

Article

Pore pressure analysis for distinguishing earthquakes induced by CO₂ injection from natural earthquakes

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Abstract: It is important to distinguish between natural earthquakes and those induced by CO₂ injection at carbon capture and storage sites. For example, the 2004 Mw 6.8 Chuetsu earthquake occurred close to the Nagaoka CO₂ storage site during gas injection, but we could not quantify whether the earthquake was due to CO₂ injection or not. Here we simulated changes of pore pressure during CO₂ injection at the Nagaoka site and compared them with estimated natural seasonal fluctuations of pore pressure due to rainfall and snowmelt as well as estimated pore pressure increases related to remote earthquakes. We clearly distinguished changes of pore pressure due to CO₂ injection from those due to rainfall and snowmelt. The simulated local increase in pore pressure at seismogenic fault area was much less than the seasonal fluctuations related to precipitation and increases caused by remote earthquakes, and the lateral extent of pore pressure increase was insufficient to influence seismogenic faults. We also demonstrated that pore pressure changes due to distant earthquakes are capable of triggering slip on seismogenic faults. The approach we developed could be used to distinguish natural from injection-induced earthquakes and will be useful for that purpose at other CO₂ sequestration sites.

Keywords: pore pressure, CO₂ injection, induced earthquakes, seasonal earthquakes, remote earthquakes, seismogenic faults

1. Introduction

Subduction zones along active convergent plate margins are areas of high seismicity that drive mountain building processes [1, 2]. Many Asian countries lie along such convergent margins, where earthquakes occur when elevated pore pressure reduces the effective stress on fault planes and unclamps faults, thus triggering slip [2–4]. Because the stresses in seismogenic faults could be commonly close to critical levels [1, 5–11], minor increases of pore pressure can lead to fault rupture. Such increases can be caused by non-tectonic processes such as earth tides, rainfall, snowfall, typhoons, and changes of atmospheric pressure [1, 5–7, 9, 10, 12–17]. Snowfall and rainfall can increase subsurface pore pressure either by hydraulic loading of shallow sediments or by deeper pressure diffusion within fault zones [15, 18–21]. Human activities such as groundwater extraction and fluid injection (e.g., CO₂ storage) can also change the subsurface stress regime and trigger earthquakes [18, 20, 22, 23].

A pilot project for carbon capture and storage (CCS) was in operation at Nagaoka, Japan, from 2003 to 2004 [24–30]. During injection of CO₂ at Nagaoka on 23 October 2004, the Mw 6.8 Chuetsu earthquake struck the area [31–34] with its epicenter about 20 km from the site. In 2018, the Mw 6.6 Hokkaido Iburi-Tobu earthquake struck with its epicenter about 31 km from a CCS demonstration project in Tomakomai, Hokkaido [35]. Because the distances of both of these facilities are not far from

the earthquake epicenters, people worried about the relationship between the earthquakes and CCS activities. Apart from this issue, the location of the Japanese Islands on an active subduction zone means that a reliable method is needed to distinguish between natural subduction-related earthquakes and those possibly induced by CO₂ injection. There will not be a perfect method to classify these earthquakes, because many geological and hydraulic parameters are related to the earthquake generation. However, we should develop a science-based, quantitative approach for the difficult issue we need to solve in CO₂ geological storage. Here we focus on the pore pressure change to evaluate the earthquake rupture initiation. Comparing natural (or seasonal) pore pressure change with the pressure change due to CO₂ storage could enable us to evaluate whether the earthquake is natural or artificial one.

In this study, we calculated the seasonal changes of pore pressure from rainfall and snowfall data from the Nagaoka CO₂ storage site during 2003 and 2004. Then, to allow comparison of those seasonal changes to the effect of CO₂ injection on pore pressure, we used a three-dimensional model of the hydraulic system at the site to numerically simulate pressure changes during CO₂ injection, including their effect on seismogenic faults at various distances. We used the results of the simulation to determine the lateral extent and magnitude of changes of pore pressure due to CO₂ injection and compared them with remote earthquake occurrences [36, 37]. Application of the approach we used will contribute to distinguishing natural earthquakes from those induced by CO₂ injection during CCS projects.

2. Study area

We focused on the region around the Nagaoka CO₂ storage project, in the Niigata back-arc basin of northeastern Japan in **Figure 1** [26]. This region lies above the boundary between the Amur and Okhotsk tectonic plates [33, 34, 38, 39], a region of high seismicity due to convergence of the two plates at a relative velocity of ~1.5 cm/year. The sediments of the Niigata back-arc basin were deposited during the early Miocene opening of the Japan Sea [33]. They comprise a sequence of up to 7 km of sedimentary and volcanic rocks of Miocene to Holocene age that contain oil and gas reservoirs [38, 39]. Earthquakes in this region have been caused by thrust-related fold ruptures within the Muikamachi fault system [31–33]. The 2004 Chuetsu earthquake (Mw 6.8) caused coseismic surface rupture and subsequent landslides that changed the topography in this region [34].

The CO₂ injection layer for the Nagaoka CCS project is in the early Pleistocene Haizume Formation of the Niigata basin. The Pleistocene sediments in the basin are deltaic and shallow-marine sediments (interbedded sand, silt, and mudstone) that provide both reservoirs and caprocks [27, 38–40] within an anticlinal structure related to seismogenic thrust-related folding [33]. CO₂ has been injected into a saline aquifer at ~1100 m depth and is capped by overlying mudstone [27, 40]. The aquifer reservoir is composed of alternating sand and silt beds dipping at 15° and was selected for pilot-scale storage of 10,400 t of CO₂ [27, 40]. As previously mentioned, the 2004 Chuetsu earthquake occurred during CO₂ injection at Nagaoka with its epicenter ~20 km from the site in **Figure 1** [31, 33, 34].

3. Data and Methods

We estimated and compared various pore pressure changes due to CO₂ injection and natural pore pressure changes at the hypocentral depth (13km) of the 2004 Mw 6.8 Chuetsu earthquake by the following approaches. Firstly, we used numerical simulations of fluid flow in a reservoir to estimate pore pressure during and after CO₂ fluid injection. Secondly, we applied the pore pressure diffusion equation for snowfall and rainfall data from Nagaoka in order to determine changes of seasonal pore pressure. Lastly, we estimated the pore pressure change due to remote earthquakes (i.e., the 2011 Mw 9.1 Tohoku-Oki earthquake).

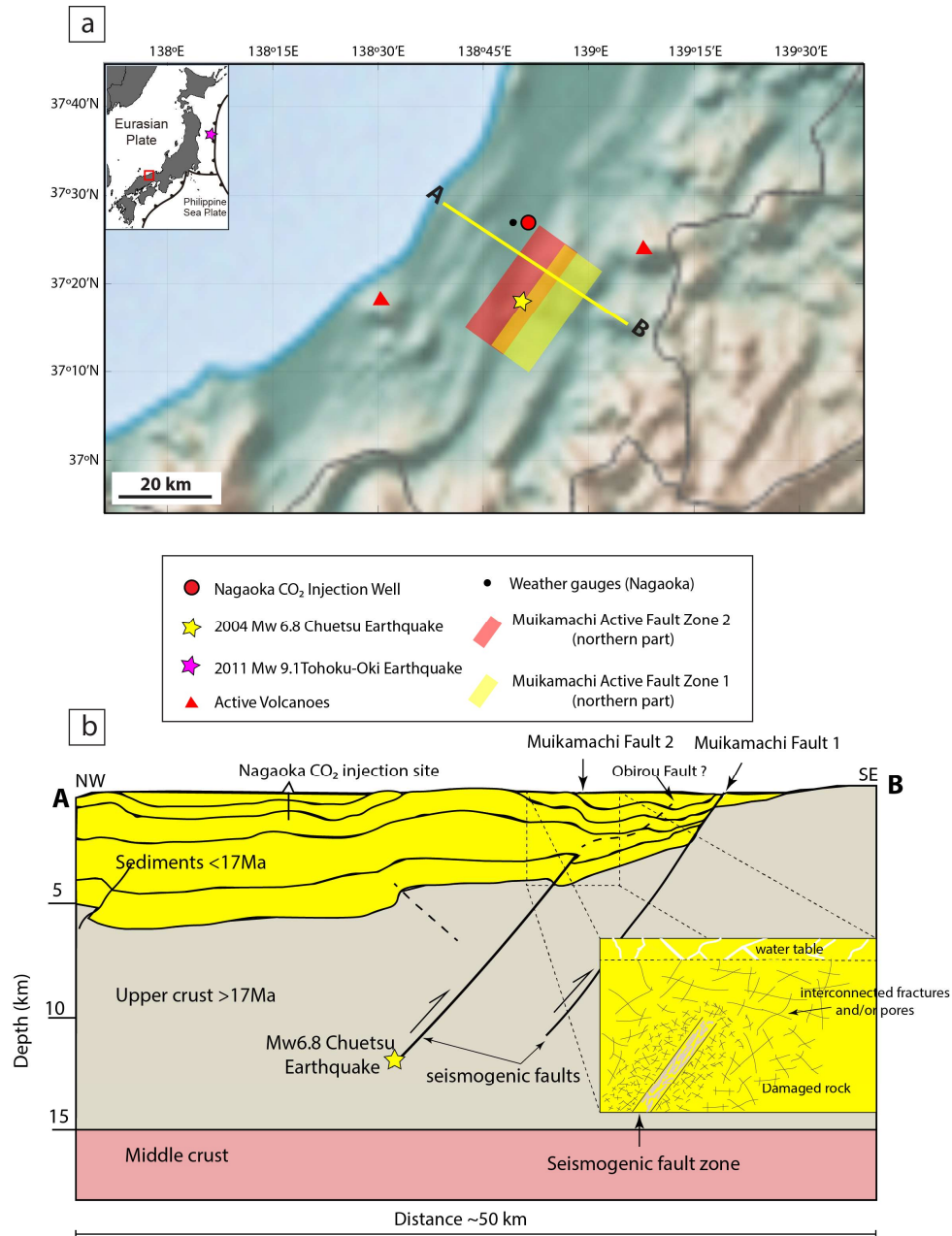


Figure 1. (a) Maps showing the location of the study area. The Mw 6.8 Chuetsu earthquake occurred on 23 October 2004. CO₂ was injected from 7 July 2003 to 1 January 2005. (b) Schematic geological cross section (AB) along the yellow line in panel (a). The cross section is modified from [32] and [41].

3.1. Change of pore pressure due to CO₂ injection

The change of pore pressure due to CO₂ injection was estimated using a dynamic fluid flow numerical simulation. The key parameters of the geological model that we used are provided in Table 1 [28–30, 42]. We first simulated fluid flow without CO₂ injection to determine the steady state

reservoir conditions. We then simulated injection of supercritical CO₂ into the aquifer at rates of 20 to 40 t/day (comparable to the injection rate used at the Nagaoka site) over 18 months from July 2003

Table 1. Key parameters of the geological model used for numerical simulation of fluid flow.

Parameter	Model
Injection depth	1095 - 1105 m
Injection rate	From 20 to 40 t per day
Simulation duration	10 years
Boundary condition	Closed boundaries (top and bottom)
Fluid phase	supercritical CO ₂ and brine
Initial reservoir condition	Pressure: 11.1 MPa, Temperature: 48°C, Salinity: 10000 ppm
Grid size	250 m x 250 m (horizontal), 1 m (vertical)
Porosity	0.22
Permeability	$Kh = 5.00 \times 10^{-15} \text{ m}^2$; $Kz/Kh = 0.1$
Relative permeability (Gas residual)	0.18 (Sand), 0.1 (Mud)
Relative permeability (Water residual)	0.20 (Sand); 0.7 (Mud)

to January 2005. In total, we simulated injection of 10,400 t of CO₂ into an aquifer [26, 27, 40]. Injection was restricted to a 10 m thick layer representing the porous and permeable reservoir sequence encountered at 1095–1105 m depth in the injection well [29, 30, 40]. To simplify our analyses and discussions for pore pressure and its influence upon the earthquake, the model we used for our simulation was relatively simple.

3.2. Seasonal changes of pore pressure

Changes of subsurface pore pressure in response to seasonal changes of rainfall and snowfall can be large in Japan [21, 43, 44]. We estimated these seasonal changes by applying the pore pressure diffusion equation [15, 20] to groundwater recharge from precipitation data [43] for the Nagaoka area (**Figure 1a**) that we obtained from the Japan Meteorological Agency. The equation includes two hydrological loading mechanisms. The first of these considers instantaneous hydrological loading at depth (the undrained response), whereas the second mechanism (the drained response) is based on increased pore pressure diffusion by virtue of a hydraulically connected fracture system extending from the surface to the seismogenic fractures and faults [15, 18–20, 45]. Here we assumed that pore pressure changes were caused only by drained pore pressure diffusion. Pore pressure increases due to undrained instantaneous hydrological loading are difficult to estimate because of the many geological and hydraulic parameters that should be considered. Indeed, for this reason, previous studies by [46] and [15] considered only drained pore pressure changes. In reality, pore pressure changes due to overburden do occur under undrained conditions [15, 47]. Therefore, the natural changes of pore pressure we estimated here are only part of total diffused response values.

Pore pressure P_f at depth r and at time t , expressed by pore pressure diffusion equation, is described as follows:

$$P_f(r, t) = \sum_{i=1}^n \delta p_i \operatorname{erfc} \left[\frac{r}{4c((n-i)\delta t)^{1/2}} \right], \quad (1)$$

where δt is the time increment of the rainfall (i.e., fixed 1 day), n is the number of time increments for our two year calculation (i.e., number of days), δp_i is the precipitation load change (the product of water density ρ , gravitational acceleration g , and precipitation data δh at day n), r is the hypocentral distance from the surface, c is the hydrological diffusivity rate, and $erfc$ is the complementary error function. The value of c for fractures associated with seismicity is in the range 0.1–10 m²/s, decreasing with depth [15, 18, 22]. Here, the diffused pore pressure after n days (P_f) at the hypocentral distance r after the start of rainfall series is the sum of the diffused pore pressure generated by daily precipitation load changes. Here, we estimated the diffused pore pressure at $r = 13$ km, and we considered the sensitivity change of c as 0.1, 0.5, 1, 2, and 4 m²/s in our diffused pore pressure calculation.

Because snow cover is deep in the Nagaoka area in winter, we needed to consider the effect of the supply of water from snowmelt (snow water equivalent). We revised the rain precipitation data to include snow water equivalent by considering snow depth. [48] determined a “degree-day factor” k (mm/°C-day) that they derived from observations in central Japan (Iwate, near our study area; [48, 49]) as follows:

$$k = 0.039x + 2.3, \quad (2)$$

where x represents the snowmelt starting date (Julian date, where 1 January is day 1). That empirical relationship can be used to estimate daily snowmelt rate M according to equation (3) [43, 49, 50].

$$M = \frac{k}{2}(T_x + T_{x-1}), \quad (3)$$

where M is daily snowmelt rate (mm/day), T_x is mean daily air temperature (°C) on day x , and T_{x-1} is mean temperature on the day preceding day x . Finally, after snow depth was obtained and added to the precipitation data, we used equation (1) to estimate seasonal changes of pore pressure in the study area.

3.3. Pore pressure change due to remote earthquakes

We estimated pore pressure change due to remote earthquakes (i.e., the 2011 M_w 9.1 Tohoku-Oki earthquake). Although this earthquake did not occur during CO₂ injection at Nagaoka, seismic velocity data acquired during the event are available [51, 52] and can be used to estimate the changes of pore pressure that would have occurred in the Niigata Chuetsu region.

Laboratory experiments have shown that the relationship between S-wave velocity and pore pressure in sediments from the southern Japan [53] can be expressed as:

$$\frac{\Delta V_s}{\Delta P_f} = 10, \quad (4)$$

where ΔV_s is the change of S-wave velocity (m/s) and ΔP_f is the change of pore pressure or effective stress (MPa). Although this relationship does not necessarily hold for the data from our study area, similar relationships can be obtained for other sedimentary rock types. We calculated the decrease of S-wave velocity that would have occurred in our study area during the 2011 Tohoku-Oki earthquake (M_w 9.1) to be 0.04% on the basis of research by [51] and [52]. If we assume that the S-wave velocity at 13 km depth was 2.5 km/s, the change of S-wave velocity due to that earthquake would have been 1 m/s. Then, according to equation (4), the pore pressure increase during the 2011 Tohoku-Oki earthquake would have been 100 kPa.

4. Results

4.1. Pore pressure changes due to CO₂ injection

As a result of fluid flow simulation considering the geological condition in this study area, our pore pressure and CO₂ saturation distribution results can be consistent with the history of CO₂ injection at the Nagaoka site in **Figure 2** [29, 30, 40]. During the period of injection of CO₂ (**Figure 2c**), the simulated bottom-hole pressure in the well increased from an initial value of 11.1 MPa to ~12.2 MPa. After injection ceased, the pressure decreased dramatically, returning to the initial pressure and remaining there for the rest of the simulation period (**Figure 2c**).

In this study, we mainly focus on pore pressure variation far from the injection well (or close to seismogenic fault). On the day of the Mw 6.8 Chuetsu earthquake (23 October 2004), the simulated elevated pressures due to CO₂ injection extended ~2 km laterally from the injection site (**Figures 2a** and **3**). Therefore, the pore pressure increase due to injection resolved by the numerical simulation would not have extended as far as the seismogenic fault that caused the Chuetsu earthquake (**Figures 1** and **4**).

4.2. Natural variations of pore pressure

We estimated the natural variations of pore pressure at a depth of 13 km using precipitation and snow data, because the hypocenter is at 13 km depth in the epicentral area of the Chuetsu earthquake in **Figure 1** [32]. We calculated the diffused pore pressure changes from 1 January 2003 to 31 December 2004. In the study period, we can observe the increase hydrological loading after adding snowmelt to rainfall data (**Figure 3**). Within two years, our estimates of diffused pore pressure at 13 km depth were varying up to 23 KPa in this region (**Figure 3c**). Therefore, a period of heavy snowmelt and long-term series rainfall considerably influenced groundwater level, leading to increased pore pressure due to subsurface pore pressure diffusion.

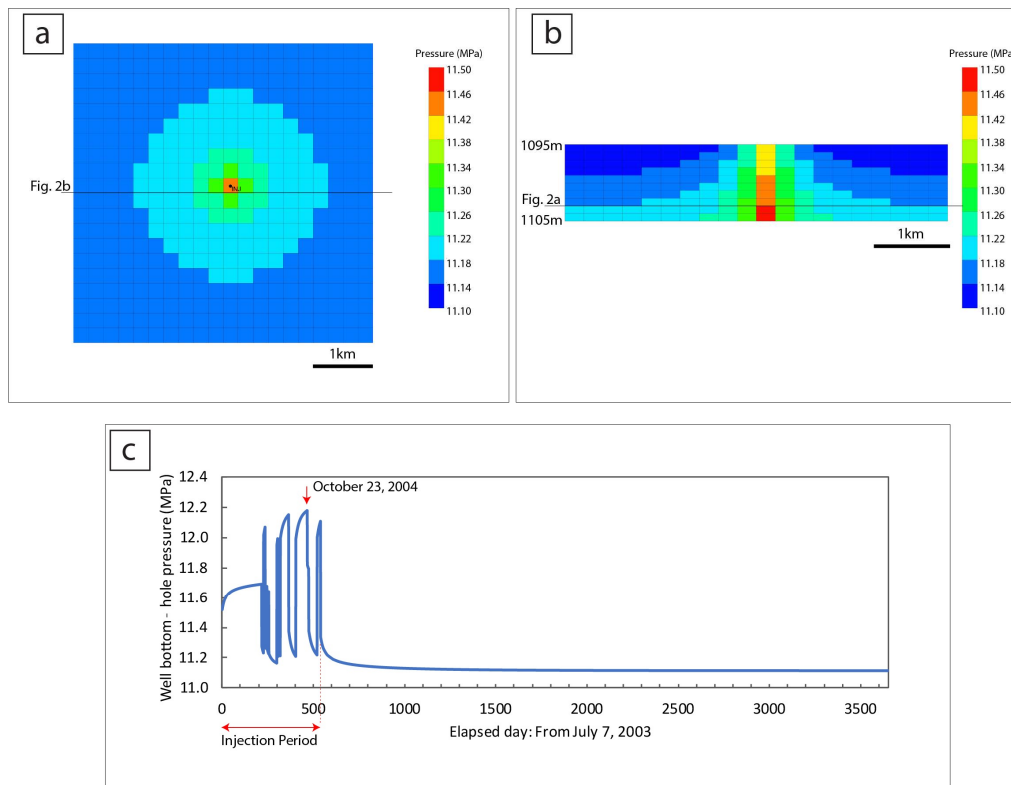


Figure 2. Simulated pore pressure during and after the period of CO₂ injection from 7 July 2003 to 1 January 2005. (a) Plan view, centered on the location of the injection well, of simulated pore pressure at 1103 m depth on the day of the Mw 6.8 Chuetsu earthquake (23 October 2004); (b) profile view of simulated pore pressure for 1095–1105 m depth on the same day. (c) Simulated bottom-hole pressure for 10 years after the CO₂ injection started.

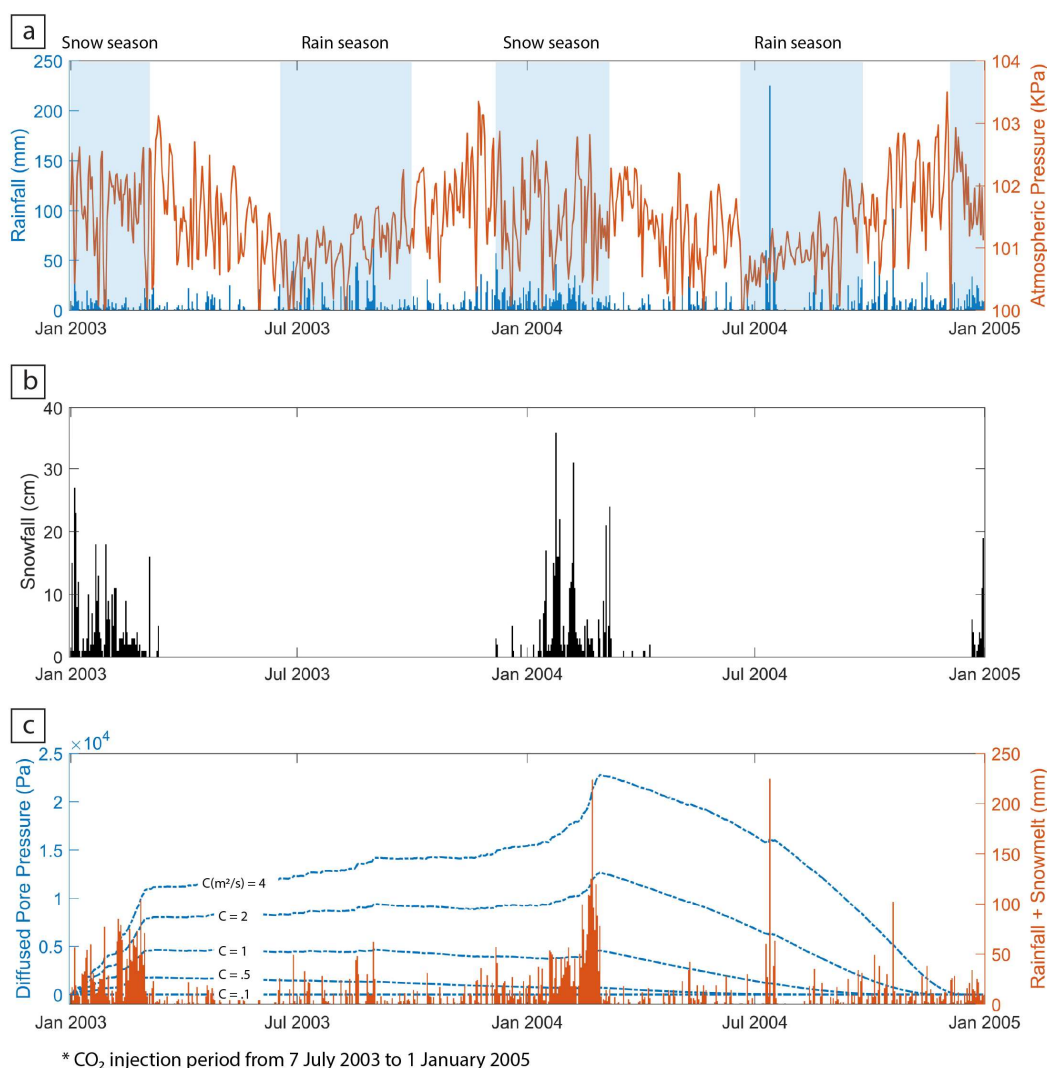


Figure 3. Diffused pore pressure estimated from seasonal variations in the Nagaoka area in 2003 and 2004, (a) rainfall (blue bars) and atmospheric pressure (orange line). (b) Snowfall (black bars). (c) Diffused pore pressure estimation with the sensitivity range of hydraulic diffusivity $c = 0.1, 0.5, 1, 2$, and $4 \text{ m}^2/\text{s}$ (blue lines); snow water equivalent added to the rainfall (orange bars).

5. Discussions - comparison of pore pressure increase due to CO₂ injection with natural variations

Based on our results, the simulated increases of pore pressure due to CO₂ injection were much higher than the seasonal variations of pore pressure close to the injection well (**Figure 4**), but only within a radius of $\sim 2 \text{ km}$ around the well (**Figure 4**). And the vertical extent of the increase due to CO₂ injection was restricted by the caprock overlying the reservoir and the almost impermeable layer 10 m beneath it [29, 30, 40, 42]. Our 10-year simulation showed that the bottom-hole pressure decreased dramatically when injection ceased, returning relatively quickly to the initial steady state pore pressure (**Figure 2c**).

The hypocenter of the Chuetsu earthquake is >20 km from the site of the injection well at a depth of 13 km in **Figure 1** [32, 34]. Therefore, our simulation clearly showed that in the hypocenter the pore pressure increase due to CO₂ injection (**Figure 2**) was very much smaller than the natural fluctuations

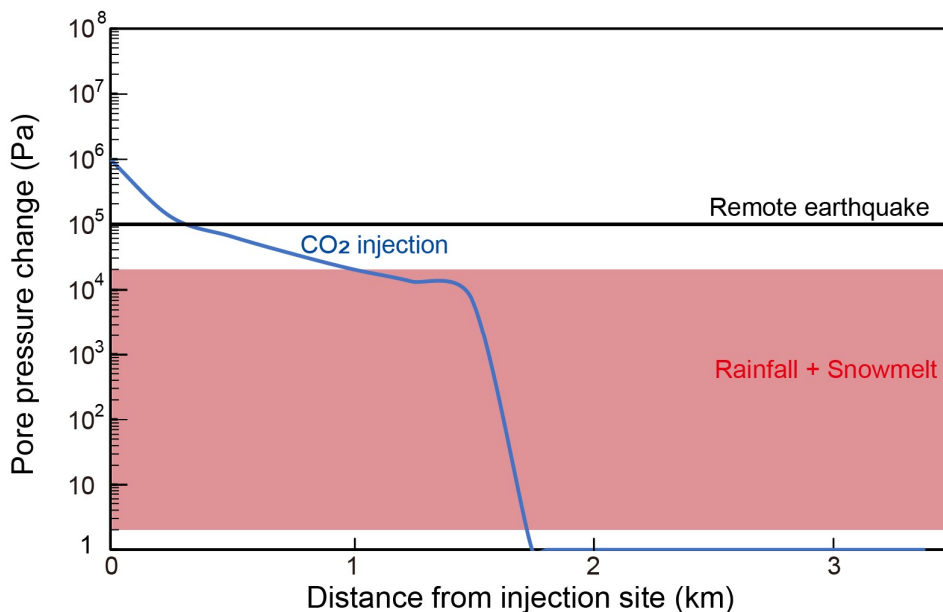


Figure 4. (a) Comparison of the change with distance from the injection well (inferred from Figure 2) of the simulated increase of pore pressure with those related to precipitation (rainfall and snowmelt) and a remote earthquake (here, the 2011 M_w 9.1 Tohoku-Oki earthquake).

of pore pressure (**Figures 3c** and **4**). Furthermore, the estimated natural pressure variation is the total diffused value because we ignored the effect of undrained instantaneous hydrological loading. Therefore, the natural pressure variation is more dominant, suggesting that the 2006 Chuetsu earthquake is natural event. In more details, earthquake could be triggered by shear stress in addition to pore pressure variation. However, the shear stress perturbation due to CO₂ injection is also minor around the hypocenter (similar order to pore pressure).

According to the earthquake catalog by [36], none of the hypocenters of the earthquakes that occurred in the Nagaoka area in 2003 and 2004 were near the injection depth of ~1100 m or within a 2 km radius from the injection site. This is likely because the injected reservoir is within a thick and stable sequence of deltaic and shallow-marine sediments of the Niigata basin [30, 38, 39]. The reservoir is sealed by a mudstone caprock that effectively traps the fluid, and there are no seismogenic fractures or faults within the reservoir (**Figure 1b**). In addition, post-injection fluid sampling and reactive transport modeling of the supercritical injected CO₂ indicate that most of it are dissolved and will be progressively precipitated in the host reservoir by mineral carbonation over the years [28–30, 42]. The dissolution and mineralization processes can reduce the elevated pore pressures caused by the CO₂ injection.

Other natural phenomena that can affect pore pressure include changes of sea surface height, and remote large-magnitude earthquakes. The Nagaoka injection well is about 15 km from the coast; thus, we did not consider effect of sea surface height in this study (**Figure 1**). The effects of large-magnitude remote earthquakes on pore pressure, however, are not negligible. The pore pressure variation due to remote earthquakes is difficult to estimate, though we can roughly estimate it from temporal variation of seismic velocity. [54] investigated subsurface stress changes associated with the 2011 Tohoku-Oki earthquake and found that during the earthquake seismic velocity decreased

greatly over a wide area. A decrease of seismic velocity during the large earthquake were reported by several studies [4, 51]. Seismic velocity variation phenomena such as these are likely caused by mobilization of fluids and elevation of fluid pressure in the crust during shaking; it is possible that the resultant pressurized fluids inflate shallower formations and open cracks in them [4]. Thus, large-magnitude earthquakes can change pore pressures in areas that are distant from them.

Several large and remote earthquakes occurred during the period of CO₂ injection at Nagaoka (e.g. the Mw 6.4 Northern Miyagi and Mw 6.8 Tokachi-Oki earthquakes). Pore pressure changes in response to these earthquakes might have influenced those at seismogenic faults near Nagaoka CO₂ injection. Here, we consider this possibility on the basis of previous research on the influence of the 2011 Tohoku-Oki earthquake (Mw 9.1) on the Niigata Chuetsu region, some 400 km from the epicenter of the 2011 earthquake (**Figure 1a**). According to equation (4) the pore pressure increase during the 2011 Tohoku-Oki earthquake was estimated to be 100 kPa (see section 3.3), clearly demonstrating that a large earthquake can have a marked influence on pore pressure in a remote region up to 400 km from its epicenter (black horizontal line in **Figure 4**). This estimation demonstrates that the large earthquake significantly affects the remote region. Indeed, because of this pore pressure variation, aftershocks frequently occur around the seismogenic faults. Moreover, these increases of pore pressure were larger than the seasonal variations of pore pressure we obtained from daily precipitation data (**Figures 3c and 4**), thus lending further support to the presumption that remote earthquakes can influence pore pressure at considerable distances from their epicenters, which is more significant than those from seasonal change behavior on the seismogenic faults.

6. Conclusions

We have developed a method to distinguish natural earthquake and CO₂ injection-induced earthquake, based on pore pressure. We examined the changes of pore pressure caused by injection of CO₂ at the Nagaoka CO₂ storage site and compared them to natural variation. Our main conclusions are as follows:

- Apart from an area within ~2 km of the injection site, the natural seasonal fluctuations of pore pressure in the broad area around the Nagaoka CO₂ injection site are much greater than those induced by CO₂ injection. Therefore, CO₂ injection at Nagaoka during 2003 and 2004 could not trigger the 2004 Chuetsu earthquake.
- Although seasonal increases of pore pressure are relatively small in the Nagaoka area, they can be large enough to trigger slip on seismogenic faults that are already in a critical stress state due to regional subduction tectonics, especially during periods of snowmelt and rainfall.
- Further investigation is needed of other phenomena that may cause increases of pore pressure large enough to trigger earthquakes (e.g. changes of sea surface height, and large-magnitude remote earthquakes) in order to evaluate the influence of pore pressure change more precisely. The remote earthquake could largely influence upon pore pressure variation. In our result, it shows that pore pressure increase of 100 kPa in Nagaoka area due to 2011 Mw 9.1 Tohoku-Oki earthquake is more significant than those from seasonal fluctuations.
- Our methodology provides a means to distinguish natural earthquakes from those induced by CO₂ injection and can be useful at other CO₂ sequestration sites and at geothermal field developments.

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precipitation, snowfall, and atmospheric pressure data from the Japan Meteorological Agency website (<https://www.data.jma.go.jp/gmd/risk/obsdl/index.php>). Locations of the seismogenic faults considered in this study can be obtained from Japan Seismic Hazard Information Station website (<http://www.jshis.bosai.go.jp/map/JSHIS2/download.html?lang=en>).

Conflicts of Interest: “The authors declare no conflict of interest.”

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