Tracking CO₂ plume footprints in reservoir-caprock system by fibre optic strain sensing

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Underground fluid storage and utilization, e.g., geological storage of carbon dioxide (CO₂) and natural gas, require effective tools to monitor the vertical pressure, deformation, and saturation migrations, and verify the secure containment of the reservoir-caprock system. Here we demonstrate how to utilize the swelling strain signals attributed to the footprints of pressure build up and the adsorption of supercritical CO₂ in natural clay-rich rocks to track the displacement of supercritical CO₂/brine under typical conditions of CO₂ geological storage. Our study effectively captured the breakthrough of CO₂ plume from the analogue “reservoir” part to the “caprock” part using the distributed strain, measured by a high-resolution single-mode Rayleigh-scattering based optical fibre sensor. The magnitude of strain change induced by CO₂ adsorptions on the clay minerals is found to be significantly greater than that caused by pore pressure.
changes alone. The findings suggest that the measured strain changes can not only reveal the in situ deformation state but also be a valid indicator for tracking the movement of CO$_2$ plume as it enters the clay-rich critical region in reservoir-caprock systems, and thus serves as an early warning to the potential occurrence of large deformations caused by high pressure build up.

Underground geological reservoir engineering, e.g., enhanced oil recovery by water or gas injections, geothermal exploitations, shale gas fracking, and natural gas and CO$_2$ storages, often involve fluid injections and/or extractions. During these operations, the in situ state of pressure in the porous space would be inevitably changed, leading to the mechanical deformations in geological formations due to the poroelastic mechanism—the coupling between the deformation of porous matrix and pore fluid flow under stress. The deformations may be significant to cause induced seismicity$^1$ and observable uplift or subsidence of earth ground$^2$. CO$_2$ sequestration into underground geological reservoirs is now considered as one of the best near-term solutions to mitigate global warming effects$^{3-5}$. In a large-scale geological CO$_2$ storage project, another potential problem is associated to the impact of pressure build up on the long-term integrity of a CO$_2$ repository$^6$ and the risk of CO$_2$ or brine leakages$^7$. CO$_2$ could migrate into the caprock if the pressure in the reservoir overwhelms the threshold pressure of caprock. In addition, the reactivation of faults and breach of caprock could also create or enhance vertical leakage pathways, contributing to an unexpected leakage of CO$_2$$^{8,9}$. For these reasons, valid methods are required to closely monitor the development of pressure build up, deformations and CO$_2$ plume migration in reservoir formations and caprocks above the storage reservoir.

Besides poroelastic changes, one of the poromechanical responses, i.e., clay swelling phenomena has been well studied from different aspects of geoscience, e.g., in shales, coals, soils, etc. CO$_2$ can be energetically adsorbed on the surface and edge of clay
minerals or into the crystal interlays, resulting in significant swelling\textsuperscript{10–12}. The swelling can be also significant to change the stress state\textsuperscript{13}. At a given pressure, the swelling is more pronounced with carbon dioxide than with other fluids, like water and methane\textsuperscript{12}. Therefore, it might be anticipated that, as CO\textsubscript{2} displaces brine through clay-rich strata (e.g., caprocks), strain changes due to the preferential adsorption of CO\textsubscript{2} in the clay, in addition to the poroelastic mechanism, could be observed. Taking advantage of this characteristic, we propose to monitor the migration of CO\textsubscript{2}/brine displacement front in clay-rich region in a reservoir-caprock via monitoring the strain (Fig. 1 a).

With the recent development of distributed fibre optical strain sensing (DFOSS) technique\textsuperscript{14}, the response at each spatial location due to rock deformation may be tracked in real-time. Therefore, the tool can potentially give an improved understanding of the roles of pressure migration and CO\textsubscript{2} plume migration along the vertical direction while incorporating the concept of in-reservoir and above-zone pressure monitoring\textsuperscript{15} (e.g., at Decatur CO\textsubscript{2} storage site\textsuperscript{16}), and also give important constraints in geomechanical modelling\textsuperscript{7,17}.

This study aims to measure rock swelling strain caused by CO\textsubscript{2} displacing brine through an analogue reservoir-caprock system. A clay-rich Tako sandstone (from Gunma, Japan) developed with both coarse-grain high-permeability (“reservoir”) and fine-grain low-permeability (“caprock”) regions is used for the experiment (Fig. 1 b). The strain is continuously measured using a high-resolution DFOSS tool (see Methods) during CO\textsubscript{2} drainage and brine imbibition in the sample under a typical reservoir condition (10 MPa and 40 °C). In addition, the X-ray CT is used to image the spatial fluid saturation in the rock.

\textbf{Experimental tests}
The experiment was started from a dry state of the rock sample after two days of vacuum-drying. Then the sample was pressurized step-by-step by increasing the confining pressure (0~15 MPa). After this the confining pressure was reduced to 5 MPa and then the brine (potassium iodide solution, 11.5 wt%) was injected to the vacuumed sample until the sample was fully saturated. Continuous brine injection was conducted to measure the permeability. Then we elevated the confining pressure (to 15 MPa) and pore pressure (to 10 MPa) to investigate the poroelastic effect. After that the CO₂ drainage and brine imbibition were conducted. During the CO₂ drainage, the injection pressure at the inlet and outlet were initially set to 10.1 and 10 MPa, respectively. Under the low differential pressure, the CO₂ fluid flow front gradually migrated with the displacement at the coarse-grain part for approximately 40 hours and then it was blocked by one low-permeability capillary barrier in the fine-grain part. After we elevated the inlet pressure up to 10.3 MPa step-by-step (8 steps, approximately 1 hour/step), the CO₂ flow was able to percolate into the fine-grain part. The overall drainage persisted approximately 68 hours. After the drainage, a forced brine injection from the outlet with a pressure of approximately 10.8 MPa was conducted. The brine injection lasted approximately 20 hours. During these operations, the X-ray CT imaging was only conducted at the day time intermittently to obtain the information of spatial saturation of CO₂ in the rock sample. The distributed strain was continuously measured using the DFOSS system.
Fig. 1a, Schematic geological model of CO₂ storage site, with emphasis on the clay-rich components in the caprock-reservoir transition, tight clay-rich layers within reservoir formations, and paleo-fault with clay smearing. An observation well with the DFOSS installation is used to illustrate the distributed strain sensing across the overall system. b,
The Tako sandstone sample—an analogue to the reservoir-caprock system or clay-rich layers. c, The experimentally obtained profiles of averaged CO₂ saturation (S_{CO₂}) (computed from X-ray CT imaging) along the rock sample. Note that the displayed saturation data are linearly interpolated and coloured with elapse time for a better view. The only measured data is shown in the Supplementary Fig. 7. d, The profiles of circumferential strain (experimentally measured using the DFOSS) on the surface of the rock sample. e, The circumferential strain against time coloured with spatial distance to the inlet end of the sample. Note that the pressure increase between 40 and 50 hours cause only slight swelling strains (< 10 με).
Fig. 2. Differential strain changes (strain/hour) calculated by subtracting two sets of measured strains with a time interval of approximately 3.3 hours. Overall results are divided into six stages (with a time interval of approximately 10 hours) that expressed...
in different colours to emphasize the temporary changes. **a**, Changes before stage 5 (former 40 hours); **b**, Changes of all stages. Colours in **a** and **b** denote time. **c/d**, Images of CO₂ saturation (SCO₂) at 40/60 hours are attached. The changes clearly show the structure-affected deformation behaviour and the breakthrough of CO₂ plume from the high permeability (“reservoir”) part to the low permeability (“caprock”) part.
CO₂ plume migration and distributed strain response

The experimental results reveal that the deformation in the reservoir-caprock system can be effectively monitored using the DFOSS tool. The strain changes well correspond to the spreading of CO₂ plume and show significant differences between the reservoir and caprock parts. During the CO₂ drainage (Fig. 1c-e), the injected CO₂ displaced the brine out from the rock sample as indicated by the saturation changes. The CO₂ plume was retarded by the low-permeability caprock part and then migrated through it after elevating the injection pressure. Before the breakthrough of CO₂ plume to the caprock part, the corresponding strain mainly responded at the reservoir region with the gradually increased strain magnitude (0~260 με). Unlike the relatively steep gradients near the CO₂ saturation front, the changes of strain showed a more gradual trend and occurred earlier than the changes in the CO₂ saturation due to the mechanical effect and forward pressure migration. However, the large changes (~200 με) were mainly within the reservoir part where the CO₂ plume developed. Moreover, the strain changes show spatial dependence on the rock structure. Several local low-porosity layers showed strain changes with a reduced magnitude and also a lower CO₂ saturation. These layers acted as the temporal in-passing capillary barriers for the forward CO₂/brine displacement.

The breakthrough of CO₂ plume occurred after the injection pressure was step-elevated from 10.1 MPa to 10.3 MPa. Subsequently, significantly large and rapid strain changes in the caprock part were observed (Fig. 1d and e). The breakthrough pressure for CO₂ percolating through the rock was less than 300 kPa under the setting condition. The breakthrough behaviour was well indicated by the strain signals. Note that the pressure change (200 kPa) itself only produced a small strain (< 10 με) (Fig. 1e). The large strain changes in the caprock part mainly occurred following the migration of CO₂ plume with CO₂/brine replacement. The dynamic deformations are better depicted using the
differential strain between steps, which show more discernible time-dependent
behaviour (Fig. 2). Overall, during the drainage, the changes in strain can well reveal
the migration of CO₂/brine displacement front in the reservoir and breakthrough to the
caprock in the rock sample. On the contrary, during the imbibition, the rock sample
showed a general trend of shrinking after an initial short period of swelling caused by
the elevated pore pressure (Supplementary Fig. 8).

**Adsorption-induced swelling as a CO₂ migration indicator**

Note that the values of the strain changes are significantly larger than that would be
expected due to pure pore pressure effects as estimated from the poroelastic mechanism.
Under the fully brine saturated state, the bulk modulus of the rock was estimated
approximately 7.6 ~ 8.8 GPa (the coarse-grain part) and 8.3 ~ 10.0 GPa (the fine-grain
part, see Supplementary Fig. 9). Consequently, under the given maximum 300 kPa of
change in the effective pressure, the upper limit of the poroelastic (circumferential)
dereformation was expected to be smaller than 20 με. The limit well constraints the
actually produced strain changes (< 10 με) due to pressure change (200 kPa) alone
when elevating the pore pressure during the drainage. However, the measured strain
values (~260 με) after CO₂ displacing brine are in fact much larger than this limit, and
even larger than the strain value produced by 2 MPa of pore pressure changes
(approximately 100 με) when the sample is fully saturated with brine (Supplementary
Fig. 9b).

The large changes in strain are likely related to the abundant content of clay mineral
(kaolinite) in the rock. CO₂ is preferentially adsorbed on clay minerals with respect to
brine. An injection of CO₂ into a clay-rich rock initially full of brine causes a
differential swelling of the porous matrix. In contrast, during brine imbibition, the CO₂
desorption by brine induces a shrinkage. Several recent studies have shown that CO₂
can be adsorbed in clay-rich rocks accompanying significant swelling\(^1\). The CO₂
adsorption in kaolinite was supported by both physical chemistry studies\textsuperscript{18–20} and direct experimental studies\textsuperscript{12}. Unlike the very large swelling strain ($\sim 10^4 \mu \epsilon$) observed in coal samples due to CO$_2$ adsorption, however, the CO$_2$ adsorption induced strain in a kaolinite bearing rock (i.e. shales) can be as large as $\sim 10^3 \mu \epsilon$\textsuperscript{12}. Compared with other fluids, e.g., methane and water, the adsorption ability of CO$_2$ in clay minerals is more outstanding\textsuperscript{12,21}. Such enhanced swellings can also be found in several previous studies where strain measured using conventional strain gauges when CO$_2$ displacing brine in rocks\textsuperscript{22}. However, it lacks an explicit explanation in these studies.

We numerically simulated the effects of adsorption induced strain using a sequentially coupled one-dimensional two-phase fluid flow and poromechanical model. A Langmuir-type adsorption relationship with saturation scaling was used to model adsorption induced strain changes during CO$_2$ saturating\textsuperscript{32}. In order to see the maximum value of probable deformations due to the poroelastic mechanism alone, with a comparison to the adsorption included model, we used a lower limit of measured bulk modulus (7.6 GPa). The modelling results show that the poroelastic alone can only produce a maximum circumferential strain of approximately 16 $\mu \epsilon$ (Supplementary Fig. 10). In contrast, by adding the adsorption induced deformation mechanism, the magnitude of measured strain ($\sim 260 \mu \epsilon$) can be well interpreted (Supplementary Fig. 11). Moreover, the modelling can generally reproduce the behaviour of the breakthrough to caprock and structure-dependent deformations. The rock porosity structure controls the spatial distribution of capillary entry pressure, which further causes differences in the spatial CO$_2$ saturation. The latter controls the adsorption induced deformations together with the role of pore pressure.

**Implications for reservoir monitoring using DFOSS**

Clay-rich rocks are common in a reservoir-caprock system for geological storage of CO$_2$ and natural gas. These rocks may appear at the transition between the reservoir and
caprock, tight interbedding shale-contained layers within overall high-permeability reservoir (e.g. the CO\textsubscript{2} storage sites at Sleipner, Norway\textsuperscript{23} and Nagaoka, Japan) and sealed paleo-fault zones with the clay smearing\textsuperscript{24}. In a large-scale CO\textsubscript{2} storage project, during CO\textsubscript{2} injection and post-injection stages, the appearances and migrations of CO\textsubscript{2} and deformations at all these parts are critical and required to be closely monitored. In addition, even some of the targeted reservoir formations for CO\textsubscript{2} storage have been found to contain a rich amount of clay minerals. For example, the sampled rocks from the Takinoue formation, which is the targeted CO\textsubscript{2} storage reservoir for a large-scale CO\textsubscript{2} storage demonstration project at Tomakomai, Hokkaido, Japan, have been found containing smectite and montmorillonite\textsuperscript{25}. Our studies indicate that the changes in strain can be significantly enhanced (in several hundreds of \( \mu \epsilon \)) with the adsorption of CO\textsubscript{2} in the clay-rich parts, under slight pore pressure changes, compared with the role of poroelastic effect played alone. Moreover, to field applications, utilizing these signals, one can directly monitor the migration of CO\textsubscript{2} plume—whether the CO\textsubscript{2} plume has passed through the monitored regions (e.g., lower caprocks), and diagnose the potential fluid leakage risk, to assist in further decision making, injection planning and reservoir management. The study helps in how to distinguish between the pore pressure propagation effects (pressure footprint) and CO\textsubscript{2} migration through caprock (saturation footprint) from the deformation pattern and magnitude. The former shows gradual changes with the magnitude increasing from small to large with the pressure build up; whereas the latter could give a relatively large strain change in a short term once CO\textsubscript{2} has migrated to the clay-rich caprock.

Our study straightforwardly demonstrates that the spatial strain can be effectively measured using the DFOSS with high accuracy and resolution. Overall, the utilization of DFOSS tool can not only directly give the information in deformation but also the migration of fluid plume in a reservoir-caprock system. The findings and application of distributed fibre-optical strain sensor are thought to be advantageous in underground
reservoir monitoring and management. In practice, the technique can be integrated with other tools, e.g., pressure\textsuperscript{16}, seismic\textsuperscript{33}, electric, microseismic monitoring\textsuperscript{9}, etc., for further more solidly tracking CO\textsubscript{2} plume and diagnosing potential reservoir geomechanical and fluid flow problems in a broad area. Here we focus on the strain responses to CO\textsubscript{2} injections for the purpose of CO\textsubscript{2} storage in underground reservoirs. However, the same technique can be also valid for other geological problems involving geomechanical monitoring, e.g., fluid extractions or injections in oil and gas reservoirs\textsuperscript{26} and geothermal exploitations, mine exploitations, crustal deformations relevant to earthquakes\textsuperscript{27}, etc.

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METHODS

Rock sample

The rock sample used in this study is cored along a direction perpendicular to the bedding plane from a low-permeability (~ 0.02 mD) heterogeneous Tako sandstone (from Gunma, Japan). The cylinder sample, with a diameter of 35 mm and length of 80 mm, visually contains two regions, a coarse-grain and a fine-grain region (Fig. 1 b). The two parts have different petrophysical characteristics, including permeability, porosity (Supplementary Fig. 1) and pore size (Supplementary Fig. 2). The coarse-grain part has a larger pore size, porosity and permeability than the fine-grain part. Both of the two parts have high content of the clay mineral—kaolinite (Supplementary Fig. 3).

According to the results of X-ray powder diffraction (XRD) analysis, the mineral compositions of the two parts (coarse and fine) are as follows: quartz (52.2% and 38.0%), kaolinite (36.0% and 52.8%), Muscovite (2.8% and 8.3%), K-feldspar (8.0% and 0.9%) (Supplementary Fig. 4). The sample could be seen as an analogue for two typical components in a reservoir-caprock system, such as the transition part between caprock and reservoir, sand mud alternation, and the tight interbedding layers within a reservoir (Fig. 1 a). The rocks in these components are usually clay-rich and have a low permeability compared to common reservoir sandstones.

Experimental settings

A quartz-made single-mode holey optical fibre was spirally bonded on the surface of the cylindrical sample in order to increase the measurement density (Supplementary Fig. 5). The holey fibre, with empty holes distributed in the cladding outside fibre’s glass core, has a low bending loss for light signals, making it is suitable to measure the circumferential deformation of cylindrical sample under high stress conditions. To be able to apply a high injection pressure and confining pressure, the sample was jacketed
using the epoxy paste to insulate the confining oil and pore fluids and then put into a core holder (Supplementary Fig. 6), which is made of an X-ray transparent and high strength material (PEEK). Two high accuracy syringe pumps were connected to the two side of rock sample to control the pressure and injection. In order to keep the CO₂ in a supercritical condition, the pore pressure was set above 10 MPa and the temperature of the whole system was kept at 40 °C using the carbon cloth heaters or water circulation heaters. The fibre was passed through the being pressurized core holder by a feedthrough component, which prohibits the leakage of fluids. The entire core holder was put on the bed of a medical X-ray CT scanner to make imaging available. The fibre segment was connected to prolonged segments and then connected to an integrated measurement equipment (Neubrex 7020 type). The strain sensing tool is developed on the basis of a coherent optical time-domain reflectometer (COTDR) method utilizing Rayleigh backscattering signals from the inherent random defects in an intact fibre to detect deformations\textsuperscript{28,29}. It can give a high measurement accuracy (0.5 \(\mu\varepsilon\)) and spatial resolution (2 cm), allowing to monitor very small strains in a long-range distributed mode. The accuracy of the DFOSS technique has been demonstrated in several prior tests with a comparison with the conventional strain gauges\textsuperscript{30,31} and successfully applied in field wellbores with water injection tests and measurements\textsuperscript{32}.

**Measurement principle of COTDR using optical fibre**

The COTDR (coherent optical time domain reflectometry) technique calculates strain or temperature using the shift in the frequency of the power spectral of the Rayleigh backscatter traces from a single-mode fibre\textsuperscript{28}. In the method, the light source is precisely frequency-controlled. The frequency shift is calculated using the cross-correlation between two spectral of COTDR measurements at two time points. At a spatial location of a fibre, if there is no change in strain and temperature during the time interval, the two power-spectral should be coincident in the frequency domain. Instead,
a phase difference between them exists if there are changes in strain or temperature due
to the changes in local refractive index. The strain or temperature is calculated from the
shift in the frequency of the power spectral.

**Model of adsorption induced swelling strain**

The adsorption induced swelling strain $\varepsilon$ in confine pores can be described by a refined
poromechanical model\textsuperscript{33},

$$\varepsilon = \varepsilon_0 + \int_{P_{b0}}^{P_b} \frac{dP_b}{K} \{\alpha(1-\chi)^{-1} - 1\} \quad (1)$$

where $\varepsilon_0$ is the initial strain, $K$ is the bulk modulus, $\alpha$ is the Biot’s coefficient, $P_b$ (0
denotes the initial state) is the new defined effective pore pressure, and $\chi$ is the
confinement degree. The confinement degree $\chi$ scales the pore fluid pressure $P_f$ and $P_b$
as

$$dP_f = \frac{dP_b}{1-\chi} \quad (2)$$

The equation (1) predicts a swelling strain similar to the Langmuir type sorption model.  
Analytically, it is equivalent to an empirical Langmuir type deformation model\textsuperscript{34},

$$\varepsilon_{\text{ sorp}} = \frac{\varepsilon_{\text{ max}} P}{P + P_{\text{ f}}^\varepsilon} \quad (3)$$

where $\varepsilon_{\text{ sorp}}$ is the adsorption induced volumetric strain at pressure $P$, and $\varepsilon_{\text{ max}}$ and $P_{\text{ f}}^\varepsilon$
are similar to the Langmuir-type constants for scaling the strain.

**The poroelastic model for the two-phase fluid flow**

A sequentially coupled one-dimensional two-phase fluid flow and poromechanical
model was used for the numerical simulation. The model was developed on the basis of
an open source reservoir simulator (MRST)\textsuperscript{35}.
The two-phase fluid flow equation is as following,

$$\phi \rho_a S_a \frac{\partial S}{\partial t} + \nabla \cdot (\rho_a v_a) = \rho_a Q_a$$  \hspace{1cm} (4)

where $\phi$ is the porosity, $\alpha$ (w or nw) denotes the wetting and nonwetting fluid, $\rho$ and $S$ are the density and saturation of the fluids, and $Q$ is the source. The flow flux $v$ is expressed using the extended Darcy’s law,

$$v_\alpha = -\frac{k_{ra}}{\mu_\alpha} (\nabla p_\alpha - \rho_\alpha g \nabla h)$$  \hspace{1cm} (5)

where $K$ is the permeability, $k_{ra}$ is the relative permeability, $\mu_\alpha$ is the viscosity of a fluid, $p$ is the pressure, and $\rho_\alpha g \nabla h$ accounts for the gravity force.

In the modelling, the permeability at each location is estimated using the Leverett J-function as following:

$$K_i = \phi_i \frac{1}{P_c(S_w)} [\sigma \cos(\theta) J(S_{w,i})]^2$$  \hspace{1cm} (6)

where $i$ denotes the spatial location, $\sigma$ and $\theta$ are the interfacial tension and contact angle between CO$_2$ and brine, and $P_c$ is the global capillary pressure at each saturation ($S_w$) estimated from mercury injection method. The Leverett J-function $J$ is expressed as

$$J(S_w) = \frac{P_c}{\sigma \cos \theta} \sqrt{\frac{k}{\phi}}$$  \hspace{1cm} (7)

The local capillary pressure is also accounted by scaling the global capillary pressure using local porosity ratio as following,

$$P_c(S_w, i) = \overline{P_c}(S_w, i) \left(\frac{\phi_0}{\phi}\right)^n$$  \hspace{1cm} (8)

where $\phi_0$ is the mean porosity and $n$ is a tuning exponent.

The mechanical responses are modelled using following equations,

$$\nabla \cdot \sigma_{ij} + f = 0$$  \hspace{1cm} (9)

$$\varepsilon_{ij} = \frac{1}{2} (\nabla u_i + \nabla u_j)$$  \hspace{1cm} (10)
where \( \sigma_{ij} \) is the stress tensor, \( f \) is the body force, \( \varepsilon_{ij} \) is the strain tensor, \( u_i \) is the displacement, \( G \) and \( K \) are the shear and bulk modulus, \( b \) is the Biot’s coefficient, \( p \) is the pore pressure, \( \delta_{ij} \) is the Kronecker delta, and \( \varepsilon_{\text{sort}} \) is the adsorption-induced strain.

**Calculation of CO\(_2\) saturation from X-ray CT imaging**

A medical X-ray CT scanner (Aquilion ONE TSX 301A, Toshiba Medical Systems Corp.) was utilized to image the rock sample. The reconstructed image volume has total 160 slices along the axis direction (80 mm long). Each slice has total \( 512 \times 512 \) pixels. The length of each pixel is approximately 71\( \mu \)m.

The following equations is used to determine the CO\(_2\) saturation, \( S_{\text{CO}_2} \), of each voxel,

\[
S_{\text{CO}_2} = c \left( CT_{\text{obs}} - CT_{\text{brine sat}} \right) = \frac{CT_{\text{obs}} - CT_{\text{brine}}}{CT_{\text{CO}_2} - CT_{\text{brine}}} \tag{12}
\]

where \( CT_{\text{brine}} \) and \( CT_{\text{CO}_2} \) are the voxel CT values of the brine-saturated and CO\(_2\) saturated states, respectively, \( CT_{\text{obs}} \) is the CT value of the state which saturation is being calculated, \( c \) is the coefficient that relates \( S_{\text{CO}_2} \) to the changes between CT values.

**Mineral analysis**

The mineral analysis was conducted using the Rigaku Smartlab Intelligent X-ray diffraction (XRD) system.

**Acknowledgements**

This work is part of an R&D project “the Development of Safety Management Technology for Large-Scale CO\(_2\) Geological Storage, commissioned to the Geological Carbon Dioxide Storage Technology Research Association by the Ministry of Economy, Trade and Industry (METI) of Japan”. We thank K. Nakano for the help in XRD mineral analysis.

**Author contributions**

Z.X. and Y.Z. conceived the project, Y.Z. designed the experiments, H.P., Y.Z. and T.K. performed the experiments, Y.Z., J.S. and X.L. contributed to data analysis and
theoretical interpretations, Y.L contributed to theoretical interpretations and molecular
dynamics simulations, Y.Z wrote the first draft of the paper and all co-authors improved
the final version.

Data availability

The authors declare that all necessary data supporting the findings of this study are
available within the article and its Supplementary Information files. Any further data
(for example, X-ray CT images and strains) are available from the corresponding author
upon request.

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