Testing the Efficacy of Active Pressure Management as a Tool to Mitigate Induced Seismicity

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Abstract

It has been suggested that industrial operators may modify injection or production rates to actively manage fluid pressures in disposal reservoirs as a means of reducing the risk of induced seismicity. We evaluate the efficacy of such active pressure management (APM) techniques by coupling a multiphase reservoir model, NUFT, with the earthquake simulator, RSQSim. We simulate-seismicity induced by CO_2 injection into a brine saturated reservoir near an optimally oriented fault. Fluid overpressure in the reservoir is modified by co-productionof brine at various fractions of the injected CO_2 volume from one of five potential wells.

We evaluate the performance of the operation in terms of the total number of seismic events and the maximum event magnitude. Results indicate that APM methods may be used to control fluid overpressure and subsequently reduce the risk of induced events. Simulations such as those presented here will aid in the design of a field management plans geared toward maximizing CO_2 volume disposal while limiting the risk of induced seismicity.

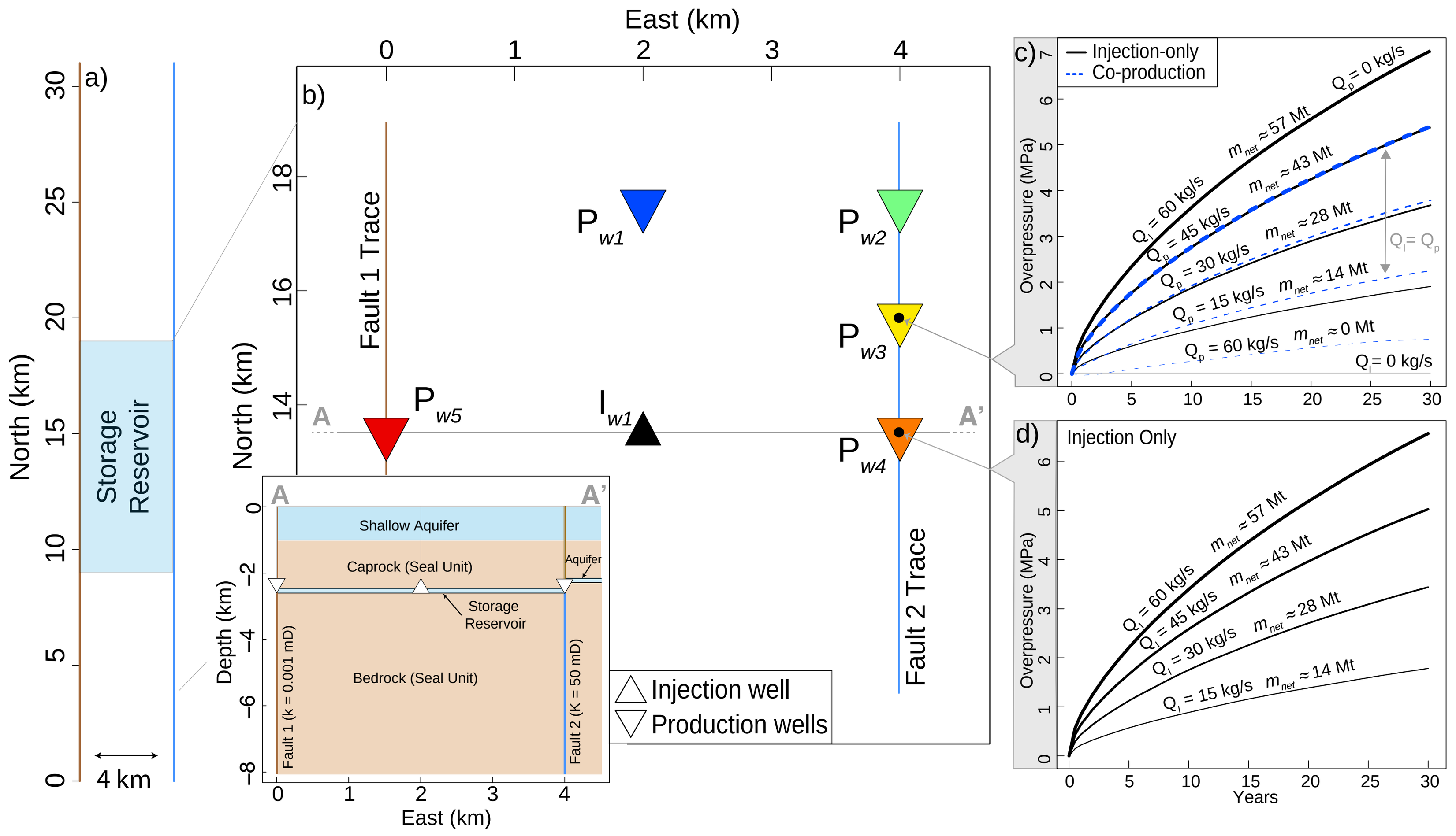
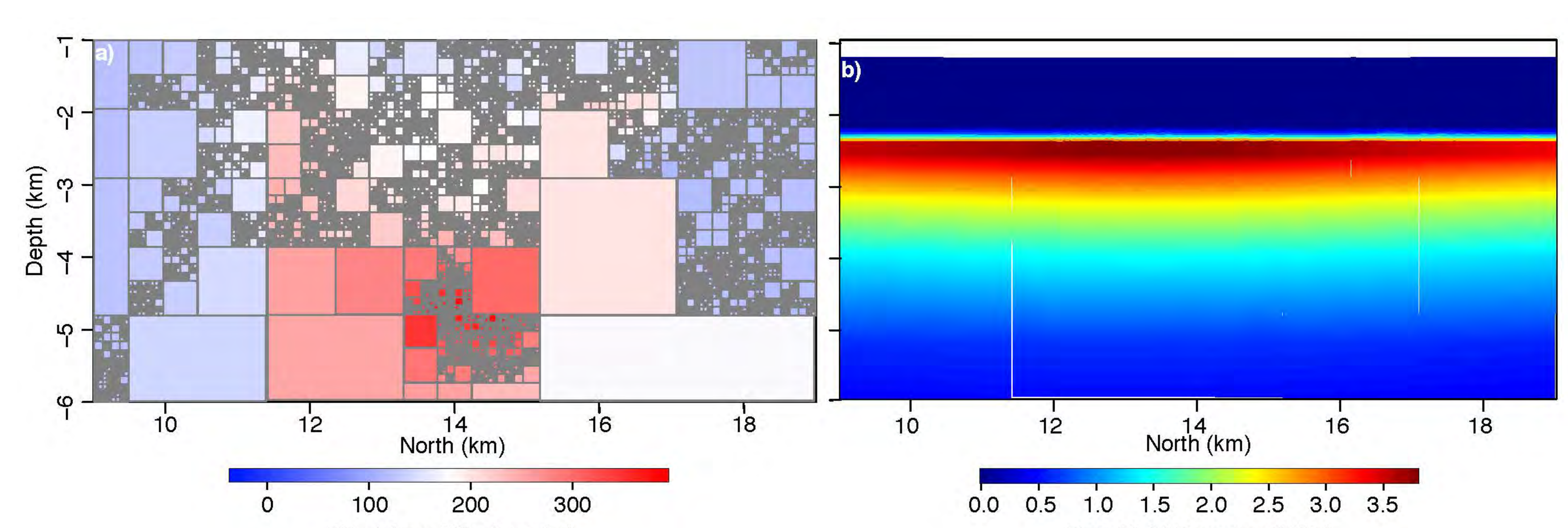


Figure 1: a) Overview map of the computational domain used in the reservoir simulation. b) Map of storage reservoir, the CO_2 injection well location (I_{w1}) and five potential production well locations, P_{w1-w5}. Inset shows a schematic cross-section of the storage complex between A and A'. The disposal reservoir is located at depths between 2400 m and 2600 m. Depths of injection and production wells are given by the right-side-up and up-side-down triangles, respectively. overpressure are evaluated on the eastern-most, high permeability fault. The fault trace used in RSQSim extends from 1 to 6 km depth. c) Overpressure at a point (black circle) on the fault surface equidistant between I_{w1} and P_{w1} for a reservoir model with injection-only (solid black lines) and injection plus co-production from P_{w1} (dashed blue lines). Injection rates and the associated net equivalent CO_2 injection mass (m_{net}) are listed for each curve. Injection and production rates are equal, unless otherwise noted. d) Overpressure on the indicated point along the fault that arises from injection-only operations.

Modeled Fault Surface



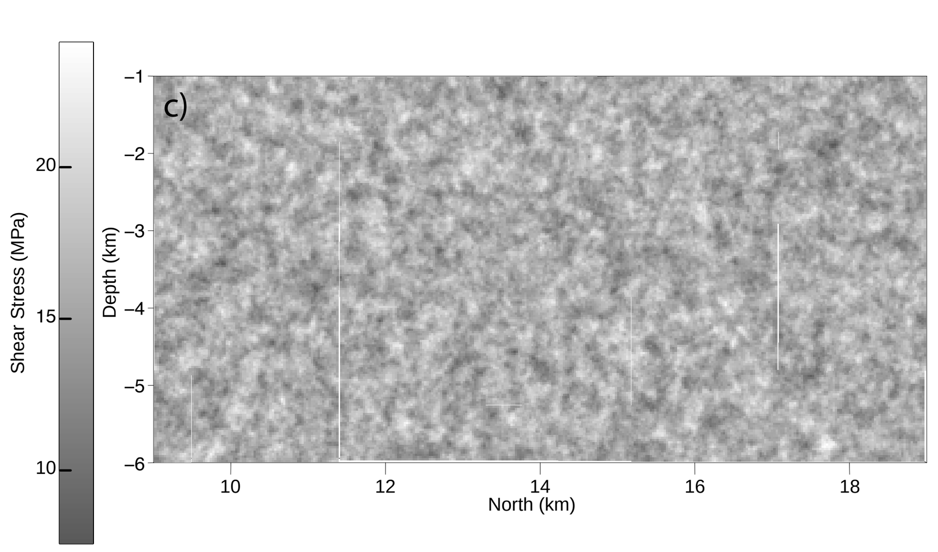


Figure 2: a) Fractally segmented fault surface used in the earthquake simulation. Color represents the horizontal offset from the north-south plane. Each planar segment is tiled in 30 m elements. b) Example of the fluid overpressure that develops on the fault surface after 30 years of injection at a constant rate of 45 kg/s, with no co-production. c) Map of the pre-existing shear stress field employed in all simulations in this study. The heterogeneous stress fieldis generated using the von Kármán auto-correlation function (Goff and Jordan, 1989; Mai and Beroza, 2002) as described by Kroll et al., 2017. Here, the Hurst exponent, correlation length, standard deviation of the amplitude of the heterogeneity are 0.8, 60 m, and 2 MPa, respectively, with a random seed.

Simulated Catalog Results

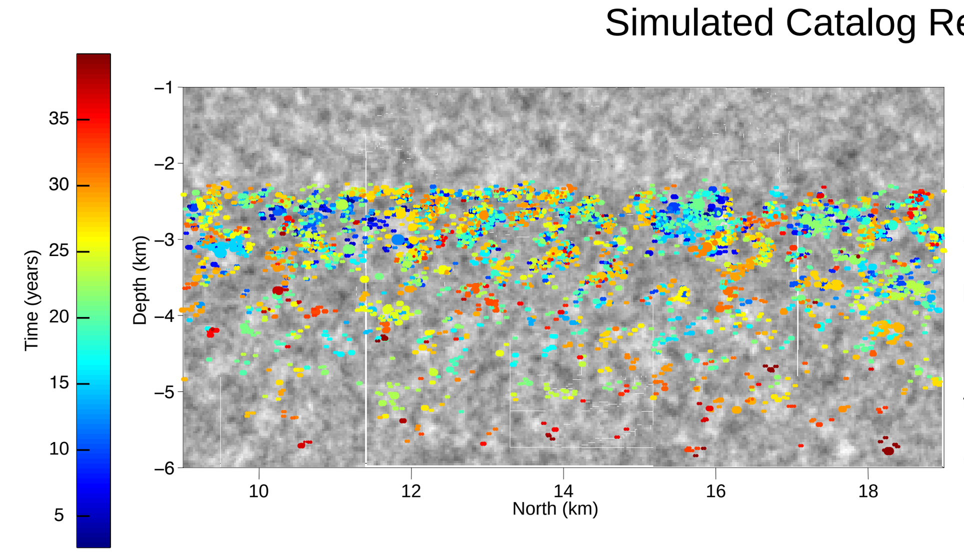


Figure 3: Event hypocenters plotted for the synthetic catalog example shown in Figure 5. Hypocenters are colored by time. Gray scale corresponds to the distribution of pre-existing shear stress shown in Figure 2. Random noise of 15~m (half the element size) is added to the depth and along-strike component of the hypocenter locations.

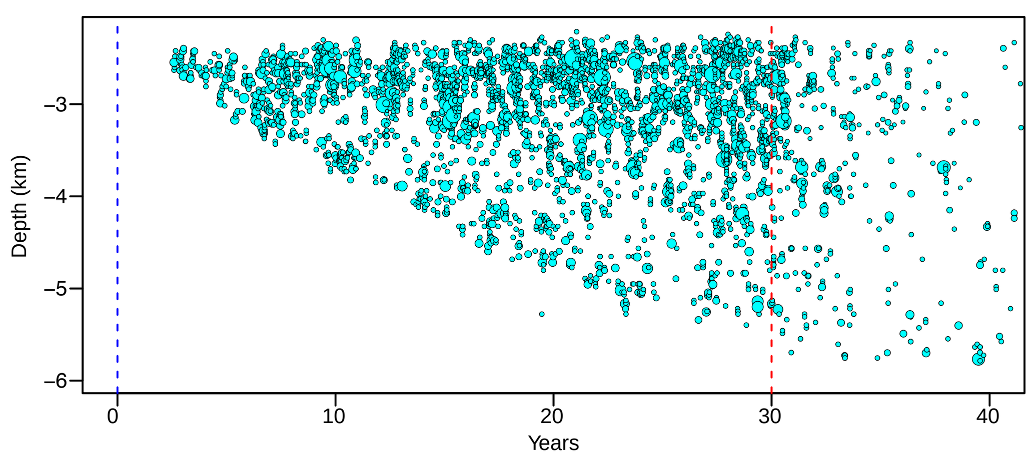


Figure 4: Distance-time distribution for the synthetic catalog example shown in Figures 2 , 3, and 5. Distance is define as the difference in depth of event hypocenter and the bottom of the storage reservoir at -2.6 km. Injection begins at 0 years and continues for 30 years before the well is shut-in. The size of each circle is scaled by the event magnitude.

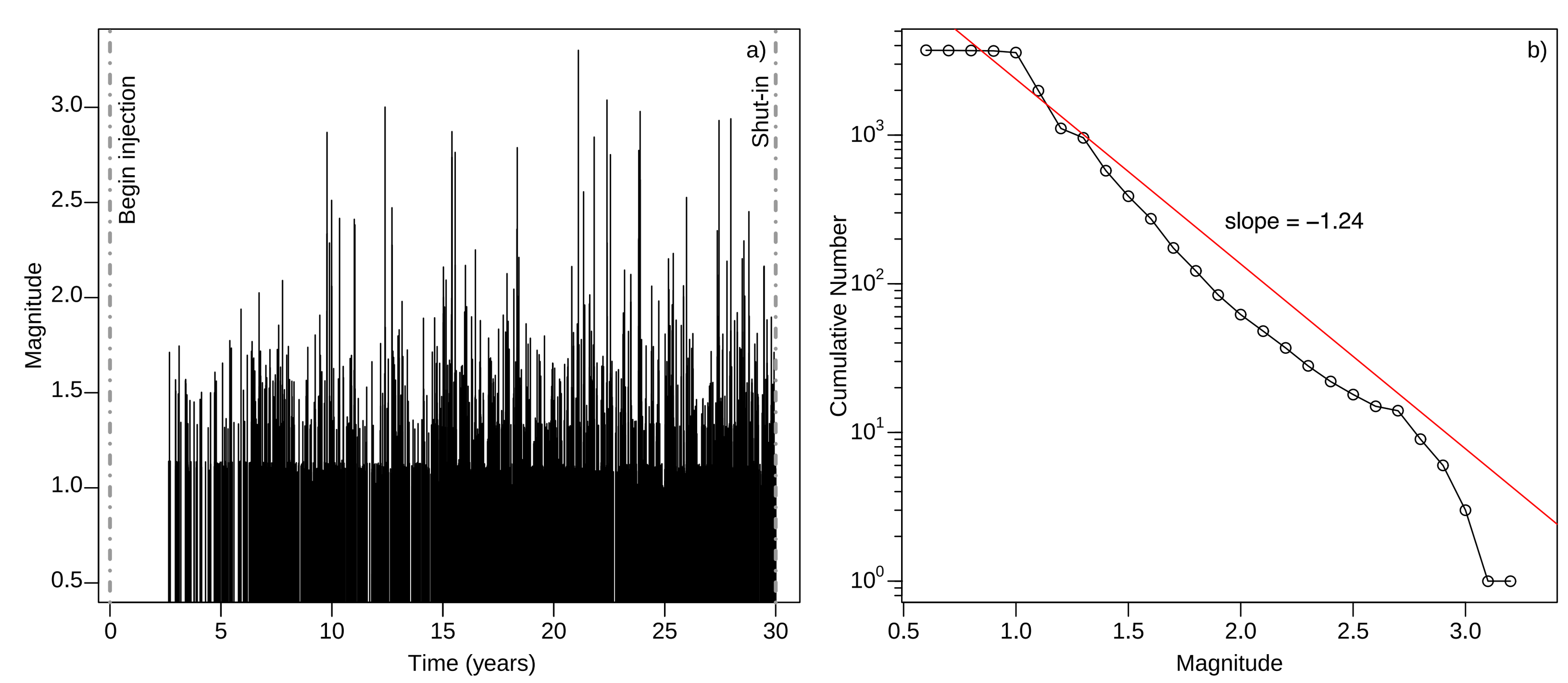


Figure 5: a) Example of a synthetic earthquake catalog generated for the $0.50I_{w1}$scenario (i.e. injection-only simulation of ~28 Mt of CO_2. The distribution of overpressure computed for this scenario is given in Figure 2b. a) Event magnitude as a function of time after injection begins at 0 years. b) Frequency-magnitude distribution for the synthetic catalog in (a).

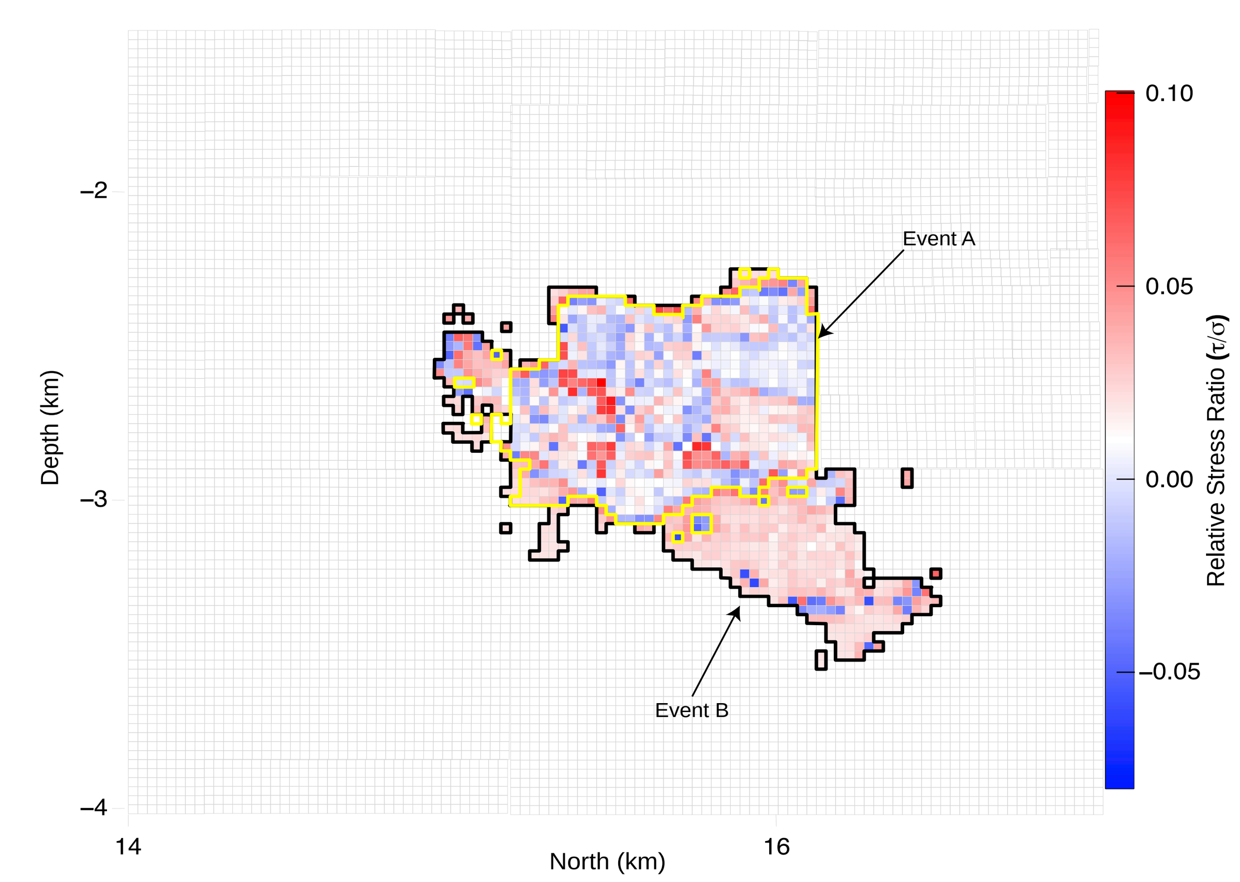


Figure 6: Relative stress ratio distribution over the rupture area of two similar events. The rupture area for Event A is outlined in yellow and is the largest event in the $0.50I_{w1}$ simulation with injection-only (M_w3.3; t_0 = 21.1 years). The rupture area for Event B is outlined in black and is the largest event in the $0.50P_{w5}$ with injection plus co-production (M_w3.5; t_0= 28.3 years). The color of each element that ruptured in each event represents the "relative stress ratio" or the ratio of the shear stress to the effective normal stress on that element. Co-production in the $0.50P_{w5}$ scenario has the effect of delaying the time of the largest event, however, this allows the overpressure to affect a larger region of the fault towards the south. This shear stress in this region is higher (as shown by the warmer colors) and allows the Event B to propagate farther than Event A. The average relative stress ratio for elements that rupture in Event B is 20% larger than that for elements that rupture in Event A.

Active Pressure Management Impact on Induced Seismcity

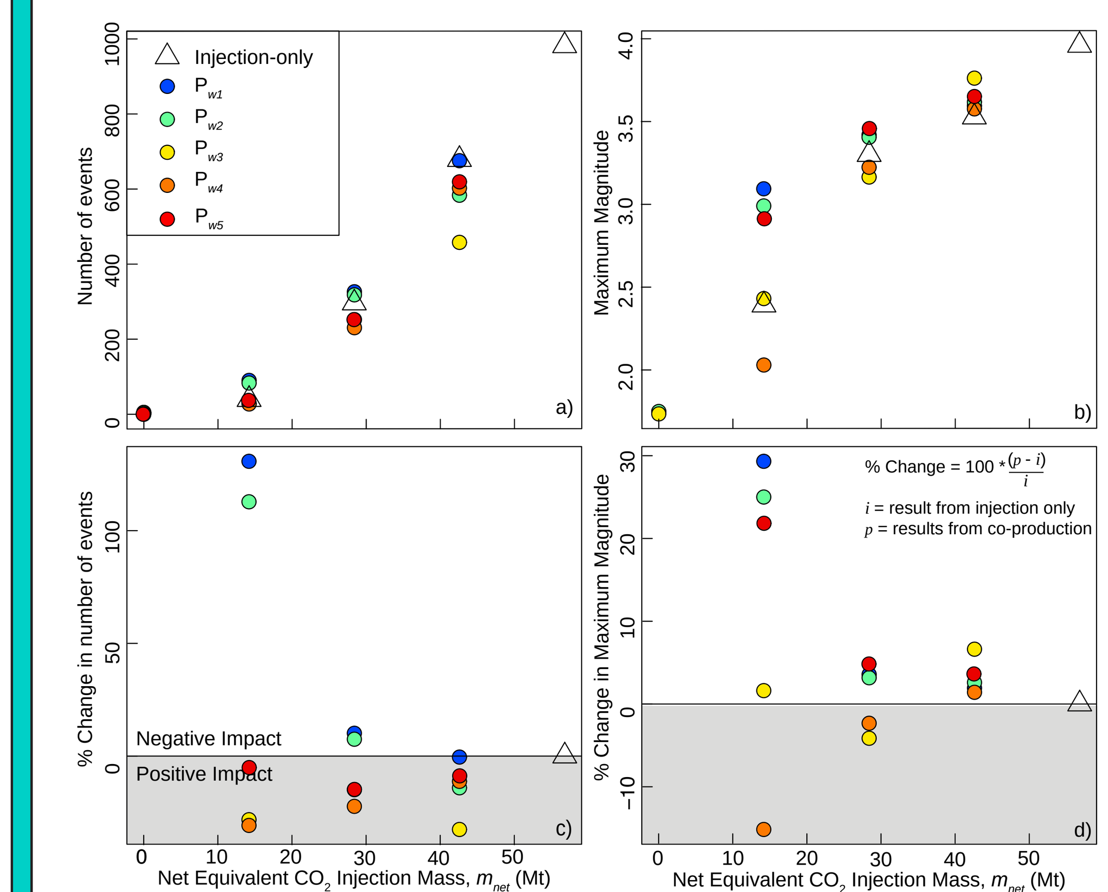


Figure 6: The effect of co-production on the total number and maximum magnitude of induced events for the 25 scenarios evaluated. a) The total number ofseismic events that arise in simulations with co-production resulting in the given m_{net}, color coded by production well location (Figure 1a). Open triangle represents the number of events that result from injection-only operations at the listed m_{net}. b) Results for the maximum event magnitude. Panels (c) and (d) represent the percentage change (inset in d) in the total number and maximum event magnitude compared to the reference case for each m_{net}. The shaded region in each panel highlights simulations that result in a positive impact on the performance metrics.

Note, for m_{net} ~0 Mt simulations, there are 5, 5, and 3 events in the P_{w1} through P_{w3} scenarios, respectively. The maximum magnitude in each of those scenarios is 1.75, 1.75, and 1.74, respectively. For M_{net}~0 Mt simulations there are zero events in the P_{w4} and P_{w5} scenarios. In all panels, there are also no co-production results shown for M_{net}~58 Mt because co-production volume of 0~Mt as that is simply the reference case.

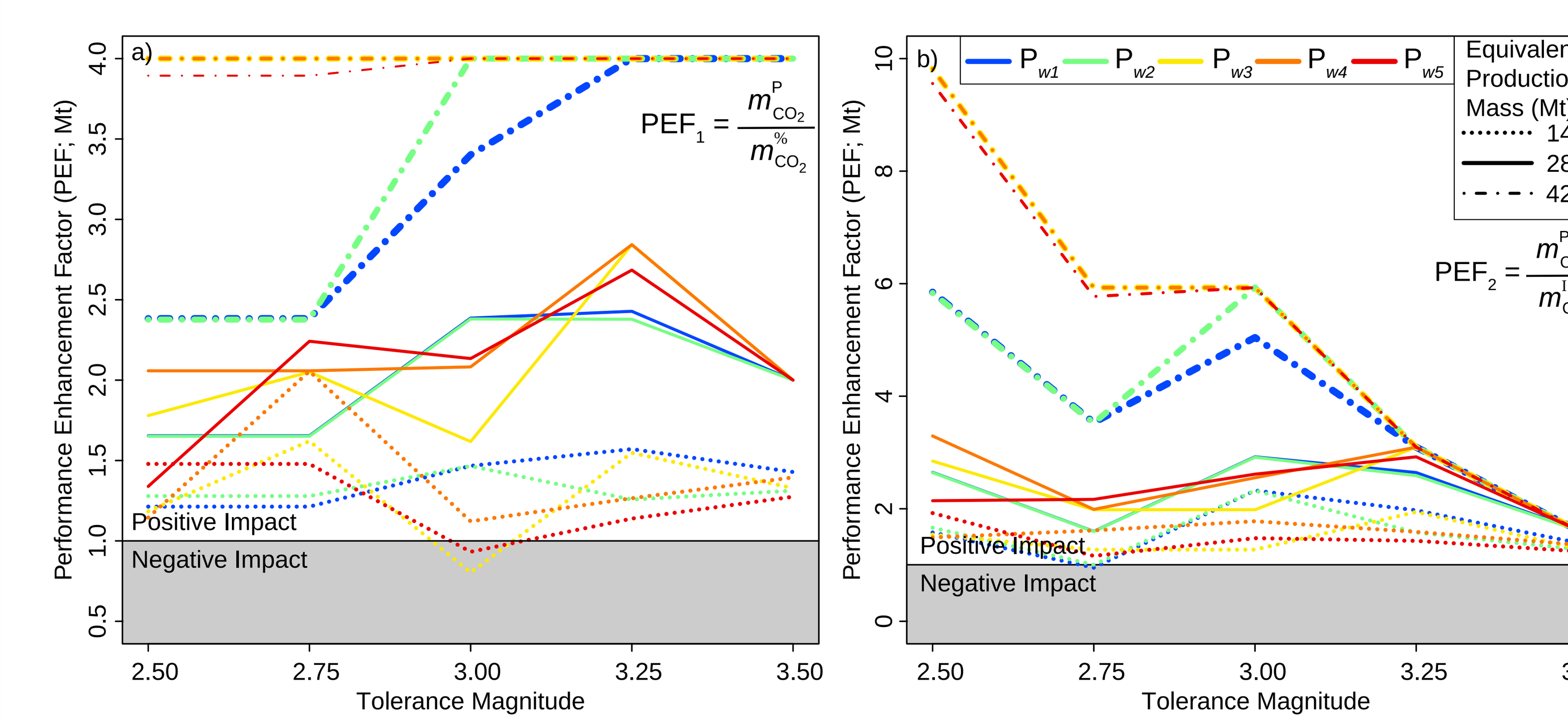


Figure 7: Performance enhancement with co-production. Results are presented in terms of the performance enhancement factor (PEF) that describes that improvement in performance achieved through this APM strategy. The PEF is evaluated based on the total volume of CO_2 injected before regulatory shut down due to the occurrence of a seismic event exceeding a tolerance magnitude. In panel (a), PEF_1 is defined as the ratio of total injected fluid before shut down of operations with co-production, $m^{p}_{CO_2}$, to the total injection fluid in operations with injection-only at at the equivalent m_{net}, $m^{\%}_{CO_2}$. In panel (b) PEF_2 is defined as the ratio between $m^{p}_{CO_2}$ and the total injected fluid before shut down of operations where no APM strategies are employed, $m^{i}_{CO_2}$ (i.e. injection-only operations at the maximum rate and volume). In each panel, the line style represents the co-production volume and the color represents a production well location. Any performance enhancement factor larger than 1, indicates that the APM strategy has a positive impact on the volume of CO_2 stored before the exceedance of the threshold magnitude.

Conclusions

While the results presented here are for an idealized case, they suggest that APM via injection plus co-production may be a viable tool for reducing the risk of induced seismicity. These methods may be particularly useful at reducing risk along a large, known fault that is capable of generating moderate earthquakes. Because the most useful scenarios involve co-production of large volumes of brine, this form of active pressure management may be most useful in CCS settings where CO_2 is considered a "riskier" fluid than brine. APM may be especially advantageous if brine can be treated at the surface and does not needto be disposed of elsewhere.

It is imperative to development field management plans that reduce the risk of induced seismicity related to large-scale CCS and wastewater disposal operations. These plans must consider a variety of factors, including economic considerations, the availability of existing wells, total fluid volume to be stored, available active pressure management tools, and the relative risk of causing alarming earthquakes. Simulations like those presented here, especially when informed with site-specific field data, can provide critical insight to help develop well-informed management plans.