Research Paper

The role of fault-zone architectural elements on pore pressure propagation and induced seismicity

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44 **Abstract**

45 We used hydrogeologic models to assess how fault-zone properties promote or inhibit the
46 downward propagation of fluid overpressures from a basal reservoir injection well (150
47 m from fault zone, $Q = 5000 \text{ m}^3/\text{day}$) into the underlying crystalline basement rocks. We
48 varied the permeability of the fault-zone architectural components and a crystalline
49 basement weathered layer as part of a numerical sensitivity study. Realistic conduit-
50 barrier style fault zones effectively transmit elevated pore pressures associated with four
51 years of continuous injection to depths of $\sim 2.5 \text{ km}$ within the crystalline basement while
52 compartmentalizing fluid flow within the injection reservoir. The presence of a laterally
53 continuous, relatively low-permeability altered/weathered basement horizon ($k_{\text{weathered layer}}$
54 $= 0.1 \times k_{\text{basement}}$) can limit the penetration depth of the pressure front to $\sim 500 \text{ m}$. On the
55 other hand, the presence of a discontinuous altered/weathered horizon that partially
56 confines the injection reservoir without blocking the fault fluid conduit promotes
57 downward propagation of pressures. Permeability enhancement via hydromechanical
58 failure was found to increase the depth of early-time pressure front migration by a factor
59 of 1.3 to 1.85. Dynamic permeability models may help explain seismicity at depths of
60 $> 10 \text{ km}$ such as is observed within the Permian Basin, NM.

61 **Introduction**

62 The link between wastewater reinjection into basal reservoirs – that is, reservoir
63 formations located directly on basement rocks – and triggered seismicity within the
64 underlying crystalline basement has been documented at a number of sites, including
65 Ohio, with injection into the basal Mt. Simon Sandstone (Kim, 2013; Nicholson &
66 Wesson, 1990), New Mexico Permian Basin; with injection into the basal Ellenburger

67 Limestone (Zhang et al., 2016), Oklahoma; with injection into the basal Arbuckle
68 Limestone (Keranen et al., 2013, 2014; Walsh & Zoback, 2015, 2016; Yeck et al., 2016),
69 Texas Fort Worth Basin; with injection into the Ellenburger Limestone (Hornbach et al.,
70 2015), Kansas; with injection into the Arbuckle Limestone (Choy et al., 2016), and
71 Arkansas; with injection into the basal Ozark Aquifer (Horton, 2012). Earthquake
72 hypocenters occur at a wide range of depths (typically 2 – 8 km) below the injection
73 reservoir within the underlying crystalline basement (Table 1), sometimes at significant
74 lateral distances (>10 km) from injection wells (Keranen et al., 2014; Zhang et al., 2016).
75 Although wellhead injection pressures can be relatively high, the estimated increases in
76 hydraulic head where triggered seismicity occurs within the crystalline basement, up to
77 tens of kilometers from the well screen, are much lower. Hsieh & Bredehoeft (1981)
78 found that the pressure increase threshold associated with induced seismicity at the
79 Rocky Mountain Arsenal in Colorado was 320 m of hydraulic head (~3.2 MPa) at an
80 average depth of 5 km; Keranen et al. (2014) used hydrologic models to conclude that a
81 head increase of only 7 m (~0.07 MPa) was consistent with induced seismicity within the
82 crystalline basement in central Oklahoma.

83 Relocation studies of earthquake hypocenters associated with crystalline basement
84 seismicity suggest that fluid migration can occur along conductive sub-vertical fault
85 zones (e.g. Horton, 2012; Shapiro et al., 1997; Zhang et al., 2016). Faults can act as
86 barriers or conduits to fluid flow (e.g. Antonellini & Aydin, 1995; Caine et al., 1996) or
87 as conduit-barrier systems (Bense & Person, 2006). Previous work has conceptualized
88 fault-related fluid flow based on fault zone architectural elements (e.g. Caine et al. 1996;
89 Evans et al. 1997). Faults zones can include a low-permeability fault core, where the

majority of slip is accommodated, and high-permeability damage zones, which are mechanically related to the growth of the fault (Caine et al., 1996; Forster & Evans, 1991). The proportion of these components in a given fault zone varies (Antonellini & Aydin, 1995; Caine et al., 1996; Evans et al., 1997) and affects the hydraulic structure of faults (Bense & Person, 2006).

We assess how fault zone architectural elements influence fluid pressure propagation from basal injection reservoirs into crystalline basement rocks using a suite of idealized three-dimensional models in which the hydrogeological properties of fault core and damage zone permeability are systematically varied. We determine whether realistic hydrogeologic architecture (e.g. a damage zone width of about 10 m) produces downward propagation of pore pressures to depths of 2-8 km consistent with field observations of triggered seismicity. We also test the effect of a thin, relatively low permeability altered basement zone. Recent field studies focusing on the bedrock-sedimentary basin interface revealed the presence of an altered/weathered basement zone up to 20 m thick in some locations (Cuccio, 2017; Kerner et al., 2015) that has lower permeability than the surrounding rocks. We also explore the effect of dynamic permeability enhancement (Rojstaczer et al., 2008) on downward propagation of pore pressures using a simple cross sectional models. This dynamic model allows permeability increases to be triggered when pore pressures increase above some threshold value.

Table 1 - Injection, seismicity, and fluid pressure data from case studies documenting instances of induced seismicity across the USA.

Location	Basal Reservoir Name	Maximum earthquake magnitude/ Average hypocenter depth (km)	Maximum cumulative injection rate (m ³ d ⁻¹)**	Maximum depth of seismicity below injection wells (km)
Jones, OK [†]	Arbuckle Limestone	3 / 4.5	95,392	3.75
Guy, AR [‡]	Ozark Aquifer	4.7 / 5	9,539	5.2
Prague, OK [§]	Arbuckle Limestone	5.7 / 5	3,180	7
Dagger Draw, NM [*]	Ellenburger Limestone	3.2 / 11	15,899	8.65
Rocky Mtn Arsenal, CO [^]	Crystalline basement	5.5 / 5	1,007	3.5
Azle, TX [%]	Ellenburger Limestone	3.6 / 5	6,467	5
Milan, KS [»]	Arbuckle Limestone	4.9 / 6	2,332	4
Fairview, OK [°]	Arbuckle Limestone	5.1 / 7.5	100,692	6.5

[†]Keranen et al. (2014), [‡]Horton (2012), [§]Keranen et al. (2013), [¶]Walsh & Zoback (2015), ^{*}Zhang et al. (2016)
[^]Hsieh & Bredehoeft (1981), [%]Hornbach et al. (2015), [»]Choy et al. (2016), [°]Yeck et al. (2016). **Cumulative injection refers to the summed injection rates of all wells within a given area.

We address the following questions in this study using hydrologic modeling:

- 1) Can realistic fault-zone architectural elements explain downward fluid pressure propagation into crystalline basement rock to depths of 2-8 km, consistent with reports of triggered seismicity?;
- 2) How wide and permeable does the damage zone need to be to promote downward propagation of pore pressures?;
- 3) What effect does an altered basement zone have on hydrogeologic conditions within the crystalline basement?; and
- 4) How does dynamic permeability enhancement in response to excess fluid pressure influence the patterns and depths of the pressure envelope?

Background

127 Data from deep crystalline basement borehole tests indicate that average intrinsic
128 permeability of the rock (k or permeability herein) ranging from 10^{-16} to 10^{-14} m² to
129 depths of approximately 4 km, with extremes varying from 10^{-19} to 10^{-12} m² (Mazurek,
130 1998; Ranjram et al., 2015; Stober & Bucher, 2006, 2015) . A general permeability decay
131 relationship (Figure 1) based on heat flow and metamorphic studies is

$$132 \quad (1) \quad \log(k) = -3.2 \log(z) - 14,$$

133 where depth z is in km and k is in m², predicting a value of $k \sim 1 \times 10^{-18}$ m² in the ductile
134 crust at ~12-14 km depth (Manning & Ingebritsen, 1999). Other studies have found
135 permeability increases in narrowly defined regions. Evans et al. (2005) found that
136 hydraulic fracturing of the 3.5-km-deep Soultz geothermal well resulted in 200-fold
137 permeability enhancement along an existing naturally conductive shear zone near the
138 bottom of the well. The number of conductive fractures increased from about 20 to 100
139 after well stimulation. For tectonically active regions, Ingebritsen & Manning (2010)
140 proposed that their permeability decay relationship be shifted by two orders of magnitude
141 (Figure 1):

$$142 \quad (2) \quad \log(k) = -3.2 \log(z) - 12.$$

143 Estimates of crystalline basement fault and bulk permeability from hydrologic
144 modeling studies of triggered seismicity consistently fall to the right of the Ingebritsen &
145 Manning (1999) curve (Figure 1). Many of these study sites are located in the relatively
146 stable North American craton, so that one might expect them to fall near that curve. We
147 propose that permeability increases associated with water injection could explain this
148 discrepancy.

149 Fault-zone architecture can potentially exert important controls on fluid flow. The
150 permeability of fault-zone architectural elements can vary by several orders of magnitude
151 relative to the host rock, and fault zones can act both as flow conduits and flow barriers
152 (Evans et al., 1997). Open fracture networks greatly increase host-rock permeability,
153 whereas cataclasis and cementation in faults can greatly reduce permeability
154 perpendicular to the fault plane (Caine et al., 1996). The key architectural elements are
155 the fault core and bounding damage zone (Figure 2), both of which differ structurally and
156 mechanically from the undeformed protolith (Caine et al., 1996; Kim et al., 2004; Knott
157 et al., 1996). Grain-size reduction and/or mineral precipitation in the *fault core* generally
158 yields lower permeability than undeformed protolith (Antonellini & Aydin, 1994; Evans
159 et al., 1997). The *damage zone* is the deformed volume surrounding the fault core and
160 may contain fractures over a wide range of length scales, subsidiary faults, veins,
161 stylolites, cleavage, deformation bands, and folds (Berg & Skar, 2005; Faulkner et al.,
162 2010; Wibberley & Shimamoto, 2002). Damage zone structures in crystalline rocks tend
163 to enhance fault zone permeability relative to both the core and the undeformed protolith,
164 and the juxtaposition of these elements (Figure 2) creates major permeability contrasts
165 within the fault zone (Caine et al., 1996; Goddard & Evans, 1995; Wibberley &
166 Shimamoto, 2002). Damage zone permeability can be 2 to 3 orders of magnitude greater
167 than the permeability of fractured protolith and four to six orders of magnitude greater
168 than the fault core permeability (Caine et al., 1996). In some cases, however, core tests on
169 granitic rocks reveal slightly higher core permeabilities relative to the protolith as
170 confining pressure is increased (Evans et al., 1997). This is attributed to the smaller, more
171 poorly connected fractures in the protolith closing more readily than the throughgoing

172 fractures in the fault core. Anisotropic permeability structures are more influenced by the
173 magnitude of permeability contrasts of the fault-zone elements than their absolute values
174 (Caine et al., 1996; Evans et al., 1997). The conceptual model proposed by Caine et al.
175 (1996) evaluates the permeability structure of fault zones by identifying a range of
176 configurations of the three fault zone components: fault core, damage zone, and protolith.
177 These architectural styles are conduits, barriers, and combined conduit-barriers.

178 The presence of low-permeability altered/weathered basement rocks along the
179 sedimentary-basement nonconformity (Figure 3) has been proposed as a potentially
180 mitigating factor for seismic risk (Figure 4; Kerner, 2015). In the cases where
181 nonconformities are seals they behave as confining layers (Zhang et al., 2013). At some
182 field sites in New Mexico (Figure 3) and Colorado these zones exhibit granular flow
183 deformation along a regional nonconformity separating Precambrian crystalline basement
184 and late Devonian-Pennsylvanian sedimentary units. This zone along the nonconformity
185 can be recognized as a distinct hydrogeologic unit due to its unique properties relative to
186 the crystalline basement and overlying sedimentary layer.

187 In this study, we refer to this unit as the *altered zone* and assess the effects of its
188 hydrologic properties on downward pressure propagation. The unit may result from
189 weathering and near-surface alteration prior to burial (Kerner, 2015) or fluid-rock
190 alteration after deposition, such as sericitization of feldspar (Cuccio, 2017). Little is
191 known about the occurrence, lateral continuity, and controls on such zones. In outcrop
192 studies, thicknesses vary between 0 and 7 m over lateral distances of as little as 10-20 m,
193 possibly as a function of pre-burial interface topography (Cuccio, 2017; Cuccio et al.,
194 2016; Hesseltine et al., 2016; Kerner, 2015). A laterally discontinuous altered zone that

195 pinches in and out has less ability to attenuate the downward migration of pore pressures
196 than a laterally continuous zone. The absence of an altered basal seal was noted by
197 Horton et al. (2012) and Zhang et al. (2013) as a potential factor contributing to fluid
198 migration along conductive basement faults near Guy, Arkansas. Few models of fault-
199 controlled induced seismicity explicitly take into account fault-zone architectural
200 elements. Rinaldi et al. (2014) used a hydro-geomechanical model to assess seal failures
201 resulting from CO₂ injection. They incrementally increased the damage zone thickness
202 (5-45 m) and permeability and included brittle failure of protolith and damage zone in
203 their coupled governing equations. The most important factors controlling seal breach
204 and CO₂ leakage were hydraulic and mechanical properties of the damage zone (Rinaldi
205 et al., 2014). Homogeneous, continuous damage zones with relatively high permeability
206 (10^{-15} m²) allowed seal breach. Reducing damage zone permeability by two orders of
207 magnitude (to 10^{-17} m²) resulted in CO₂ containment.

208 Zhang et al. (2013) considered a permeable, 2-m-wide, anisotropic Precambrian
209 basement normal fault ($k_x = 10^{-15}$ m², $k_z = 10^{-13}$ m²) with a proximal (25 m) basal
210 reservoir injection well ($Q = 5455$ m³ d⁻¹). The failure envelope, which encompassed
211 elevated pressures between 60 and 160 m head (0.6 and 1.6 MPa), extended to 4 km
212 depth after 10 years. Zhang et al. (2016) considered fluid migration along a much wider
213 (2 km) conductive ($k = 10^{-14}$ to 10^{-15} m²) fault zone in their analysis of potential linkages
214 between triggered seismicity (mean hypocenter depth ~ 11 km) and oil field brine
215 reinjection adjacent to the Dagger Draw oil field in the Permian basin, NM. In that study,
216 elevated fluid pressures (> 7 m or 0.07 MPa) extended to depths of greater than 10 km
217 after about 6 years of injection. While the 2 km width of that fault zone seems unrealistic,

218 it is possible that hydraulic fracturing in the adjacent crystalline basement rocks increased
 219 the effective width of the damage zone. Here we extend this previous work by closely
 220 examining the impact of realistic fault zone permeability structures and low-permeability
 221 altered zones in facilitating or obstructing downward propagation of pore fluid pressures.
 222 Furthermore, we investigate a potential mechanism of deep, triggered seismic events by
 223 considering the possible role of pressure-driven permeability enhancement in promoting
 224 even deeper regions of elevated pore pressures.

225 **Research Methods**

226 *Groundwater Flow Equation*

227 We use three-dimensional hydrogeologic models to assess fluid migration along
 228 crystalline basement faults using MODFLOW, a public domain groundwater flow model
 229 (Harbaugh et al., 2000; Harbaugh & McDonald, 1996) that solves the following
 230 groundwater flow equation:

$$(3) \quad \frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) = S_s \frac{\partial h}{\partial t} + Q(x, y, z, t)$$

231 where h is the hydraulic head [L], K is the hydraulic conductivity tensor [L T⁻¹], S_s is the
 232 specific storage [L⁻¹], Q is the fluid injection source term (i.e. injection well) [T⁻¹], and t
 233 is time [T]. Equation (3) represents single-phase, constant-density groundwater flow in a
 234 three-dimensional, Cartesian coordinate system. Hydraulic conductivity is a lumped
 235 parameter that includes the influence of fluid and medium properties is defined by $K =$
 236 $k\rho_f g / \mu$, where K is hydraulic conductivity, m s⁻¹; k is intrinsic permeability, m²; ρ_f is

237 fluid density, 997 kg m^{-3} (water); g is the acceleration due to gravity, 9.81 m s^{-2} ; and μ is
238 the dynamic viscosity of the fluid, $8.9 \times 10^{-4} \text{ kg m}^{-1} \text{ s}^{-1}$.

239 *Solution Schemes, Boundary, and Initial Conditions*

240 *Three-dimensional model*

241 Models were run for 19 years with a time step size of 2.5 hours for 1 day,
242 subsequently increasing to 30 days for the remainder of the 19 years. We used a constant
243 injection rate of $5000 \text{ m}^3 \text{ day}^{-1}$ (roughly 1000 gpm) in all simulations. This injection rate
244 falls within the ranges used in other studies such as Keranen et al. (2014) near Jones,
245 Oklahoma, where four high-rate wells had an injection rate of about 4 million barrels per
246 month ($\sim 5,300 \text{ m}^3 \text{ d}^{-1}$). In all cases we placed the injection well within the basal reservoir
247 150 m from the fault zone except for one set of simulations in which we tested the effect
248 of increasing well-fault distance to 1 and 2 km.

249 The model domain is 8 km by 8 km by 10 km (Figure 5) and includes 64 columns,
250 74 rows, and 25 vertical layers (x , y , and z dimensions, respectively; 126,750 nodes). We
251 used localized grid refinement in order to more accurately resolve hydraulic head values
252 near the fault zone, injection well, and the reservoir-basement interface. Horizontal grid
253 discretization (Δx , Δy) was gradually increased from 10 to 630 m, with higher resolution
254 close to the fault zone and increasing grid spacing towards the boundaries. Vertical
255 discretization varied between 8 and 1000 m, with higher resolution near the reservoir-
256 basement interface and increased spacing towards the base of the domain. We used the
257 groundwater modeling software package Aquaveo™ GMS to build the grids and run the
258 simulations.

259 The vertical fault zone in our models was varied between 30-150 m width. In all
260 scenarios, the vertical fault zone extends to the bottom of the model domain. A scenario
261 in which the fault terminates at the reservoir-basement nonconformity is referred to as a
262 Proterozoic fault (Figure 6B). The scenario in which the fault cuts the reservoir (and
263 altered zone, where present) in addition to the basement is termed a Paleozoic fault
264 (Figure 6C-F). The uppermost (injection) horizon consists of two uniformly spaced layers
265 totaling 80 m in thickness. The altered zone between the injection horizon and underlying
266 crystalline basement (when included) is represented by five uniformly spaced layers
267 between 1-20 m in total thickness. In one scenario, we represented a discontinuous
268 (undulating) altered zone by discrete, 20-m-wide fault-parallel blocks such that the
269 altered zone “pinches out” completely in evenly-spaced intervals (Figure 6D inset). The
270 underlying crystalline basement comprises the remaining layers, which increase in
271 thickness from 8 to 1000 m with depth away from the reservoir-basement interface.

272 We imposed no-flux boundary conditions along the top and base of the model, as
273 well as along the north and south lateral boundaries. The top of the model domain
274 represents a basal reservoir overlain by a thick (~3 km) sequence of sedimentary rocks.
275 We assume that the reservoir is overlain by a very tight (i.e. non-leaky, $k < 10^{-19}$ m²)
276 confining unit such that there is no upward pore pressure leakage. We approximate this
277 by imposing a no-flux boundary condition along the top surface. Constant head boundary
278 conditions ($h = 10,000$ m) are enforced along the east and west lateral boundaries, and h
279 $= 10,000$ m was also the initial head value for all cells. These lateral boundaries are far
280 enough away from the injection well and fault zone, and the total simulation time
281 sufficiently short, that simulated head increases were not significantly affected by these

boundaries. In the simulations testing the effect of increased well-fault distance, we likewise placed the right lateral boundary 4 km from the well in keeping with our goal of minimizing boundary effects.

Two-dimensional dynamic permeability model

We also solved a two-dimensional (cross-sectional) form of equation (3) for the dynamic permeability scenarios using MATLAB. We used the Theis (1935) analytical solution to represent pressure buildup (s) at injection well nodes within the reservoir:

$$(4) \quad s = \frac{Q}{4\pi T} W(u), \quad u = \frac{r^2 S}{4Tt},$$

where Q ($\text{m}^3 \text{d}^{-1}$) is the injection rate of the well (positive), T is transmissivity ($\text{m}^2 \text{d}^{-1}$), u is the argument of the well function $W(u)$ (Theis, 1935), r (m) is the radial distance (here taken to be the radius of the injection well), S (dimensionless) is the storativity of the reservoir, and t (days) is time of injection. The well function is approximated by the infinite series:

$$(5) \quad W(u) = -0.577216 - \ln(u) + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} + \cdots + \frac{u^{20}}{20 \times 20!}$$

Permeability was allowed to increase when a threshold head was exceeded (5 m, 10 m), similar to the method specified in Rojstaczer et al. (2008). Their method increased permeability at a pressure threshold between 105%–115% of hydrostatic; at 100 m depth, this threshold range corresponds to roughly 5.1 to 15.3 m excess hydraulic head. The underlying assumption is that ambient fluid pressures are near hydrostatic, and that in any volume of fractured rock there is some appropriately oriented fracture that will slip if the pressure increases by a sufficient amount; the latter assumption is reasonable for the

301 western United States where rocks are critically stressed (Townend & Zoback, 2000).
302 Unlike the Rojstaczer et al. (2008) model, permeability does not decrease with time. We
303 employ a modified version of the predictor-corrector iterative method in order to address
304 the non-linearity introduced by large permeability enhancements (50%) during a single
305 time step. In our implicit finite-difference formulation, we make an initial estimate of
306 head at the next time step ($\hat{h}_{t+1}$). Permeability at this advanced time step ($\hat{k}_{t+1}$) is
307 increased for all cells with estimated heads exceeding the prescribed threshold. We then
308 calculate permeability in the middle of the time step by taking the arithmetic average of
309 the present and future time steps ($k_{t+1/2} = (k_t + \hat{k}_{t+1}) / 2$). We use this time-averaged
310 permeability ($k_{t+1/2}$) to make an improved calculation of head at the next time level
311 (h_{t+1}). We used the Gauss-Seidel method to calculate head changes.

312 Due to the added computational costs of these dynamic permeability simulations,
313 we constrained the dimensions of the model domain to a cross section 250 m wide and
314 10,000 m deep. Computational limitations associated with MATLAB prevented us from
315 running these models longer than 10 days; however, we were able to run the models with
316 static permeability and larger time steps for 4 years, closely approximating the overall
317 propagation depth of the 2-m head contour and well-head pressure of the three-
318 dimensional model, giving us some confidence in the shorter dynamic permeability
319 simulations. Wellhead pressure changes were represented using the Theis solution (4)
320 calculated based on a constant rate of injection ($5000 \text{ m}^3 \text{ d}^{-1}$) for 10 days with time steps
321 of 0.01 days ($\sim 14 \text{ min}$). These pressure changes were specified at two nodes in the
322 reservoir on the right side of the domain located 150 m from the fault zone. We
323 acknowledge that the radial Theis solution applied to a cross-section model is only an

324 approximation of the actual conditions. Imposing Theis head changes at injection nodes
325 is an ad-hoc way of representing injection; if we had assigned the Theis solution to all
326 nodes in the reservoir, we would be imposing heads that assume no leakage in the
327 reservoir, which would be incorrect. These are illustrative, idealized models against
328 which we are not trying to match a particular field situation.

329 The grid discretization is uniform (i.e. non-telescoping). We used a horizontal
330 discretization (Δx) of 5 m and vertical discretization (Δz) of 10 m. The injection reservoir
331 was specified as the top 80 m of the domain and the underlying crystalline basement
332 comprised the remainder. The fault zone was comprised of a fault core 10 m wide and
333 equally-sized damage zone on either side.

334 We imposed a no-flux boundary on the top and bottom of the domain. We
335 imposed a constant head boundary condition (0 m excess head) along the lateral
336 boundaries with the exception of the reservoir injection nodes that had heads prescribed
337 by the Theis solution. An initial condition of $h = 0$ m excess head was used in all model
338 runs.

339 *Hydrogeologic Framework for Sensitivity Studies*

340 Both the three- and two-dimensional models are characterized by a relatively thin
341 (80-m thick) sedimentary layer into which fluid is injected (injection reservoir), overlying
342 thick (≥ 9.9 km) crystalline basement. In some cases, a very thin (1-20 m) altered zone at
343 the reservoir-basement interface serves as an aquitard. A vertical, planar fault cuts the
344 model domain in half and spans its width; its thickness and vertical extent are variable.

345 We consider a range of permeabilities for the altered zone and individual fault-
346 zone components (Table 2). The fault is assumed to be either: (a) not present, (b) a

347 Proterozoic fault hosted solely in the crystalline basement, or (c) a Paleozoic fault hosted
 348 in the basement and cutting the injection reservoir and altered zone (where present).
 349 Throw on the fault is assumed to be negligible. The fault is represented as one of three
 350 fault-zone archetypes: (1) conduit, characterized by elevated permeability compared to
 351 the undeformed host rock; (2) barrier, represented by reduced permeability; and (3)
 352 conduit-barrier, comprising a core region of low permeability surrounded by the highly
 353 permeable damage zone. In the first two cases, the permeability across the fault zone is
 354 homogeneous; the conduit-barrier case is represented by a single low-permeability central
 355 cell with high-permeability cells on either side. Cell permeabilities are generally treated
 356 as isotropic in this study, with the exception of one simulation (run 5 in Table 2) which
 357 produces a conduit-barrier fault zone by assigning anisotropy. For calculating effective
 358 anisotropy of the conduit-barrier fault zones, we use averaging equations for the effective
 359 permeability normal and parallel to the fault (x -axis, z -axis, respectively):

$$(6) \quad \hat{k}_{\perp} = \frac{b_T}{\sum_{i=1}^n \frac{b_i}{k_i}} \quad \hat{k}_{\parallel} = \frac{\sum_{i=1}^n b_i k_i}{b_T},$$

360 where $\hat{k}$ is effective permeability for either the fault-orthogonal ($\hat{k}_{\perp}$) or fault-parallel ($\hat{k}_{\parallel}$)
 361 direction, b is the fault element width, n is the number of fault elements (2, in our case),
 362 and subscript i refers to the respective fault element. For flow parallel to the fault plane ($\hat{k}_{\parallel}$),
 363 the effective permeability is controlled by the higher-permeability damage zone. For
 364 flow perpendicular (across) the fault plane, the low-permeability core has a controlling
 365 effect.

366

367 Table 2 – Permeability (m^2) values varied in sensitivity study.

Model Run	Altered zone k	Fault age	Fault Perm. Structure	Damage zone k (res., a.z., bsmt.)	Core k (res., a.z., bsmt.)	Bulk Fault Zone Perm. (k_x, k_z)	Figure
1	—	—	—	—	—	—	7,8A
2	—	Prot.	conduit-barrier	— 3×10^{-14}	— 3×10^{-16}	—	7,8B
3	—	Pz	conduit-barrier	3×10^{-10} 3×10^{-14}	3×10^{-16} 3×10^{-16}	—	7,8C
4	—	Pz	barrier	—	—	3×10^{-18} 3×10^{-18}	7,8D
5	—	Pz	conduit-barrier	—	—	3×10^{-15} 3×10^{-13}	7E
6	—	Pz	conduit	—	—	3×10^{-14} 3×10^{-14}	7F (dashed), 8E
7	—	Pz	conduit	—	—	3×10^{-14} 3×10^{-14}	7F (contoured), 8F
8	3×10^{-18}	Pz	conduit-barrier	3×10^{-10} 3×10^{-18} 3×10^{-14}	3×10^{-16} 3×10^{-19} 3×10^{-16}	—	10B,C

368 Abbreviations: k , permeability; res., injection reservoir; a.z., altered zone; bsmt., basement; Prot., Proterozoic;
 369 Pz, Paleozoic.

370

371 Results

372 *Effect of Fault-Zone Architecture*

373 For our three-dimensional sensitivity study we first consider the effects of conduit-
 374 barrier Proterozoic and Paleozoic fault zones that include core and damage zones (runs 1-
 375 3 in Table 2). The crystalline basement permeability in all scenarios is $3 \times 10^{-17} \text{ m}^2$ (Evans
 376 et al., 1997; Manning & Ingebritsen, 1999). The vertical (Figure 7) and horizontal (Figure

377 8) patterns of excess pore pressure propagation are strongly controlled by fault zone
378 properties (Table 2). None of these scenarios consider a laterally extensive, low-
379 permeability altered zone; the 80-m-thick injection horizon rests directly on crystalline
380 basement rock. Absent a fault zone, the 2-meter head (0.02 MPa) envelope extends to ~600
381 m depth, diffusing roughly 500 m into the crystalline basement rock (Figure 7A). The
382 deepest penetration of excess heads occurs directly under the injection well. Introducing a
383 30-m-wide Proterozoic conduit-barrier fault zone in which a basement fault terminates at
384 the basement-reservoir interface) extends the 2-m head change envelope to depths of ~2500
385 m. A Paleozoic conduit-barrier fault (i.e. basement fault extending into reservoir rock)
386 produced an excess pore pressure envelope extending to depths of ~2300 m (Figure 7C)
387 with significant flow compartmentalization in the injection horizon (Figure 7, Figure 8C).
388 Elevated pore pressures on the order of 38 m head occur in proximity to the well (within a
389 radius $r = 50$ m) versus only 22 m for the Proterozoic fault (Figure 7B).

390 In other simulations the fault zone was simply assigned bulk properties rather than
391 subdivided into core and damage zone (Figure 7D-F, Figure 8D-F). We considered a
392 barrier fault zone end member by assigning isotropic permeability 4 orders of magnitude
393 lower than the reservoir rock and 1 order of magnitude lower than the crystalline
394 basement protolith ($k = 3 \times 10^{-18}$ m²; Figure 7D, Figure 8D). Elevated pore fluid
395 pressures (≥ 20 m head; 0.2 MPa) built up primarily within the injection reservoir and
396 were highly compartmentalized by the fault (Figure 7D, Figure 8D). Pore pressures
397 diffused into the basement to depths < 700 m. We also computed excess heads for a 30-
398 m-wide conduit-barrier fault zone (Figure 7E) represented using bulk anisotropic
399 permeability with k_z 2 orders of magnitude greater than k_x ; in this case, excess heads were

mapped to a depth of ~4.2 km. When we treated the fault zone as a pure conduit (isotropic k set to 2 orders of magnitude greater than the host rock), widening the fault zone by a factor of 5 (to 150 m) increased the excess pressure propagation depth from ~2300 m (dashed, Figure 7F) to >5300 m (contours, Figure 7F). Pressure was unevenly distributed across the reservoir fault zone despite the lack of a horizontal flow barrier (Figure 8F).

For one simulation (run 3 in Table 2) of a Paleozoic conduit-barrier fault, we tested the effect of injection at greater distances from the fault zone (Figure 9). When the injection well was 2 km from the fault (Figure 9C), there was significant reduction in downward pore pressure propagation (~900 m) due to radial dissipation of excess pressure.

Effect of Altered Zone

Because laterally continuous altered zones occur at some outcrop analogs to modern basal reservoir injection sites (Figure 3), we added a 20-m-thick, low-permeability ($k_x = k_z = 3 \times 10^{-18} \text{ m}^2$) altered zone (Figure 10B) to a Paleozoic conduit-barrier fault with properties identical to those presented in Figure 7C. The continuous altered zone suppresses downward pressure propagation (compare Figure 10A and Figure 10B).

We also represented a spatially heterogeneous altered zone that pinches and swells discretely in 20-m-wide intervals (similar to the conceptual diagram in Figure 6D, inset) in order to test the effect of a laterally discontinuous confining layer. The fault zone in this scenario was not blocked by the altered zone. Elevated pore pressures propagated downward to depths of 2.7 km (Figure 10C) after 4 years of continuous injection.

423 *Effect of Dynamic Permeability*

424 We performed a sensitivity analysis using our MATLAB based cross-sectional
425 model testing the effects of dynamic (i.e. pressure-enhanced) permeability increases on
426 the pore-pressure envelope migration (Figure 11). We varied the differential excess
427 pressure threshold required for permeability enhancement and the hydrogeologic units in
428 which permeability was allowed to increase. Injection reservoir permeability was not
429 allowed to increase for any scenario. The results are compared to the static permeability
430 case (Figure 11A), in which the 2-m hydraulic head contour propagated to a depth of
431 ~1.9 km. When we allow a 50% permeability enhancement per 5-m excess head (0.05
432 MPa) to occur within the core, damage zone, and crystalline basement, the 2-m pore
433 pressure contour extends to 3.5 km depth (Figure 11B). Permeability is enhanced within
434 the core to the point that elevated pore pressures bleed over the left side of the fault.
435 Permeability is enhanced to the prescribed maximum (2 orders of magnitude increase)
436 within the damage zone flow conduit and also within the basement rock down to depths
437 of ~1.4 km. When we restrict dynamic permeability enhancement to the damage zone and
438 apply the same permeability enhancement criteria, we see focused propagation of fluid
439 pressures, with the 2-m head contour extending to roughly the same depth (~3470 m)
440 below the injection horizon (Figure 11C). For similar conditions, with the exception of
441 increasing the excess head threshold to enhance permeability from 5 to 10 m (Figure
442 11D), we observe reduced migration depth of the pore pressure envelope (2.5 km),
443 though still increased from the static permeability scenario (1.9 km; Figure 11A).

444

445 **Discussion**

446 When we assume no fault zone or low-permeability altered zone is present and
447 invoke representative injection-reservoir and crystalline-basement permeabilities (3×10^{-17}
448 m^2), the buildup of elevated pore pressures within the basement extends to depths of
449 less than 600 m (Figure 7A) after four years of constant injection into the basal reservoir.
450 Such conditions may be similar to the case of induced seismicity in Youngstown, Ohio
451 (Kim, 2013), and not all injection-induced earthquakes are necessarily caused by pressure
452 migration along conductive fault zones. It is clear, however, that in the scenarios we
453 considered, some other feature must be present to allow propagation of elevated pore
454 pressures to crystalline basement depths of 2-10 km (Zhang et al., 2016) where we expect
455 large, damaging induced earthquakes. Two main possibilities exist: either the bulk
456 permeability of the crystalline basement is higher than previous work suggests, or the
457 injected fluids encounter a high-permeability fault and/or fracture zone(s). Several fault-
458 zone architectures allow elevated pore fluid pressures to penetrate to significant depths
459 within the crystalline basement rock.

460 Conduit-barrier fault zones represented by high-permeability damage zones and
461 lower-permeability cores were effective in transmitting fluids to depths of 2.3-2.5 km
462 (Figure 7B, C), similar to the depths of triggered seismicity observed in Guy, Arkansas
463 (Horton, 2012). A Paleozoic fault zone was able to compartmentalize flow within the
464 reservoir (Figure 8C) due to its low- k core, while also promoting preferential downward
465 flow along the higher- k damage zone (Figure 7C), despite damage-zone permeability an
466 order of magnitude less than that of the injection reservoir.

467 This study used a very high-rate injection well ($Q = 5000 \text{ m}^3 \text{ d}^{-1}$) in the nearby
468 vicinity of a fault zone (150 m). Wellhead pressures are directly proportional to the

469 injection rates. While high, this injection rate is consistent with the injection rates in other
470 hydrogeologic models of induced seismicity (Keranen et al., 2014; Zhang et al., 2013,
471 2016). Furthermore, we invoked a single well, whereas wastewater disposal areas may
472 have well densities greater than 1 km^{-2} . Injection in the Illinois Basin found that injection
473 at adjacent wells leads to overlapping envelopes of increased pressure (Bandilla et al.,
474 2013). Pressure response is magnified by pressure change interference patterns resulting
475 from the interaction of multiple injection sites. Multiple adjacent wells injecting fluid at
476 lower rates could also produce elevated pressures similar to those in the present study.

477 We performed two simulations of wells injecting at greater distances of 1 km
478 (Figure 9B) and 2 km (Figure 9C) from a Paleozoic conduit-barrier fault zone. Increasing
479 the well distance to 1 km reduced the propagation depth of the pore pressure envelope to
480 1.9 km (Figure 9B), significantly larger than the un-faulted scenario that did not result in
481 elevated pressures below 600 m (Figure 9A). Increasing the well distance to 2 km from
482 the fault zone caused the excess pore pressure envelope to migrate to only ~900 m depth
483 within the basement (Figure 9C).

484 Representing the conduit-barrier fault zone by multiple architectural elements
485 with highly contrasting, isotropic permeabilities ($k_{\text{damage zone}} = 100 \times k_{\text{core}}$) hindered flow
486 across the fault plane and promoted flow parallel to the fault plane (Figure 7C). Overall
487 patterns closely approximated those of the simulation with a bulk anisotropic fault zone
488 ($k_{\parallel} = 100 \times k_{\perp}$; Figure 7E), but with shallower depths of penetration. By averaging the
489 fault permeability properties (Equation 6), we determine that the individual fault zone
490 architectural elements create an effective permeability anisotropy in the basement fault
491 zone whereby the ratio of orthogonal to parallel fault zone permeability ($k_{\perp} / k_{\parallel}$) was

0.04, whereas for the simulation with assigned anisotropy this ratio was 0.01. This is consistent with the observed shallower depths of pressure propagation for the fault zone represented by individual architectural elements.

Although realistic fault-zone architectural elements and permeabilities in our model effectively transmitted elevated pore pressures to depths of about 2.5 km, we are unable to explain much deeper (>10 km depth) instances of seismicity (Zhang et al., 2016) without introducing a wide or very high-permeability fault zone (Figure 7F). We examined pressure-induced dynamic permeability enhancement as one possible way to increase pressure transmission in a multi-component conduit-barrier fault zone (Figure 11). Our dynamic permeability simulations ran for only 10 days rather than 4 years, as in the three-dimensional model, because of computational costs. Dynamic permeability enhancement expands the pore pressure increase envelope relative to the static permeability simulation (Figure 11A). The geometry and extent of expansion depends on which hydrogeologic units undergo permeability enhancement, and on the enhancement parameters (e.g. the excess pressure threshold required to trigger enhancement). Great increases in penetration depth occurred when pressure thresholds were low (5 m excess hydraulic head, or 0.05 MPa; Figure 11B, C). Dynamic permeability enhancement over 10 days extended the pressure front migration depth to from 1.9 km to 3.5 km in these scenarios. .

We present such models as idealized proof-of-concept simulations. For the dynamic permeability scenarios, we used an arbitrary but representative overall maximum magnitude (100-fold) of permeability increase (Evans et al. 2005). We did not formally couple groundwater flow with geomechanical deformation, nor did we consider

515 changes in shear or normal stress in calculating failure (Rutqvist et al., 2016). It is worth
516 noting that permeability enhancement in the field is not aseismic – fracture stimulation is
517 generally accompanied by microseismicity caused by very small shear dislocations
518 (Evans et al., 1995). However, most seismic networks are not nearly dense enough to
519 detect this level of microseismicity, and quantitative insight into the resulting changes in
520 fracture permeability can only be accurately determined within or very close to the
521 borehole. It is therefore not always clear whether permeability enhancement will occur
522 based on pressure alone; critically stressed faults/fractures do not occur everywhere and
523 not all are well connected – our model assumes both are true.

524 Evans et al. (2005) showed that massive fluid injections into relatively low-
525 permeability crystalline basement rock ($\sim 10^{-17} \text{ m}^2$) focused 95% of the flow at just 10
526 discrete fractures. The resultant permeability enhancement occurred primarily within
527 these preexisting fractures while also creating local, newly permeable fractures. Our
528 model restricting permeability stimulation to the fractured damage zone is analogous.
529 Permeability enhancement in the fault core is less likely because there is often a high
530 degree of alteration that reduces the likelihood of brittle failure (Kerner, 2015).
531 Hydrothermal alteration, which is commonly present in granite fault cores (Evans et al.,
532 2005), tends to suppress dilation from shear dislocations (Sausse, 2002). Illite present in
533 altered crystalline fault core can also clog pores and microcracks (Evans et al., 2005;
534 Sausse & Genter, 2005).

535 Several recent triggered earthquake sequences can potentially be explained by
536 conductive fault zones and/or dynamic permeability. Hornbach et al. (2015) attributed a
537 series of deep earthquakes (up to 5 km below the injection interval) in the Fort Worth

538 Basin in 2013 to downward pressure propagation within a fault system. Assuming very
539 low (10^{-19} m^2) granite permeability, they posited preferential flow along higher
540 permeability damage zone conduits parallel to the fault. The injector wells in their study
541 were roughly 2 km away from the fault zone.

542 Conductive fault zones may have also played a role in the 2014 triggered seismic
543 sequence in Milan, KS. Choy et al. (2016) calculated bulk hydrologic diffusivity between
544 0.3 and 2.0 m s^{-2} ($k \sim 3 \times 10^{-14}$ and $2 \times 10^{-13} \text{ m}^2$) to explain a large mainshock occurring
545 3.5 km below the injection interval of wells located 4-8 km away, 5 months after a rapid
546 increase in injection rates. Such permeabilities are quite probable within the Arbuckle
547 Formation and the uppermost basement; however, an alternative scenario is similar to
548 that presented in Figure 9B, wherein pressures propagate horizontally within the injection
549 reservoir and then downward parallel to the fault plane.

550 The Fairview, OK triggered earthquake sequence in early 2016 (Yeck et al., 2016)
551 is a possible example of hydraulic fracturing owing to far-field pressurization. This
552 sequence exhibited diffuse seismicity near the clustered highest-rate wastewater injection
553 wells. The majority of large seismic events occurred 12+ km to the southwest, along part
554 of a 14-km-long fault segment. While the authors posit that the permeable ($k \sim 1 \times 10^{-12}$
555 m^2) Arbuckle injection horizon could have transmitted elevated pressures reflecting a
556 sevenfold increase in injection rates from mid-2014 to mid/late-2015, preferential flow
557 paths along conductive fault zones might also have served to propagate increases in fluid
558 pressure. Yeck et al. (2016) ruled out any impact from sporadic daily variation in well
559 operations, calculating that this would require permeability between 2.5×10^{-11} and $3.5 \times$
560 10^{-10} m^2 , roughly 1-3 orders of magnitude greater than the largest permeabilities observed

561 in previous cases of induced seismicity. However, hydraulic stimulation could possibly
562 have served to increase permeability to this degree, allowing short-term variations in well
563 injection rates to play a role in seismicity.

564 Some of our simulations depicted a thin, laterally continuous altered zone at the
565 reservoir-basement interface, and confirmed our hypothesis that such a unit could
566 significantly reduce the depth of pore pressure front propagation (<500 m) into the
567 basement, even in the presence of a conductive fault zone (Figure 10B). Field
568 observations in New Mexico and Colorado by Kerner (2015) suggest that reduced
569 permeability is caused by surficial weathering pre-burial and circulation of hydrothermal
570 fluids post-burial. The fault zone in the altered layer typically remains unfractured due to
571 the semi-ductile behavior of its phyllosilicate matrix (Kerner, 2015); for this reason,
572 conduit and conduit-barrier fault zones generally do not communicate through the altered
573 zone (Figure 10B). However, ongoing fieldwork reveals, in some locations, spatially
574 heterogeneous altered zones that pinch and swell along the nonconformity, reducing its
575 overall ability to inhibit pressure transmission.

576 **Conclusions**

577 Conductive fault zones represented by realistic permeability architecture are a
578 viable mechanism for transmitting elevated fluid pressures from a basal injection horizon
579 to considerable depths (~2.5 km) within crystalline basement rock. We hypothesize
580 dynamic permeability enhancement caused by excess pressures to be a potential
581 mechanism for triggering deeper induced events (6-10 km) and confirm that this process
582 can greatly increase the depth of pressure front propagation. We also note the
583 effectiveness of even a thin (5-20 m), laterally continuous altered zone at the reservoir-

584 basement interface in hindering the downward propagation of elevated pore pressures
585 that could otherwise be transmitted by conductive faults. However, more field and core
586 log observations are needed to confirm both the existence and lateral continuity of this
587 distinct hydrogeologic unit.

588

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595

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Figure 1 - Hydraulic diffusivities and permeabilities derived from model reconstructions of triggered seismicity studies (boxes and vertical lines) and crustal permeability trends inferred from geophysical, petrological, and geophysical data (red and blue lines). The red permeability-depth curve is from Manning & Ingebritsen (1999). The blue permeability decay curve is from Ingebritsen & Manning (2010). The permeability axis assumes a specific storage coefficient of 10^{-6} m^{-1} . The gray boxes are permeabilities reported by Zhang et al. (2016) for the Dagger Draw oil field in southeastern New Mexico (Figure from Zhang et al., 2016).

Figure 2 - (A) View of typical fault zone architectural components including undeformed host rock, fractured damage zone, and central fault core. (B) Conceptual plot of order-of-magnitude permeability variation along an imaginary transect across the fault zone showing increased permeability in the damage zone (yellow) and reduced permeability in the fault core (gray) (Adapted from Rinaldi et al., 2014).

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770 Figure 3 - Field outcrop showing an altered zone located along a basal nonconformity in the Sangre
 771 de Cristo Mountains near Las Vegas, NM (Adapted from Kerner et al., 2015).
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775 Figure 4 - Conceptual diagrams showing relative risk of injection-induced seismicity given (A) lack
 776 of altered zone/basal seal and (B) presence of altered zone/basement seal (gray) (Adapted from
 777 Kerner, 2015).

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780 Figure 5 - MODFLOW model domain grid discretization and boundary conditions presented in (top)
 781 plan view, and (bottom) cross-sectional view. No-flux boundary on top of model domain simulates
 782 a very tight (i.e. non-leaky) confining unit overlain by a thick (~3 km) sequence of sedimentary
 783 rocks.

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787 Figure 6 - Hydrogeologic framework used in sensitivity analysis (not to scale): (A) Unfaulted case,
 788 (B) Proterozoic conduit-barrier fault; (C) Paleozoic conduit-barrier fault; (D) Paleozoic conduit-
 789 barrier fault with a laterally continuous altered zone as a basal seal and also showing (inset) a
 790 discontinuous or undulating altered zone; and permeability architecture end-members: (E) conduit
 791 fault zone, and (F) barrier fault zone. Note that top of the model domain is intended to represent a
 792 confined basal reservoir overlain by thick (~3 km) sequence of sedimentary rocks (not shown).

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Figure 7 – Cross-sectional views of pore pressure envelope propagation after 4 years of constant-rate injection with no altered zone. Simulations presented are: (A) unfaulted (B) Proterozoic conduit-barrier fault zone (C) Paleozoic conduit-barrier fault zone, (D) Paleozoic barrier fault zone assigned bulk isotropic properties ($k_x = k_z = 3 \times 10^{-18} \text{ m}^2$), (E) Paleozoic conduit-barrier fault zone assigned bulk anisotropic permeabilities (basement $k_x = 3 \times 10^{-15} \text{ m}^2$, $k_z = 3 \times 10^{-13} \text{ m}^2$), and (F) Paleozoic conduit fault zones assigned bulk isotropic permeabilities (basement $k_x = k_z = 3 \times 10^{-14} \text{ m}^2$), both for a thin (30-m-wide) fault zone (dashed line) and a thick (150-m-wide) fault zone. Vertical gray lines indicate location of the fault zone, and horizontal gray line denotes the reservoir-basement interface. Injection takes place 150 m to the right of the fault zone within the reservoir (well location indicated).

Figure 8 - Plan view of pore pressures within the injection reservoir layer after 4 years of constant-rate injection with no altered zone and (A) no fault zone, (B) Proterozoic conduit-barrier fault zone, (C) Paleozoic conduit-barrier fault zone, (D) Paleozoic barrier fault zone assigned bulk isotropic properties ($k_x = k_z = 3 \times 10^{-18} \text{ m}^2$), (E) thin (30-m-wide) Paleozoic conduit fault zone, and (F) wide (150 m) Paleozoic conduit fault zone. Both conduit fault zones were assigned isotropic permeabilities (basement FZ $k_x = k_z = 3 \times 10^{-14} \text{ m}^2$). Injection takes place 150 m to the right of the fault zone.

Figure 9 - Effects of variable injection well distance from a Paleozoic conduit-barrier fault zone. Well distances (A) 150 m (identical to Figure 7C), (B) 1 km, and (C) 2 km. Injection well location is indicated on top of each panel. Transition from gray to dark blue contour denotes a 2-m increase in hydraulic head (0.02 MPa).

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837 Figure 10 - Excess heads after 4 years of constant-rate injection for a Paleozoic conduit-barrier
 838 fault scenario (A) absent an altered zone (identical to Figure 7C), (B) with an altered zone present
 839 as a continuous 20-m-thick confining layer, and (C) with a discontinuous altered zone that pinches
 840 in and out in 20-m horizontal intervals but reservoir and basement fault zones fully connected
 841 (similar to Figure 6D inset). Transition from gray to dark blue contour (and all subsequent contour
 842 lines) denotes a 2-m increase in hydraulic head (0.02 MPa).

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850 Figure 11 - Simulations testing the effect of pressure-controlled dynamic permeability enhancement
 851 on pore pressure envelope migration depth along a Paleozoic conduit-barrier fault (vertical gray
 852 lines delineate central core and damage zone) after 10 days of pumping. The following scenarios
 853 were tested: (A) static permeability, (B) 5-m head threshold enhancing permeability step-wise by
 854 50%, with permeability allowed to increase everywhere except the injection reservoir, (C) 5-m
 855 pressure threshold enhancing permeability step-wise by 50%, with permeability allowed to increase
 856 only in the fault damage zone, (D) 10-m pressure threshold enhancing permeability step-wise by
 857 50%, where permeability can only increase in the damage zone. Dotted line shows the extent of
 858 the static permeability result in A for comparison. Results shown for the top 5 km of the model
 859 domain with 10x horizontal exaggeration. Injection well location is indicated on top of each panel.

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