. By doing numerical modeling of brine injection into the North Star #1 well, it is possible to better understand the relationship among induced-seismicity hypocenter locations, pressure diffusion, and formation geology. The effects of geologic and geomechanical characteristics of subsurface formations have been studied, the potential of hydraulic fracturing during brine injection has been considered, and the potential presence of conductive fault or fractured zones has been evaluated. Results show that conductive fractures and faults could be considered one of the main causes of deep induced seismicity by serving as conduits to the deeper, critically stressed basement faults. In addition, heterogeneity along the fault zone could be one of the reasons for lateral migration of earthquake hypocenters over time.

Introduction

During the last decade, significant earthquakes in the United States midcontinent region are suspected to be induced events triggered by fluid injection in underground sedimentary formations (Ellsworth, 2013). In general, earthquakes result from sudden release of stored elastic strain energy by frictional sliding along preexisting faults. The hazard associated with fluid injection is that it might act locally to reduce effective frictional strength of a fault below the critical threshold stress, which leads to sudden slip on a fault and triggers an earthquake.

The reduction in effective strength of a fault is the main induced-seismicity mechanism provided by decreasing the normal stress on the fault because of an increase in pore pressure. The conditions needed for triggering seismicity by fluid injection generally include (1) presence of a preexisting, favorably oriented fault of considerable size, (2) an in situ stress field close to failure, and (3) pore-pressure disturbance on the fault surface (Nicholson and Wesson, 1990).

Although the general mechanism for induced seismicity is firmly founded in theory (McGarr et al., 2002), characteristics of induced seismicity, i.e. spatial, temporal, and maximum potential magnitude, remain a matter of debate. In the documented cases of injection-induced seismicity (Verdon, 2014), hypocenters of many induced earthquakes are in crystalline basement rock, which is far below the injection zone in the sedimentary section. In this case, the geologic properties of reservoir and basement rock could have a strong effect on the potential of deep induced seismicity by controlling spatial extent and magnitude of pore-pressure disturbance.

The critical characteristic of a target reservoir for injection is its permeability. Low-permeability formations cause more confinement of pressure and are more likely to have high fluid-injection pressures, increasing the concern of earthquake triggering. Geologic properties of a reservoir are also responsible for how rapidly fluid is accepted and pore-pressure increases dissipate with distance from the point of injection.

Underground formations that can dissipate pressure more rapidly ensure that unless fluid is injected directly to a fault, pore-pressure changes from injection will not extend an appreciable distance from the well. Thus, the distance between a favorably oriented fault capable of slip and an operating injection well also becomes a critical factor in determining the potential of seismicity.

From January 2011 through February 2012, the Youngstown, Ohio, area experienced several seismic events ranging from 2.1 to 4.0 magnitude with average depth of 3.5 to 4 km along a previously unknown fault line into the crystalline Precambrian basement, showing an example of induced earthquake with deep hypocenter (Kim, 2013). The analysis by Kim (2013) of the spatiotemporal distribution of seismicity in detail and its comparison with available fluid-injection parameters reveal that seismicity in the Youngstown area was triggered by fluid injection into the North Star #1 well. That well was drilled into the Basal Cambrian Sandstone with 15-m net thickness and average 10.3% porosity (Ohio Department of Natural Resources [ODNR], 2012). The well was completed open hole to a depth of 2802 m involving 60 m of Precambrian basement at the bottom of the open hole.

The importance of studying the Youngstown induced earthquakes is that they have been related directly to injection into North Star #1. No nearby active injection well at the time of brine injection into North Star #1 existed that might contribute to the Youngstown induced seismicity (Ohio Department of Natural Resources [ODNR], 2012). In addition, availability of different types of data, especially the image log, can provide the opportunity to study the importance of the geologic parameters of the reservoir and basement that are critical for induced seismicity. The interpreted image log of North Star #1 well (Figure 1) reveals the presence of a natural fracture zone in the Precambrian basement section.

In our work, numerical modeling of brine injection into the North Star #1 well is presented to investigate how injection of brine, mainly in sedimentary formations, could cause seismicity deep in the crystalline Precambrian basement. Also studied is the potential of hydraulic fracturing, caused by brine injection into the underlying basement, to provide a pressure-diffusion pathway and permeable conduit similar to faults and fracture networks.

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http://dx.doi.org/10.1190/tle34060684.1.

Building model and pressure diffusion caused by brine injection

A 3D fluid-flow simulator, CMG-GEM, is used to model the behavior of brine plumes during injection periods (Computer Modeling Group Ltd., 2010). We assume an isothermal condition during brine injection into the reservoir. We neglect hydrodynamic dispersion and chemical reactions between the aquifer minerals and the components in the system.

Table 1 shows different parameters used to build the model. Daily injection volumes for the fluid-injection operation (Ohio Department of Natural Resources [ODNR], 2012) are divided into four periods, which are used as the input data. In the first 70 days, fluid injection was carried out with a low injection rate of 86 m^3/day, then an injection rate of 187 m^3/day was used for 30 days, then 259 m^3/day for 100 days, followed by 316 m^3/day for 127 days. Thickness, depth, and porosity of different formations in the North Star #1 well are interpreted from well-log data. Basement permeability is assumed to be 0.1 mD, which is considered a high value based on the information about fluid-flow properties of crystalline granite rock in the U. S. midcontinent region (Haimson and Doe, 1983).

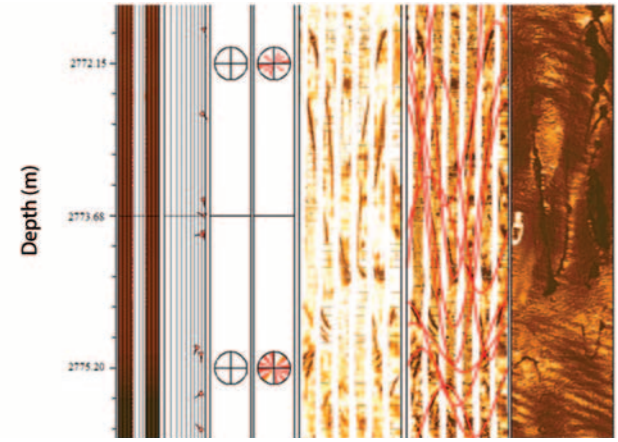

Figure 1. Natural fractures interpreted from image logs in the Precambrian crystalline basement in the North Star #1 well. Red sinusoids and rose-diagram plots are the interpreted natural fractures.

Table 1. Model parameters.

Hydraulic-fracture model parameters	
Porosity of injection zone	0.1
Permeability	Layers chosen by porosity
Poroelastic constant	1.0
Fluid-pressure gradient	10 MPa/km
Fracture gradient	14.7 MPa/km
Fluid-flow model parameters	
Number of grids	30 × 30 × 25
Model dimension	12 km × 12 km × 2.5 km
Permeability of injection zone	3 mD
Permeability of basement	0.1 mD
Porosity of injection zone	0.1
Fluid-pressure gradient	10 MPa/km
Fracture network and fault	
Fracture-network permeability	10 mD
Network spacing	150 m
Fault permeability	100 mD, 50 mD, 10 mD
Fault distance to injection well	800 m, 100 m, 30 m
Fault thickness	5 m
Fault length	1 km

In the first step, the model is constructed without any fault or fracture network in the basement. The permeability of the main injection reservoirs, Basal Cambrian Sandstone and the upper part of Precambrian basement, is the main parameter altered to history-match surface-pressure data as a function of provided injection rates. The simulated surface-pressure data shown in Figure 2a provide a good match with the measured pressure (Ohio Department of Natural Resources [ODNR], 2012) by assuming reservoir permeability of 3 mD.

Figure 2b shows reservoir pressure after injection. As we can see in the postinjection model, formation pressure is increased mainly in the reservoir injection zone, and no changes in pressure are observed in the Precambrian basement at depths similar to the hypocenters of the Youngstown induced earthquakes (3.5 to 4 km), which is the same as the zone of interest in Figure 2b. We should mention that the permeability of Precambrian basement is typically much lower than the assumed value in our work, which reduces the chance of pressure diffusion to the Precambrian basement rock even more.

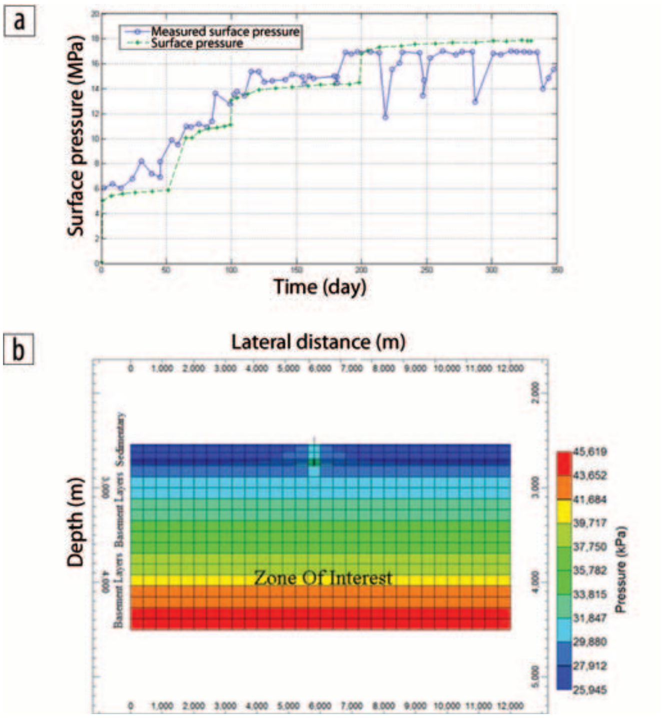

Figure 2. (a) Measured and simulated wellhead pressure during brine injection into North Star #1 well. (b) Effect of brine injection on reservoir pressure in the shallow part of the Precambrian basement for a model without a fault zone.

Potential of injection-induced hydraulic fracturing

The stress change produced as a function of fluid injection could cause hydraulic fractures in the target reservoir and provide a leakage pathway to the underlying formations. The potential hydraulic fracturing also could change pressure-diffusion behavior in the Precambrian basement. Coupled fluid-flow, geomechanical, and hydraulic-fracturing modeling can be used as a tool to predict the potential for fracturing in reservoirs and surrounding formations. Through applying the coupled modeling by a finite-element-based hydraulic-fracture simulator (Smith and Hannah, 1996; Smith et al., 2001), we can study whether stress changes in Basal Cambrian Sandstone and Precambrian crystalline basement during fluid injection provide different pressure-diffusion behaviors by propagation of hydraulic fractures into the basement.

Table 1 shows the parameters used to build the model. Rock dynamic elastic parameters (Figures 3a and 3b) are determined from knowing the compressional-wave and shear-wave velocities obtained from a dipole sonic well log of the North Star #1 well. The dynamic moduli then are calibrated with static rock-core-derived values obtained from limited triaxial tests on reservoir rocks. The minimum horizontal-stress gradient of 14.7 MPa/km (0.65 psi/ft) and maximum horizontal-stress gradient of 25 MPa/km (1.1 psi/ft), near to vertical stress gradient, are used, based on limited regional hydraulic-fracturing data in the strike-slip stress regime of the northern Appalachian Basin (Evans, 1989). The fluid injection rate is the same as the previous section.

The model results indicate that the injection rates used for brine injection into North Star #1 well cannot cause the propagation of hydraulic fractures (Figures 3c and 3d). The net pressure, difference between bottom-hole pressure and minimum horizontal stress, inside the assumed hydraulic fracture is mainly negative during injection. In addition, the poroelastic effect of fluid injection puts additional resistance on the generation of hydraulic fracturing.

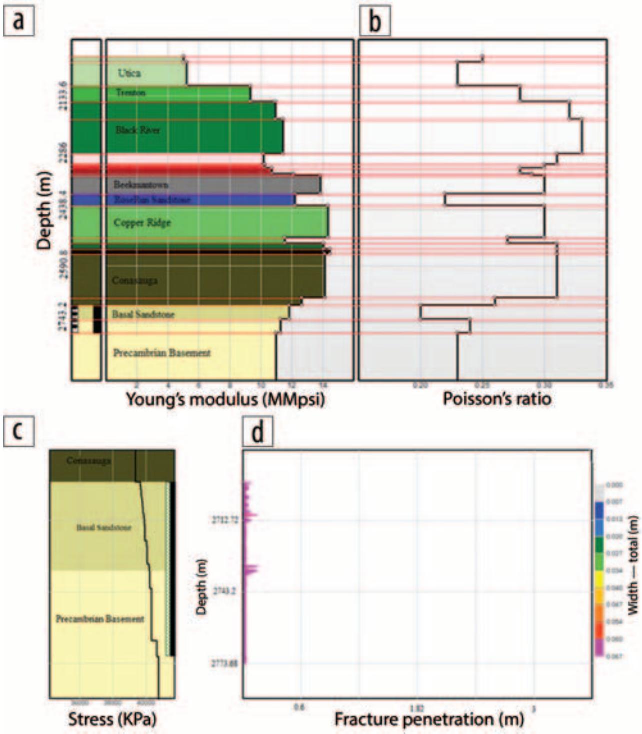

Figure 3. Formation dynamic mechanical parameters, (a) Young's modulus and (b) Poisson's ratio, along the North Star #1 well. (c) Minimum horizontal stress and (d) depth of penetration of hydraulic fracturing.

Diffusion of pressure by a fault-and-fracture network

In the previous sections, we concluded that pressure cannot diffuse into the deep section of nonfractured Precambrian basement, and hydraulic fracturing of the basement is not possible either. However, image logs of the Precambrian basement in the North Star #1 well show natural fractures in different orientations that can be modeled by a fault-and-fracture network.

A fault zone is modeled within the previously described CMG-GEM model by placing grids of small width and high permeability in the Precambrian basement within distances of 30 m, 100 m, and 800 m from the injection well (Figure 4a). Figure 4b shows pore-pressure changes at a total depth of 4000 m below the injection well during fluid injection in the case of fault presence with different distances from the injection well. The presence of a conductive fault could cause pore pressure to reach depths in low-permeability crystalline basement similar to those observed in the Youngstown earthquakes. Figure 4b also shows that unless the fault is near the injection well, there is no possibility of significant pressure diffusion.

The effects of permeability variation of a fault located 100 m from the injection well on pore-pressure changes also were

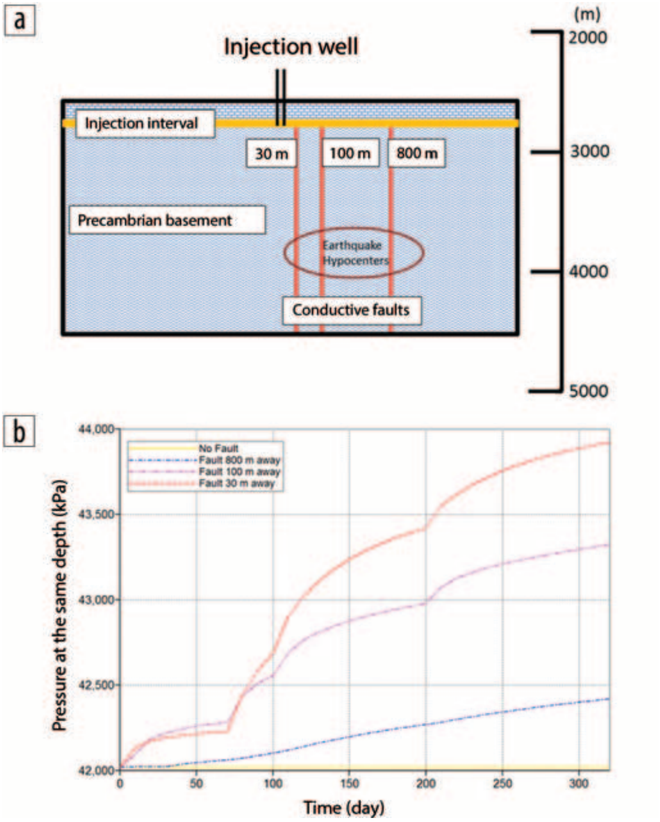

Figure 4. (a) Schematic of distance for a hypothetical fault zone away from the injection well. (b) Effect of assumed faults on pressure increment of a grid at a depth of 4000 m as a function of fault distance from injection well (pressure does not change in the case of no fault).

modeled (Figure 5). As the conductivity of a fault decreases, the pore-pressure change in the basement also decreases with depth.

An iterative coupling approach in CMG-GEM, used for coupling fluid flow and geomechanics, shows that the total minimum and maximum horizontal stresses also can change in the basement formation in the presence of a fault by pore-pressure diffusion, although it is not significant. Figure 6 shows the effective stress state at a depth of 4000 m before and after brine injection with the presence of a fault with permeability of 100 mD 100 m from the injection well with a different basement permeability.

Figure 6a shows the effect of basement permeability on pressure increasing at depth of interest. Lower basement permeability could cause higher pressure in the conductive zone by avoidance of pressure dissipation into the basement formation around the conductive zone. As we can see in Fibure 6b, the change of stress state is not significant, suggesting that there must be an optimum oriented fault in a critical stress state for inducing an earthquake, which shows by a cohesionless fault with typical coefficients of friction of 0.6 and 0.8. Injection of fluid into a basement layer with very low permeability could cause fault failure under low- and high-friction coefficients. By dissipation of pressure into the basement, the chance of fault activation is limited to lower fault friction coefficients.

Deep pressure diffusion through a natural fracture network in the Precambrian basement is also a possibility instead of a fault zone within the basement. Simulation of fractured reservoirs using the dual-permeability approach involves discretization of the solution domain into two continua, called the matrix and the fracture. In this model, rectilinear prisms of the rock matrix are separated by an orthorhombic continuum of fractures. The matrix and fracture domains are linked to each other through an exchange term that connects each fracture cell to its corresponding matrix cell in a grid block.

A fracture network is modeled using a dual-permeability model in CMG-GEM with the permeability of 5 mD and spacing of 150 m in Precambrian basement. Although we are using a dual-porosity/permeability model for presenting a fracture media, we should consider that it is a simple representation of a complex natural-fracture system.

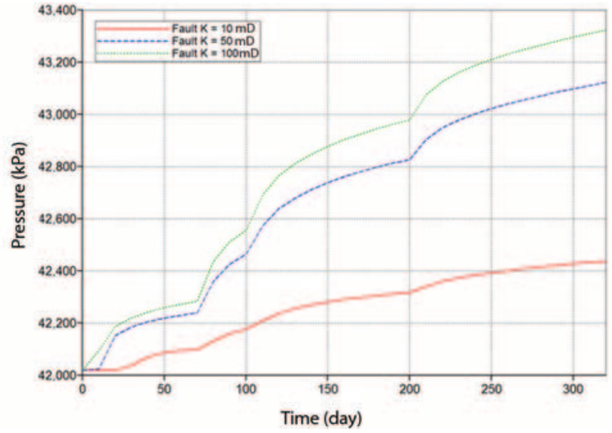

Figure 5. Effect of assumed fault permeability 100 m from the injection well on the pressure increment of a grid at a depth of 4000 m.

The modeling results show that pressure could be transferred to a depth of as much as 4 km with the presence of a fracture network (Figure 7a). Although the pressure increment is not significant, it could activate faults at depth that are in critically stressed condition. As in the conductive zone, the pressure increase in the zone of interest is a function of basement matrix permeability that determines pressure dissipation by interaction of fractures and matrix.

Lateral migration of earthquake hypocenters by fluid injection

In Youngstown, Ohio, seismicity started in the eastern end of the subsurface fault, close to the injection point, and migrated west, away from the wellbore, indicating that the expanding high-pore-pressure front laterally and progressively triggered earthquakes (Kim, 2013). Migration of earthquake hypocenters laterally over time shows the possibility of heterogeneity in geologic properties along the fault zone and fracture network. If we assume the same permeability along the fracture network, pressure diffusion is the same along the lateral distance of the fracture network, as shown in Figure 7a, and this causes a swarm of simultaneous earthquakes in the critical stress faults.

We modeled a variable permeability along the fracture network to look at a mechanism for lateral migration of earthquakes. The permeability of the fracture network is changed from 10 mD in the 400 m around the injection well to 3 mD 400 m away and a further reduction of 1 mD for each additional

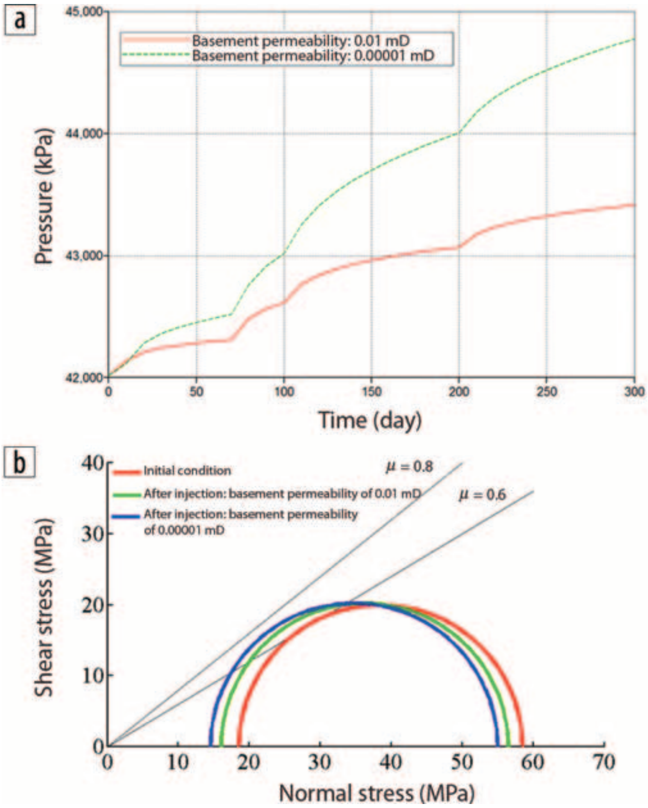

Figure 6. (a) Effect of basement permeability on dissipation of pressure at depth of interest. (b) Effective-stress state at a depth of 4000 m with a fault zone 100 m from the injection well with permeability of 100 mD.

400 m (Figure 7b). Figure 7c shows the pore pressure at different lateral distances of the fault at the same depth of 4000 m. Distance along the fracture network is chosen based on distance of hypocenters of selected induced earthquakes from the injection well.

In Figure 7c, three selected times and distances of hypocenters after the first seismicity below the injection well include point A, 80 days after injection started near the injection well; point B, 200 days after injection started and 300 m from the injection well; and point C, 300 days after injection started and 650 m from the injection well. Figure 7c shows that the pressure reached a specific value by moving along the heterogeneous fracture zone, from point A to point C, as a function of time, which is compatible with times and locations of hypocenters of earthquakes. In fact, heterogeneity along the fracture-network zone could explain how lateral migration of earthquakes occur if the fault is in critical stress condition.

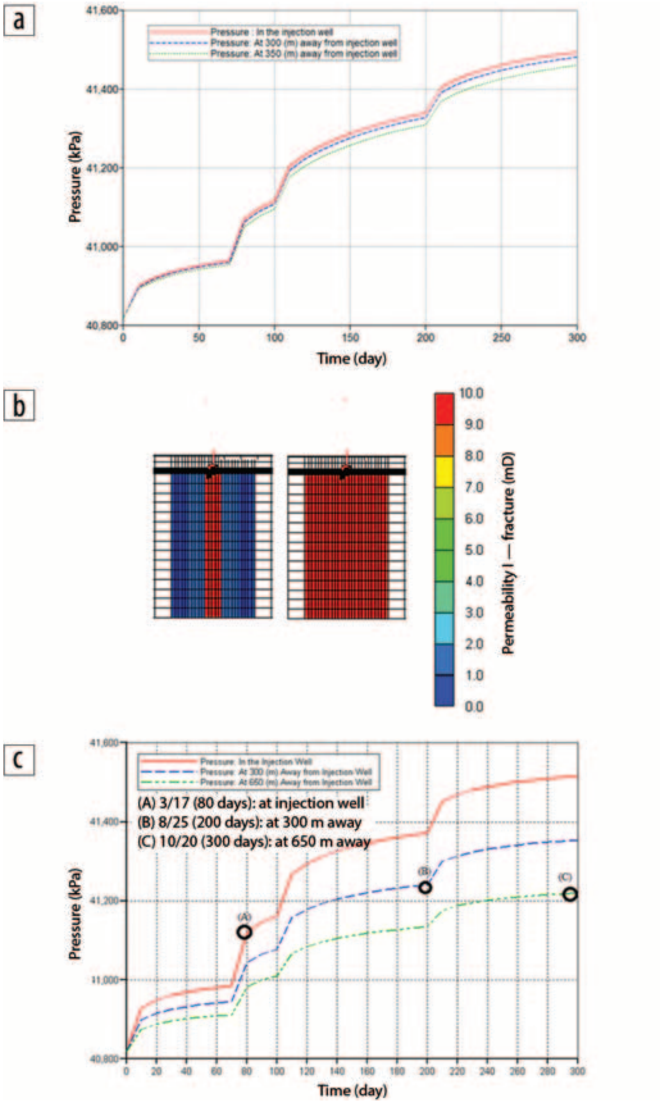

Figure 7. (a) Effect of homogenous fracture network on pressure increment of a grid at a depth of 4000 m and different distances from the injection well. (b) Location of fracture network and its (left) lateral heterogeneous permeability and (right) homogenous permeability along the fracture network. (c) Pressure diffusion at different lateral distances of the heterogeneous fracture network.

Conclusion

To find how increasing pore pressure by brine injection into sedimentary reservoirs could have caused earthquakes in the Precambrian crystalline basement in Youngstown, Ohio, we applied different types of numerical modeling, i.e., hydraulic-fracturing modeling and fluid-flow-coupled geomechanics modeling, considering the rates of brine injection in North Star #1 well. Our study shows that without faults or deep fracture networks, pressure cannot diffuse into low-permeability Precambrian basement rocks at depths similar to the Youngstown earthquake hypocenters. Our hydraulic-fracture modeling indicates that injection into the Cambrian formation and Precambrian basement does not provide an additional pathway for pressure diffusion.

Numerical investigation of the locations of induced earthquakes shows the important role of fracture network and fault proximity to the injection zone for transfer of pressure into deep basement rocks. It has been shown that such conductive zones must be in close proximity to the injection well to increase pore pressure in deep basement rocks. The pore-pressure increment is not significant even in the high-permeability fault-zone model, which indicates that the preexisting fault must be in critical condition for this mechanism. Lateral migration of induced seismicity could be the result of permeability heterogeneity along the fracture network. TLE

Acknowledgments

We thank Jacqueline Gerst, Rod Osborne, and Neeraj Gupta of Battelle Memorial Institute in Columbus, Ohio, for reviewing this article. Wireline-log data at the well were collected as part of a regional research effort funded by the Ohio Development Services Agency.

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