Ground Expansion and Seismic Hazard Induced by the Hutubi Natural Gas Repository, Xinjiang, China

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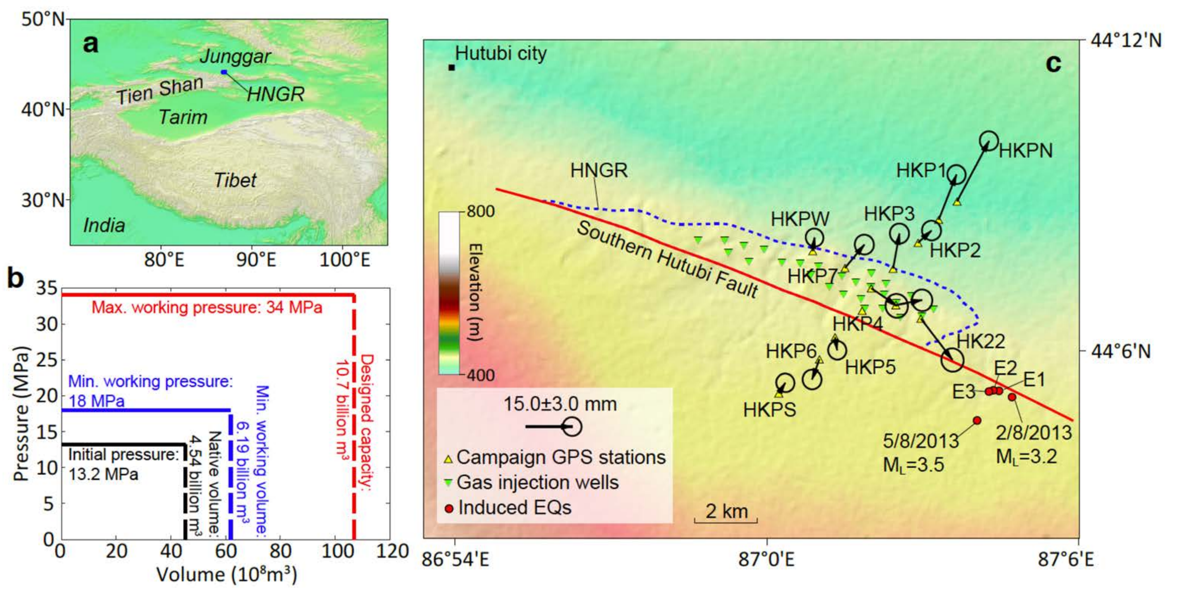
1. Introduction

Although increasing seismologic observations reveal numerous earthquake hazards linked to anthropogenic activities, ground displacements were only detected in several induced earthquake regions using InSAR and leveling approaches (*e.g., Vasco et al., 2010; Thienen-Visser and Breuness, 2015; Shirzaei et al., 2016*). Moreover, these limited studies always focused on surface uplift or subsidence induced by fluid injection/extraction, with little attentions on the horizontal deformation. On the other hand, geodetic observations of ground deformation have been demonstrated effective in assessing the natural seismic hazards, whereas very preliminary attempts were conducted for induced earthquakes.

To date, the Hutubi natural gas repository (HNGR), located near the boundary between Tien Shan and Junggar Basin, Xinjiang Province, is the largest underground gas storage facility in China. Two seismologic and geodetic studies reveal that the operation of the HNGR has induced both seismicity and ground displacements.

- The seismologic study found that five $M_L \geq 3.0$ earthquakes occurred only 52 days after the operation on 9 June 2013 with distances of only 2.2-3.0 km from the HNGR. (*Tang et al., 2018*).
- The geodetic study only investigated the vertical displacements measured by GPS and InSAR and found they were contaminated by groundwater extraction. (*Qiao et al., 2018*).

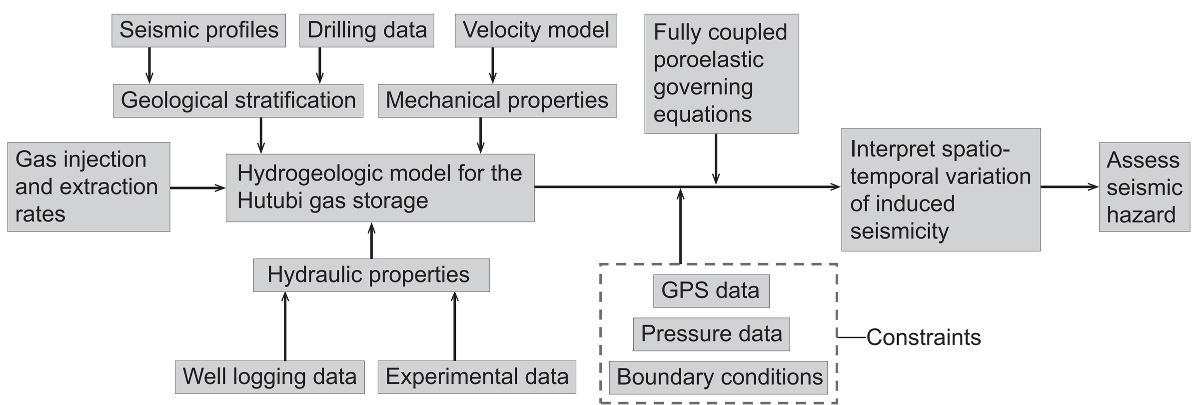
Therefore, the HNGR is a unique case with both induced earthquakes and ground displacements, due to cyclic gas injection and extraction.



Here, we focus on horizontal GPS observations and make efforts to extract robust displacement signals linked to the cyclic gas injection and extraction of the HNGR. In addition, a hydrogeologic model for the HNGR is built up by using multiple geologic and geophysical data. Fully-coupled poroelastic simulation is conducted to investigate the physical mechanisms of ground displacements and induced seismicity, and also to assess the induced seismic hazard.

- Detect robust horizontal displacements and unveil its physical mechanism
- Determine the physical mechanism of induced seismicity and assess its hazard.

2. Methodology



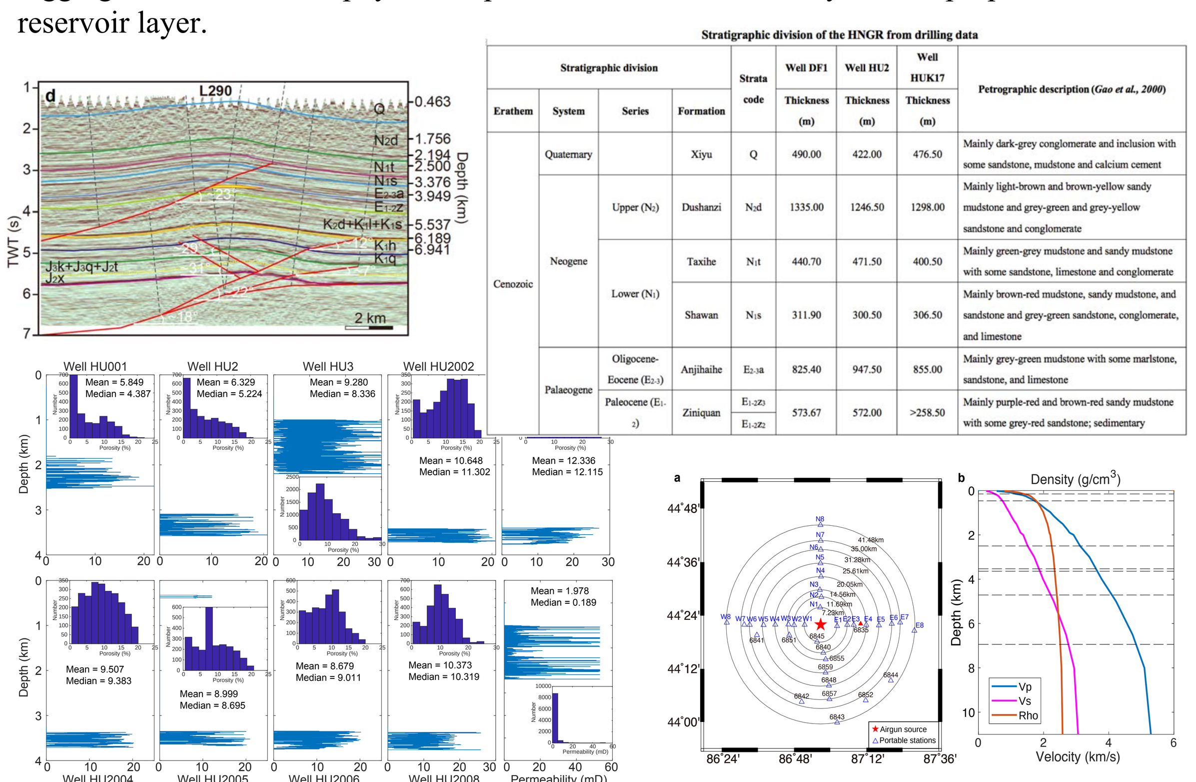
To inspect the physical mechanism behind the induced seismicity and to evaluate the seismic hazard linked to the HNGR, we propose a physical-based scheme based on fully coupled poroelasticity (*Rice and Cleary, 1976*).

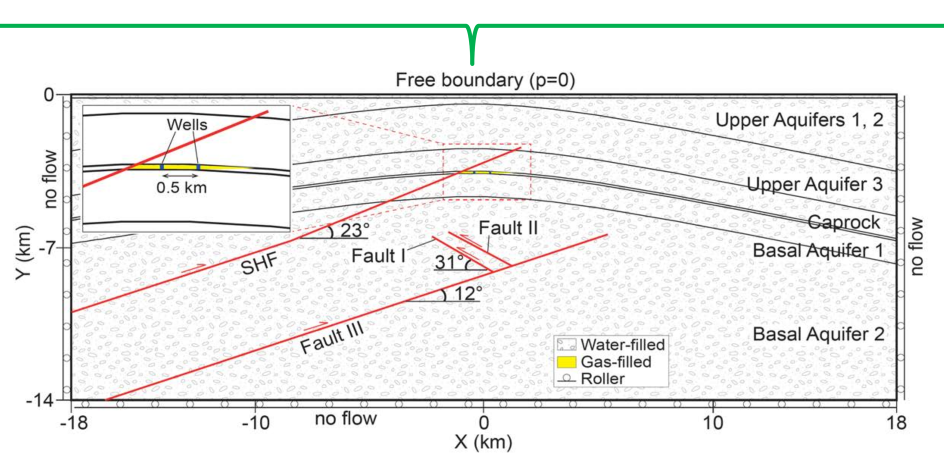
- Build up a hydrogeologic model for the HNGR based on multiple geologic and geophysical data.
- Calibrate the hydraulic parameters of the reservoir layer using constrains from GPS observed horizontal expansion and well-head pressure changes.
- Interpret the physical mechanism of saptio-temporal variation of induced seismicity.
- Assess seismic hazard including the occurrence range of induced seismicity and the maximum potential earthquake.

Besides, in our study, COMSOL Multiphysics is employed to conduct numerical simulation.

3. Hydrogeologic model

A hydrogeologic model is essential for investigating the physical mechanism of observed ground expansion as well as seismicity induced by the HNGR. We built up a 36-km-wide and 14-km-deep 2D model based on multiple geophysical and geological data including five seismic profiles, drilling data, local velocity model refined by an airgun source, well logging data, and rock physics experiment results of the hydraulic properties of the reservoir layer.





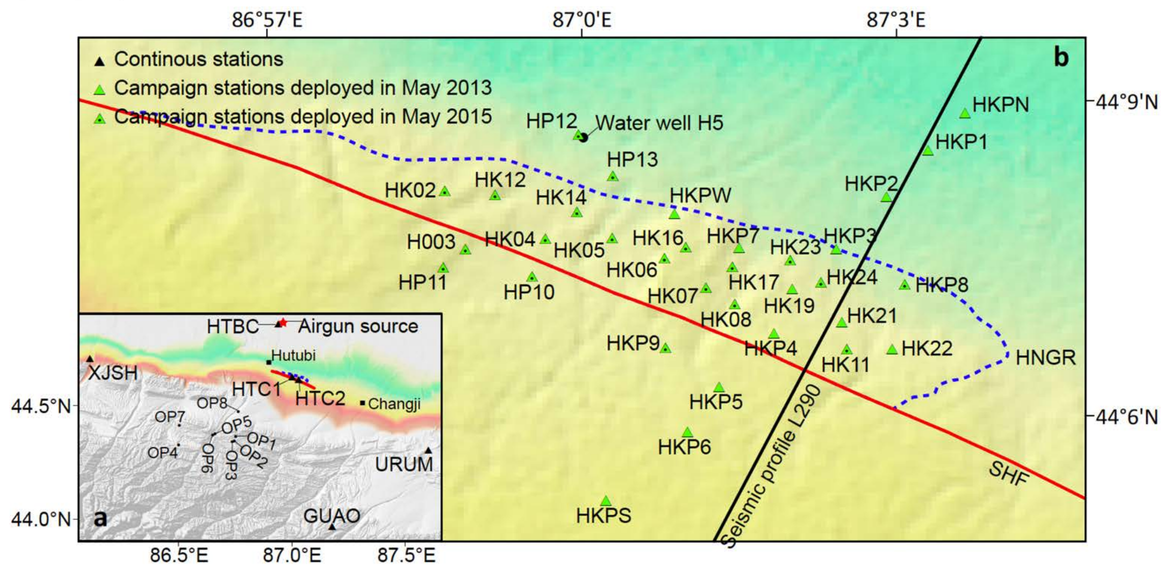
Layer	Thickness (km)	Density (kg/m³)	Young's modulus (GPa)	Poisson's ratio	Porosity (%)	Permeability (mD)	Viscosity (Pa s)	Compressibility (Pa⁻¹)
Upper Aquifer 1	0.150	1132	0.44	0.39	12	22[b]		
Upper Aquifer 2	0.313[a]	1681	2.10	0.39	8			
Upper Aquifer 3	2.037	2038	5.99	0.38	6	0.2		
Caprock	1.030	2334	21.06	0.32	2	0.00001		
Reservoir	0.110	2362	24.37	0.31	3~30 (20[c])	0.1~1000 (250[c])		
Basal Aquifer 1	1.072	2394	28.68	0.30	5	0.001		
Basal Aquifer 2	2.229	2488	44.09	0.27	5	0.01		
Faults	0.010	2488	44.09	0.27	5	0.0001		
Gas[d]		154					2.12×10^{-5}	1×10^{-5}
Water[e]		1000					55×10^{-5}	0.42×10^{-9}

4. Induced horizontal ground expansion

Our local GPS network includes 3 continuous stations and 33 campaign stations.

- 13 campaign stations started the first observation in November 2013.
- 20 campaign stations started the first observation in November 2015.
- 3 continuous stations started to work since 13 November 2015 and 1 April 2016, respectively.

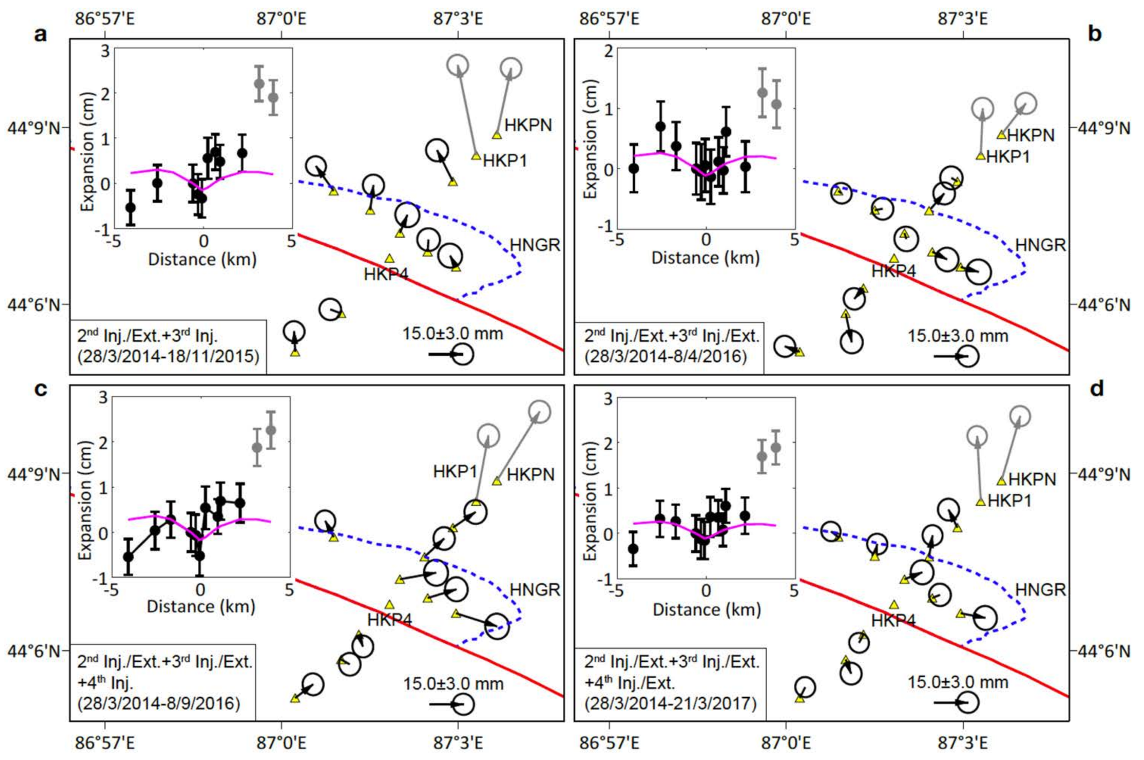
The latest campaign observation was conducted in November 2017. Besides, we also collected observation data from 3 Crustal Movement Observation Network of China (CMONOC) stations surrounding the HNGR to evaluate the influence of groundwater pumping.



We employed a classical method to process the GPS data. The resulting times series of the 13 station were used to process the cumulative horizontal ground displacements of five time periods for more observations and cross-validation. The cumulative displacements were further referenced to station HKP4 near the HNGR center for two purposes:

- to remove the regional deformation trend included in the cumulative displacements,
- to only represent the horizontal ground displacements induced by the HNGR .

Furthermore, we projected the relative displacements into the direction perpendicular to the strike of the southern Hutubi fault (SHF).



Taking no account of two stations HKP1 and HKPN with extremely large displacements probably contaminated by groundwater extraction, the observed maximum horizontal expansion increases with gas injection phases from 1.02 cm to 1.57 cm, spanning ~1.5, ~2.5, and ~3.5 years , respectively. The other two intervals with equivalent injection and extraction phases (Panel b and d) have a close maximum value of 0.8 cm. The maximum expansion magnitudes correlate with the gas volume changes in the HNGR.

All the horizontal displacement profiles exhibit a similar deformation pattern that ground expansion is symmetrically distributed on both southwest and northeast sides of the HNGR, characterized by minimum magnitudes occurring at the center and increasing laterally, similar to the theoretical horizontal deformation trend.

More quantitative evaluation to the influence of groundwater extraction using 6 continuous GPS stations reveals that, in the study region, the controlling factors of the observed horizontal GPS profiles and vertical displacements are totally different.

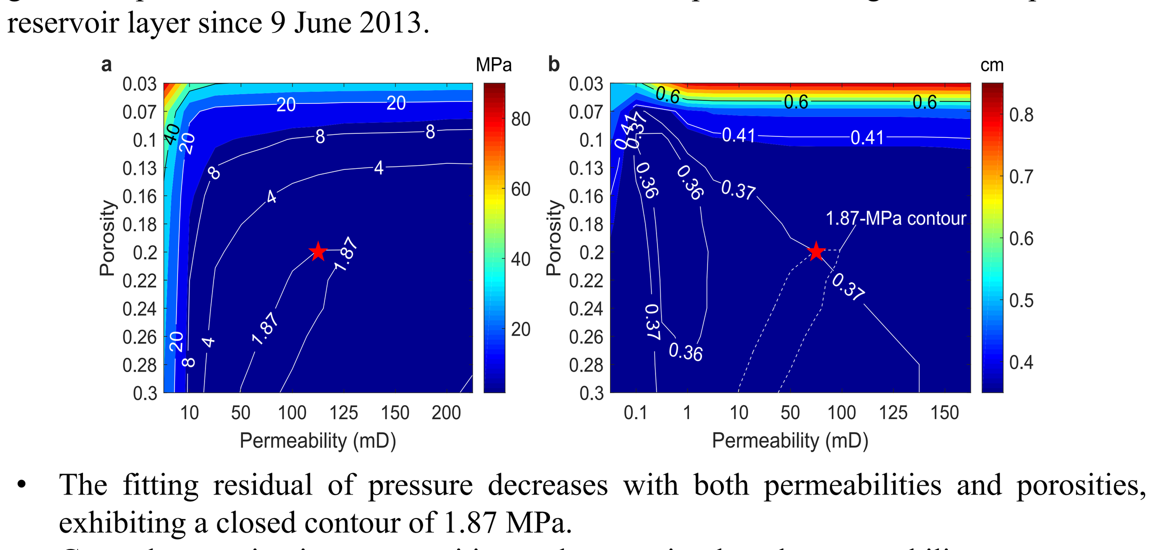
- Horizontal ground expansion is mainly induced by cyclic gas injection-extraction.
- Vertical GPS observations are controlled by groundwater pumping.

5. Calibration of poroelastic model

The porosity and permeability of the reservoir layer play a significant role in investigating subsurface fluid flow and stress perturbation, further for assessing seismic hazards. However, both of them determined by above well logging and rock physics experiment data have large ranges and need to be optimized. Here, we use grid search to identify the hydraulic properties of the reservoir layer jointly using the observed pressure changes and ground expansion data.

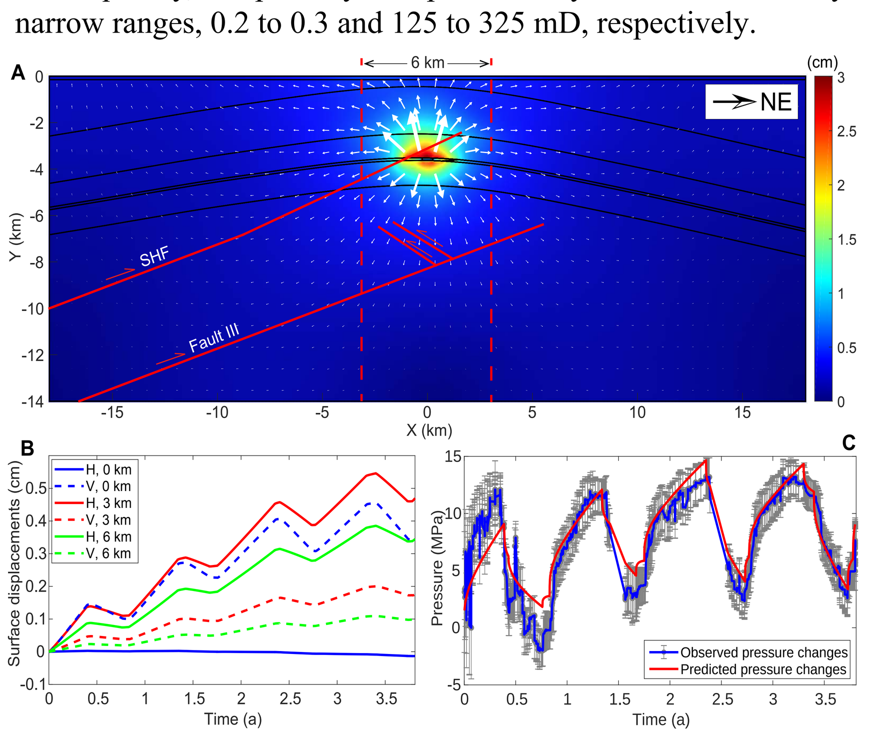
- We increased the porosities and permeabilities of the reservoir layer from 0.03 to 0.3, and from 0.01 to 1000 mD, respectively, to conduct numerical simulation.
- The simulated horizontal displacements and bottom-hole pressure changes were compared with the observations.

Based on the same fitting criteria used to determine the permeability of the two upper aquifers (*McCaffrey, 2005*), the RMS residuals between the simulation results and observations should be close to the observation errors, namely, 0.41 cm for horizontal ground expansion and 1.87 MPa for the bottom-hole pressure changes at the depth of the reservoir layer since 9 June 2013.



- The fitting residual of pressure decreases with both permeabilities and porosities, exhibiting a slightly closed contour of 1.87 MPa.
- Ground expansion is more sensitive to the porosity than the permeability.
- Around the 1.87-MPa contour, all the displacement misfits are close to 0.37 cm, slightly larger than the average error of the four expansion profiles.

Consequently, the porosity and permeability of the reservoir layer are confined to very narrow ranges, 0.2 to 0.3 and 125 to 325 mD, respectively.

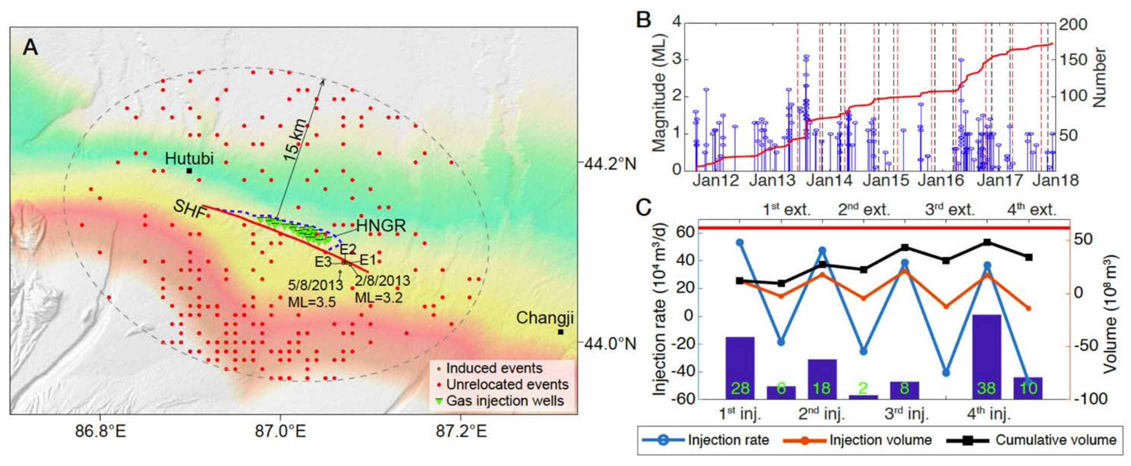


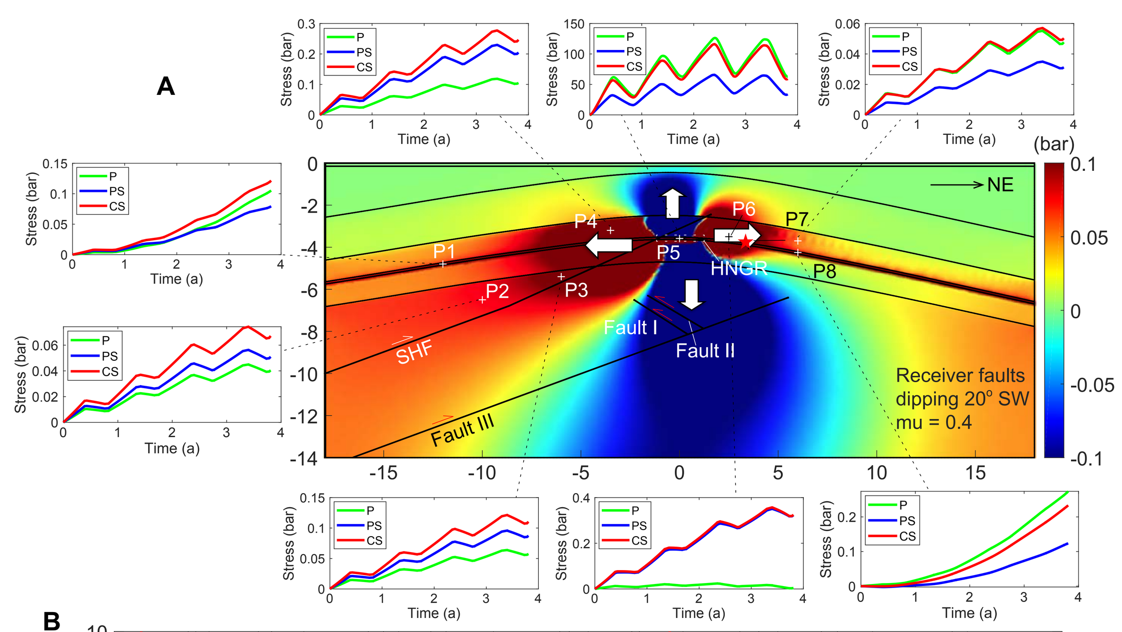
We selected a pair of hydraulic parameters (porosity of 0.2, permeability of 50 mD) to simulate the first four gas injection-extraction cycles up to 30 April 2017. Our numerical simulation reveals:

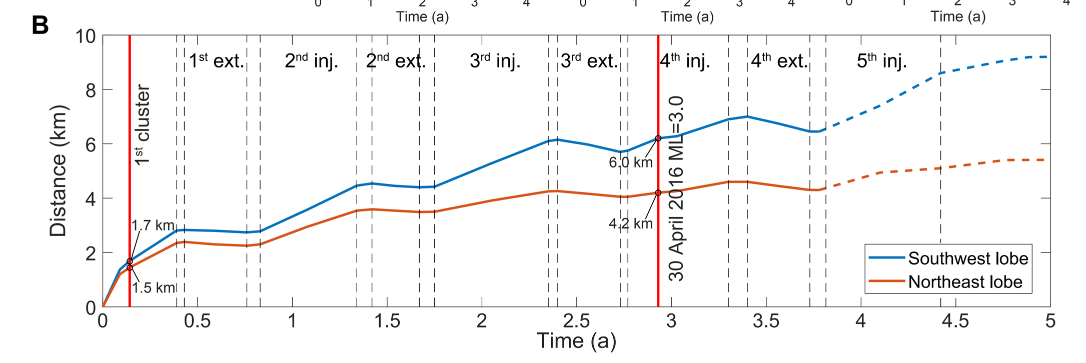
- The magnitude of horizontal ground expansion increases laterally from the HNGR center and reaches the maximum at ~3 km from the center, then decreases gradually.
- The largest expansion after four injection phases approximates 0.55 cm.
- The maximum uplift at the center is only 0.45 cm and then decreases laterally.
- At the distance of 6 km from the center, the horizontal ground expansion is about four times larger than the uplift at the end of the 4th injection phase.

Therefore, attentions should be also put on horizontal displacements induced by fluid injection into a deep reservoir, not only on the vertical displacements (*Shirzaei et al., 2016; Teatini et al., 2011*).

6. Physical mechanism of induced seismicity



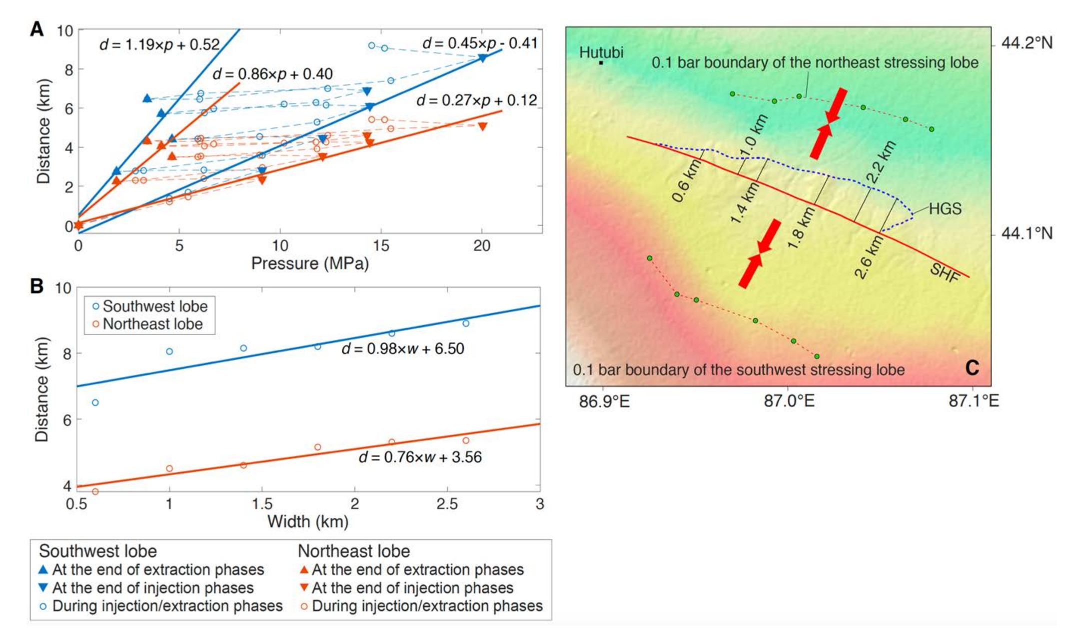




To further investigate the physical mechanism of induced seismicity, we calculated Coulomb stress changes induced by the HNGR. cyclic gas injection and extraction raised Coulomb stress in both sides of the HNGR.

- Coulomb stress increase in the two lobes attributes to poroelastic loading.
- Cyclic gas injection and extraction led to self-expansion and further extruded the surrounding region.
- Induced seismicity probably only occurs on the thrust faults dipping to the southwest in the southwest and northeast stressing lobes .
- Sharp increase of induced seismicity depends on the distances of secondary faults off the HNGR.

7. Induced seismic hazard



To assess potential seismic hazard, we conducted the simulation to make the HNGR be up to the designed maximum working pressure of 34 MPa.

- The 0.1-bar boundaries of the southwest and northeast stressing lobes can extend to distances of 8.5 km and 5.1 km, respectively.
- The two lobe sizes correlate linearly with the pressure at the ends of both injection and extraction phases.

If the lobe sizes without growing, the seismicity would not increase anymore.

The maximum magnitude of induced earthquakes depends on the scale of secondary southwestward thrust faults located in the two stressing lobes. We are interpreting 3D artificial seismic reflection surveying data provided by PetroChina for spatial distribution of secondary faults.

8. Conclusions

We provide a physical-based framework to investigate the physical mechanism of ground expansion and seismicity induced by the HNGR and to assess the associated seismic hazards including location and maximum magnitude.

- The maximum horizontal ground expansion observed by GPS is up to 1.57 cm.
- A hydrogeologic model is built up by integrating multiple geophysical and geological data.
- A method is developed to characterize the hydraulic properties of the reservoir layer using GPS and pressure data.
- Fully-coupled poroelastic simulation reveals that the horizontal ground expansion larger than uplift.
- Physical mechanism of induced seismicity is likely poroelastic loading.
- Dramatic increase of seismicity is associated with the distances of secondary faults off the HNGR.
- The potential earthquakes will only occur on the thrust-slip faults dipping to the southwest in the southwest and northeast stressing lobes.
- The sizes of the two lobes would continue extending to about 9.2 km and 5.4 km off the HNGR on the northeast and southwest sides, respectively, after achieving the maximum working pressure of 34 MPa under current regional tectonic background stress.

Therefore, multi-disciplinary observations can be incorporated into a hydrogeologic model to make a proactive earthquake hazard assessment before the construction of UGS facilities. Our framework is applicable for other cases of induced seismicity associated with UGSs, CGS, and WD into conductive reservoirs, and can provide a reference for seismicity induced by hydraulic fracturing, enhanced geothermal system, and WD into conductive reservoir layers.

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